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Centre for Climate Change Economics and Policy

Background Paper

The Economic and Social Benefits of Low-Carbon Cities: A Systematic Review of the Evidence

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Executive summary

Over half of the population of the world live in urban areas. This means that efforts to meet human development goals and sustain economic growth must be concentrated in cities. However, the pursuit of more prosperous, inclusive and sustainable urban development is complicated by climate change, which multiplies existing environmental risks, undermines the effectiveness of existing infrastructure, and creates new resource constraints.

In this paper, we conclusively demonstrate that there are many synergies between aspirations for urban development and the imperative for climate action. We draw on over 700 papers, focusing on the literature on low-carbon measures in the buildings, transport, and waste sectors. This systematic review clearly shows that low-carbon measures can help to achieve a range of development priorities, such as job creation, improved public health, social inclusion, and improved accessibility.

There is already strong evidence of an economic case for climate action. *The Stern Review: The Economics of Climate Change* demonstrated that the benefits of strong and early action to reduce greenhouse gas emissions far outweigh the economic costs of not acting.[1] Subsequent research for the Global Commission on the Economy and Climate demonstrated that low-carbon measures could be economically attractive on their own merits. One analysis suggested that low-carbon investment in cities might have a net present value of US$16.6 trillion by 2050.[2] This economic case is an important, but not sufficient, condition for deep decarbonisation.

Photo credit: Visty Banaji

About this working paper

This working paper was prepared by the University of Leeds. It was developed in partnership with the Coalition for Urban Transitions, which is a major international initiative to support decision makers to meet the objective of unlocking the power of cities for enhanced national economic, social, and environmental performance, including reducing the risk of climate change. The research presented here was conducted in support of the Coalition's Economics workstream, and builds on previous University of Leeds and Coalition research on the economic and social benefits of low-carbon cities. The opinions expressed and arguments employed are those of the authors.

Citation

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To accelerate action on climate change, low-carbon measures must help to realise other development priorities. So-called "co-benefits" can be defined as positive social, economic, and environmental impacts beyond emission reductions. These may or may not be monetised. We hope that identifying synergies between human development goals and climate mitigation will help to build the political will and public appetite for ambitious low-carbon action in cities.

CO-BENEFITS OF CLIMATE ACTION IN CITIES

Our systematic review of the literature focused on three sectors: energy efficiency in buildings, low-carbon transport, and sustainable waste management. Where relevant within each of these sectors, we identified and assessed four categories of co-benefits: public health, employment, congestion, and inclusion. The key findings are summarised below. In almost every sector, we found that the wider benefits of mitigation are comparable with, or greater than, the direct economic returns associated with reduced energy expenditure, transport fares, user fees, and so on.

Energy-efficient buildings

Public health:

- Up to 3 billion people rely on open fires for heating, cooking, and lighting, leading to 4 million deaths from indoor air pollution. When health benefits are considered, the benefits of adopting solar lighting and clean cook stoves in cities can be worth up to 60 times the investment needs.
- Poor heating and ventilation contribute to chronic ill health. While the direct savings on energy bills are sufficient to generate an attractive return on investment, the monetised health benefits associated with improving indoor environmental quality can be more than 10 times the value of energy savings.

Employment:

- Investments in upgrading existing buildings and raising the energy efficiency of new buildings in OECD cities could lead to the creation of 2 million net jobs annually in the period to 2050. Equivalent investments in non-OECD cities could generate between 2 million and 16 million net jobs annually in the same period.
- Workers in energy-efficient buildings have been found to be 1–16% more productive, due to an improved working environment and lower rates of illness.
- A doubling of urban population density can improve economic productivity by 3%, primarily from agglomeration effects associated with improved access to jobs and services.

Inclusivity:

- Of the total benefits associated with building retrofit programmes in Europe, 16–50% are in the form of improved health, thermal comfort, living conditions and productivity of residents, especially for residents of relatively lower socio-economic standing.

Low-carbon transport

Public health:

- The value of health benefits from investments in cycling infrastructure can amount to more than five times the investment needs. Extrapolating across Europe, this suggests that the health benefits from cycling could be worth US$35–136 billion (2017 prices) annually.
- Motor vehicle crashes are responsible for 1.3 million global deaths each year and over 78 million injuries. Where public transport networks are well developed, transport-related injuries are more than 80% lower.

Congestion and travelling time:

- Congestion costs, through lost time and wasted fuel, amount to more than 1% of GDP in most developed cities, and figures as high as 10% of GDP in developing cities. Congestion charges, planned or implemented across more than a dozen global cities, have been found to reduce traffic, travel times, and congestion by 10–30%.
- More roads often lead to even slower travel times. Conversely, public transit can provide a dramatic reduction in travel times, in some cases reducing them by more than 50%.

Employment:

- Investments in expanding public transport and improving vehicle efficiency could lead to the creation of more than 3 million net jobs annually in OECD cities, and between 3 million and 23 million net jobs annually in non-OECD cities, in the period to 2050.

Inclusivity:

- People from lower income brackets typically spend more time commuting. Improving accessibility therefore disproportionately benefits the urban poor.
- Vulnerable populations often have poorer health than the average. They may also be more likely to live and work in polluted areas. As a result, marginalised groups benefit disproportionately from interventions that improve air quality.

Solid waste management

Health:

- Pulmonary disease is 1.4 to 2.6 times more common among landfill workers compared with the overall population. Efficiently and safely collecting landfill gas for flaring and/or energy generation has the potential to significantly reduce the occurrence and prevalence of such respiratory disorders.
- After management of human waste, policies and processes for managing solid waste can be one of the most effective means of improving public health in urban areas.

Employment:

- In Bangladesh, there are potentially over 200,000 jobs and livelihoods associated with solid waste management. Composting and recycling initiatives could account for a significant number of new, and better paid, jobs.

Inclusivity:

- Investments in recycling schemes can offer new job opportunities for skilled and unskilled workers, new revenue streams for local governments, and potential for improved working conditions for waste workers.

This evidence suggests that the benefits of these low-carbon measures extend far beyond emission reductions. The wider economic, social, and environmental impacts may be much more valuable than the financial returns associated with climate action. This bundle of measures could therefore provide a platform for more transformative change by building public enthusiasm for low-carbon urban development, as well as the institutional capacities, financing arrangements, and learning needed for more ambitious action.[3]

RESPONDING TO LOCAL PRIORITIES IN CITIES

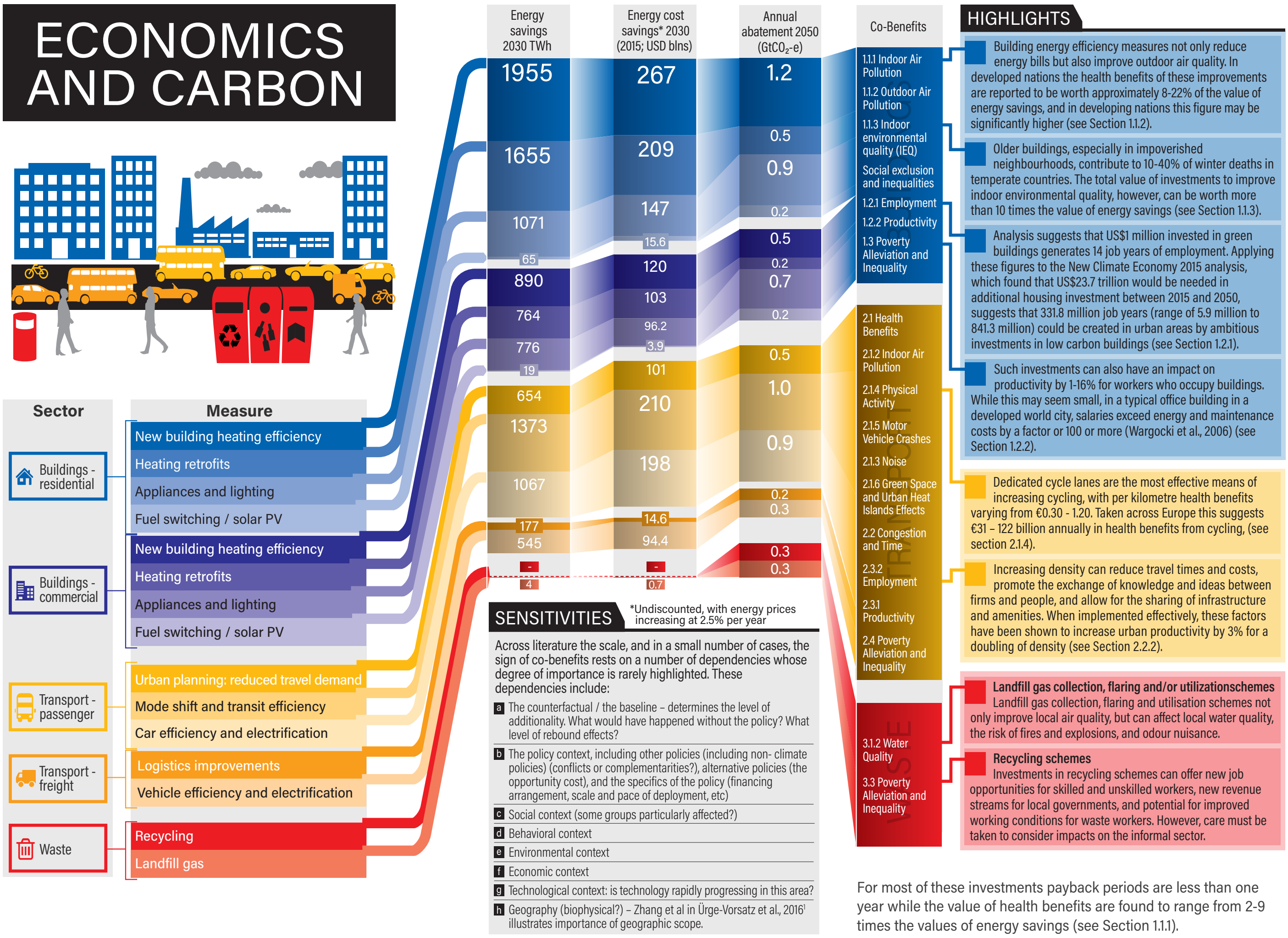
The extent to which low-carbon actions could help address wider urban challenges is significantly under-appreciated. Indeed, the evidence collated in this report suggests that development goals such as improved public health, reduced congestion, full employment, and poverty alleviation may be hard to achieve without low-carbon action.

The distribution of co-benefits and the scale of synergies varies in different contexts. Where roads are congested and vehicle numbers are rising, investments in public and non-motorised transport infrastructure are important to improve access to jobs, services, and amenities. Where older or poorly designed buildings create poor living conditions and high energy bills, retrofits can improve the health of inhabitants while reducing their energy bills. In low-income cities without comprehensive waste management systems, improvements in collection, recycling, and landfill practices can create jobs and reduce the incidence of disease. Each of these interventions therefore responds to local priorities while cutting greenhouse gas emissions.

It is important to acknowledge that such synergies are not guaranteed. The design, implementation, financing, and operation of low-carbon measures will determine their feasibility and acceptability in different contexts. Policies and programmes should be informed by a systematic analysis of the underlying relationships between different development goals, and through extensive consultation with local urban residents. Without an inclusive and evidence-based approach, low-carbon measures may not yield either their mitigation potential or deliver wider development gains.

The benefits of mitigating climate change are often uncertain in scale and global in nature. Most will also be felt in the medium to long term. By comparison, this systematic review reveals that many of the co-benefits of urban climate action are local and near-term: improved air quality, reduced fuel poverty, shorter travel times, new jobs, and better health. Decision-makers have a strong incentive to deliver these benefits today. Understanding the synergies between low-carbon measures and other development goals therefore creates opportunities to integrate climate considerations into national and local policy agendas. We do not say that deep decarbonisation will be easy. However, this systematic review of the evidence base clearly shows that there are diverse, immediate, and substantial benefits to climate action in cities.

Figure 1
Economics and Carbon



*Undiscounted, with energy prices increasing at 2.5% per year

SENSITIVITIES

Across literature the scale, and in a small number of cases, the sign of co-benefits rests on a number of dependencies whose degree of importance is rarely highlighted. These dependencies include:

- a The counterfactual / the baseline – determines the level of additionality. What would have happened without the policy? What level of rebound effects?
- b The policy context, including other policies (including non- climate policies) (conflicts or complementarities?), alternative policies (the opportunity cost), and the specifics of the policy (financing arrangement, scale and pace of deployment, etc)
- c Social context (some groups particularly affected?)
- d Behavioral context
- e Environmental context
- f Economic context
- g Technological context: is technology rapidly progressing in this area?
- h Geography (biophysical?) – Zhang et al in Ürge-Vorsatz et al., 2016[1] illustrates importance of geographic scope.

HIGHLIGHTS

Building energy efficiency measures not only reduce energy bills but also improve outdoor air quality. In developed nations the health benefits of these improvements are reported to be worth approximately 8-22% of the value of energy savings, and in developing nations this figure may be significantly higher (see Section 1.1.2).

Older buildings, especially in impoverished neighbourhoods, contribute to 10-40% of winter deaths in temperate countries. The total value of investments to improve indoor environmental quality, however, can be worth more than 10 times the value of energy savings (see Section 1.1.3).

Analysis suggests that US$1 million invested in green buildings generates 14 job years of employment. Applying these figures to the New Climate Economy 2015 analysis, which found that US$23.7 trillion would be needed in additional housing investment between 2015 and 2050, suggests that 331.8 million job years (range of 5.9 million to 841.3 million) could be created in urban areas by ambitious investments in low carbon buildings (see Section 1.2.1).

Such investments can also have an impact on productivity by 1-16% for workers who occupy buildings. While this may seem small, in a typical office building in a developed world city, salaries exceed energy and maintenance costs by a factor or 100 or more (Wargocki et al., 2006) (see Section 1.2.2).

Dedicated cycle lanes are the most effective means of increasing cycling, with per kilometre health benefits varying from €0.30 - 1.20. Taken across Europe this suggests €31 – 122 billion annually in health benefits from cycling, (see section 2.1.4).

Increasing density can reduce travel times and costs, promote the exchange of knowledge and ideas between firms and people, and allow for the sharing of infrastructure and amenities. When implemented effectively, these factors have been shown to increase urban productivity by 3% for a doubling of density (see Section 2.2.2).

Landfill gas collection, flaring and/or utilizationschemes
Landfill gas collection, flaring and utilisation schemes not only improve local air quality, but can affect local water quality, the risk of fires and explosions, and odour nuisance.

Recycling schemes
Investments in recycling schemes can offer new job opportunities for skilled and unskilled workers, new revenue streams for local governments, and potential for improved working conditions for waste workers. However, care must be taken to consider impacts on the informal sector.

For most of these investments payback periods are less than one year while the value of health benefits are found to range from 2-9 times the values of energy savings (see Section 1.1.1).

Introduction

THE IMPORTANCE OF CO-BENEFITS TO SPUR CLIMATE ACTION IN CITIES

The impact of climate change on cities will be substantial. Rising seas, heatwaves, air pollution, and weather disasters made more violent by changing weather patterns are already affecting millions of lives and costing billions to livelihoods each year.[4] Potentially of even greater importance are the indirect impacts of climate change: increased human displacement, food and water insecurity, vector-borne disease, and conflict are on the rise.[5] The benefit of climate action, however, can appear distant or in conflict with a host of other priorities for urban policy-makers. Access to sanitation and clean water, accessible and affordable transport, and energy poverty are just some of the other pressing issues urban policy-makers are faced with across developed and developing cities alike.

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[1] *Ürge-Vorsatz, D., Kelemen, A., Tirado-Herrero, S., Thomas, S., Thema, J., Mzavanadze, N., ... & Chatterjee, S., 2016. Measuring multiple impacts of low-carbon energy options in a green economy context. Applied Energy, 179. 1409–1426. Wargocki, P. and Seppänen, O. (eds.), 2006. Indoor Climate and Productivity in Offices: How to integrate productivity in life cycle analysis of building services. REHVA Guidebook No. 6. Federation of European Heating and Air Conditioning Associations, Brussels.*

Previous work completed for the Global Commission on Economy and Climate[6] has demonstrated that an economic case exists for ambitious action in cities. 11 ambitious actions across the world's urban areas could yield US$16.6 trillion in total returns over the coming decades, while reducing emissions by 8.0 Gt of CO_2e in 2050 – an amount that is 30% more than the entire emissions of the United States in 2011.[7] However, this previous work could be strengthened by providing a comprehensive assessment of the wider returns from such actions, relating for example to the benefits of cleaner air, improved mobility, warmer homes, better jobs, and access to energy.

Presenting a more robust socio-economic case by assessing these so-called 'co-benefits' of low-carbon action could unlock policy support and accelerated action in a number of ways. It could enable the mainstreaming of climate policy and its integration into core policy areas such as economic development, finance, infrastructure or energy. It could facilitate the emergence of coordinated approaches and concerted action across the national, regional, and local scales. It could lead to changes in the relationships between the public, private, and civic sectors, bringing new forms of collaboration into play so that capacities for change are developed. And it could unlock new forms of investment, redirect existing financial flows, and unlock the potential for new ways of financing and delivering change.

In the following report, a systematic review of the literature and evidence base on the co-benefits of urban climate action is presented. The aim is to understand the scale of the co-benefits, where the most significant knowledge gaps and uncertainties are, and what we need to do to develop a more complete and robust evidence base that can be drawn upon to motivate and guide climate action across the world's cities.

METHODOLOGICAL APPROACH

A systematic review of the literature and evidence on the co-benefits of different forms of low-carbon urban development was conducted to understand the current state of knowledge. Analysis was conducted across 11 mitigation measures in three sectors for which previous analysis had identified both the potential for carbon savings,[8] and the potential for direct economic savings.[9] It is important to note that these measures do not encompass all of the potential measures that could be implemented in urban areas, much less the wide array of options available outside of cities. However, they cover a broad spectrum of the currently available options in cities, and a similar set of co-benefits could be expected from other low-carbon investments.

Across these 11 mitigation measures, we assessed 16 pathways through which the measures could have an impact on the higher-level objectives of health, congestion and time, employment, and the green economy and poverty alleviation. For example, non-motorised transport options benefit public health through two 'pathways': physical activity and improved air quality. These 16 pathways were identified through expert consultation and following an initial review of the literature on co-benefits. However, these 16 pathways should not be seen as the only pathways that could lead to co-benefits from these 11 mitigation measures.

Table 1 shows the 11 climate change mitigation policy measures identified from previous New Climate Economy work, alongside the higher-level objectives and the pathways through which these objectives can be achieved. In many cases, a pathway only applied to a subset of the mitigation measures. Reduced congestion, for example, only leads to benefits through measures in the transport sector. Altogether, 84 combinations of measures and pathways were identified and are highlighted in Table 1.

For each combination of a measure and pathway that is highlighted in Table 1, a keyword combination was developed and used in database searches of the literature. The keyword combinations included: (1) search terms related to the intervention; (2) search terms related to the pathway; and (3) search terms related to the wider objectives relating to public health, congestion and time, employment, and the green economy and poverty alleviation. Search terms related to climate change action were not included as the 11 policy measures we investigate were already established as climate mitigation action measures in previous work.[10] The specific keywords used in each search are found in Appendix 1.

A three-step approach was taken to identify relevant research literature. First, search terms were run in SCOPUS and Google Scholar, limited to the years 2000–2016, and results were screened to identify comprehensive (systematic or meta) review articles. If initial searches identified two or more comprehensive reviews of the literature for a specific cell, analysis for that cell was based on the literature in those reviews, and recent literature (defined as literature published between 2015 and 2016) identified on SCOPUS and Google Scholar. In cases where more than 50 relevant articles from 2015–2016 were identified, the top 50 articles by number of citations were assessed, focusing only on peer-reviewed journal articles. The reference lists from all included papers was also screened to identify additional literature. To this literature a select number of articles from grey literature was added through Google searches.

In cases where fewer than two comprehensive reviews were identified by initial searches, but a large number of peer-reviewed journal articles from 2000–2016 were identified, a broader review of existing literature was attempted. Searches were conducted on Google Scholar and SCOPUS, which frequently identified hundreds or even thousands of articles. As a consequence, results were narrowed to the 50 most cited relevant articles and then screened so that only peer-reviewed journal articles were included. The reference lists from all included papers were also screened to identify additional literature. To this literature was added a select number of articles from grey literature identified through Google searches.

Finally, in a small number of cases neither comprehensive review articles nor a wider literature of 50 or more relevant articles on the mitigation measure and pathway were found through Google Scholar and SCOPUS. In these cases, analysis was based on the literature available from Google Scholar and SCOPUS supplemented with wider Google searches for grey literature. In these cases special attention during the screening stage was directed towards understanding the existence of this gap in the literature. Searches were completed using SCOPUS and Google Scholar between 19 October 2016 and 22 February 2017.

Once the literature relating to each cell had been identified, a screening process was undertaken with the following attributes assessed for each piece of literature:

- Scale/scope (global, regional or local, and the extent different regions are covered)
- Resolution (the extent of finer-grained impacts on different communities/groups)
- Methodology (quantitative or qualitative)
- Robustness (are the methods clear and appropriate?)
- Contingencies and sensitivities identified by the study
- Key numbers identified by the literature in terms of impacts

In addition, the following three issues were assessed across the literature:

- Consistency (various studies conducted in a similar way)
- Completeness (different studies cover all of the issues)
- Range of qualitative and quantitative findings for each pathway

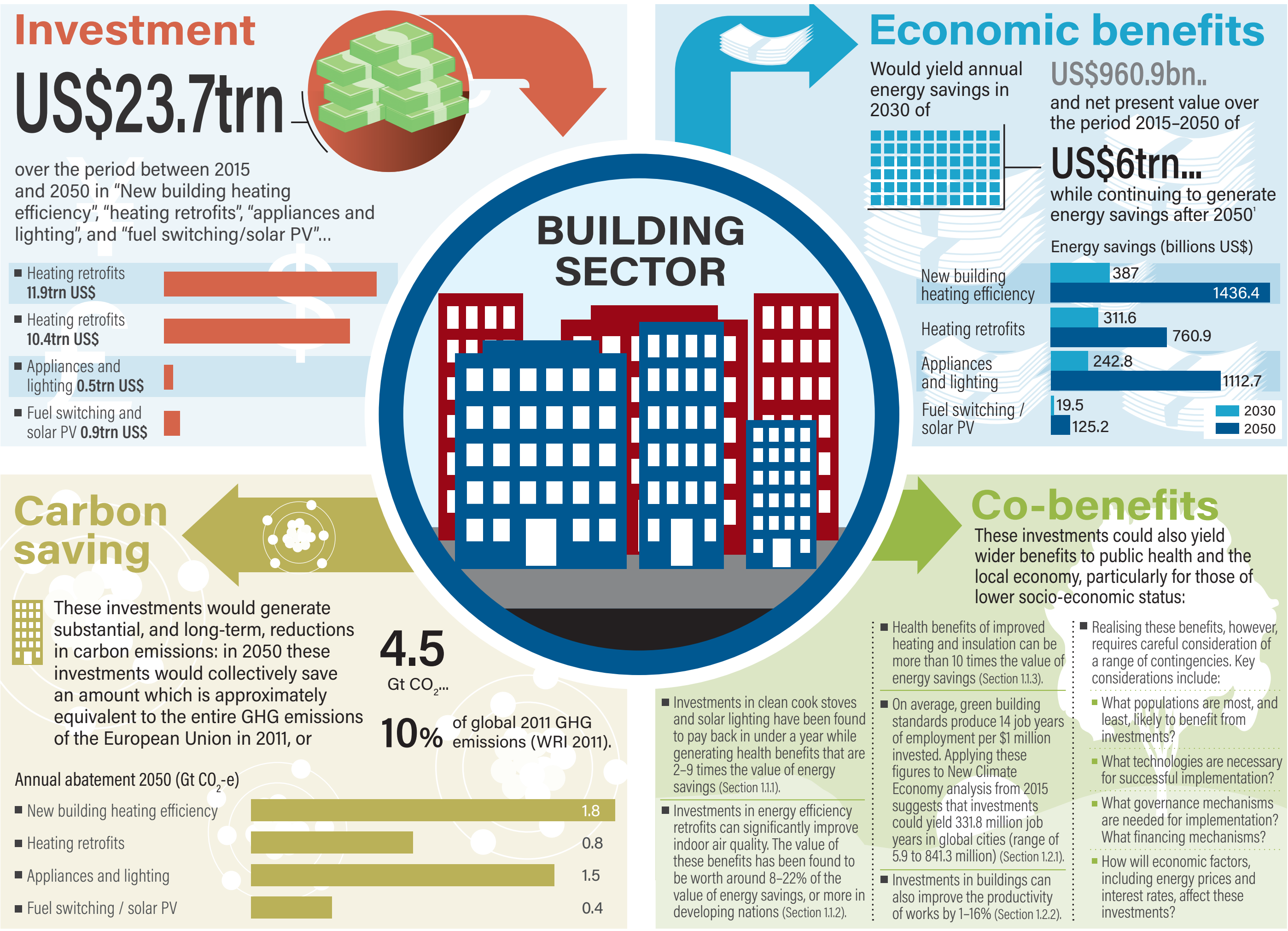
A focus on these questions within each piece of literature as well as across the literature was decided upon, based on expert consultation and assessment of existing literature reviews of co-benefits from climate action.

In the following, results of the literature review are presented for each sector and pathway, rather than each pathway and mitigation measure, in order to limit the extent of repetition between sections. The following is therefore broken into three sections, one for each of the sectors assessed: commercial and residential buildings, transport, and waste. Then, within each sector analysis is presented for each pathway leading to a specific wider objective. There is therefore a section on the benefits of investments in buildings on public health (the wider objective) that result from impacts on indoor air quality (the pathway).

Table 1
Combinations of pathways and mitigation measures investigated

Higher level objectives and pathways		**Health**									**Congestion and time**	**Employment and the green economy**		**Poverty alleviation and inequality**
Target sector	Climate change mitigation policy measure	Indoor air pollution	Outdoor air pollution	Indoor environmental quality	Physical activity	Vehicle injuries or deaths	Noise	Green space and urban heat island effects	Water quality	Odour		Employment	Productivity	
Buildings	New building heating efficiency	▨	▨	▨								▨	▨	▨
	Heating retrofits	▨	▨	▨								▨	▨	▨
	Appliances and lighting	▨	▨	▨								▨	▨	▨
	Fuel switching/ solar PV	▨	▨	▨								▨	▨	▨
Transport	Urban planning and reduced passenger travel demand	▨	▨		▨	▨	▨	▨			▨	▨	▨	▨
	Passenger mode shift and transit efficiency	▨	▨		▨	▨	▨	▨			▨	▨	▨	▨
	Passenger car efficiency and electrification	▨	▨		▨	▨	▨	▨			▨	▨	▨	▨
	Freight logistics improvements	▨	▨		▨	▨	▨	▨			▨	▨	▨	▨
	Freight vehicle efficiency and electrification	▨	▨		▨	▨	▨	▨			▨	▨	▨	▨
Waste	Recycling		▨						▨	▨		▨	▨	▨
	Landfill gas capture		▨						▨	▨		▨	▨	▨

Figure 2
Buildings Sector



Investment

US$23.7trn over the period between 2015 and 2050 in "New building heating efficiency", "heating retrofits", "appliances and lighting", and "fuel switching/solar PV"...

Economic benefits

Would yield annual energy savings in 2030 of US$960.9bn.. and net present value over the period 2015–2050 of US$6trn... while continuing to generate energy savings after 2050[1]

Carbon saving

These investments would generate substantial, and long-term, reductions in carbon emissions: in 2050 these investments would collectively save an amount which is approximately equivalent to the entire GHG emissions of the European Union in 2011, or 4.5 Gt CO_2... 10% of global 2011 GHG emissions (WRI 2011).

Co-benefits

These investments could also yield wider benefits to public health and the local economy, particularly for those of lower socio-economic status:

- Investments in clean cook stoves and solar lighting have been found to pay back in under a year while generating health benefits that are 2–9 times the value of energy savings (Section 1.1.1).
- Investments in energy efficiency retrofits can significantly improve indoor air quality. The value of these benefits has been found to be worth around 8–22% of the value of energy savings, or more in developing nations (Section 1.1.2).
- Health benefits of improved heating and insulation can be more than 10 times the value of energy savings (Section 1.1.3).
- On average, green building standards produce 14 job years of employment per $1 million invested. Applying these figures to New Climate Economy analysis from 2015 suggests that investments could yield 331.8 million job years in global cities (range of 5.9 to 841.3 million) (Section 1.2.1).
- Investments in buildings can also improve the productivity of works by 1–16% (Section 1.2.2).
- Realising these benefits, however, requires careful consideration of a range of contingencies. Key considerations include:
  - What populations are most, and least, likely to benefit from investments?
  - What technologies are necessary for successful implementation?
  - What governance mechanisms are needed for implementation? What financing mechanisms?
  - How will economic factors, including energy prices and interest rates, affect these investments?

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[1] *Based on the central scenario: energy prices rising 2.5% per year, 3% discount rate and base case learning curves (Sudmant et al. 2016).*

1. The buildings sector

Buildings account for approximately 32% of global energy use and 19% of energy-related greenhouse gas (GHG) emissions.[11] Current trends, driven by population and economic growth, and rising per capita energy consumption associated with urbanisation, suggest that their energy use and emissions could double or even triple by 2050. Indeed, China and India alone are forecast to add 400 million and 250 million people to urban areas by 2025.[12] However, even at these growth rates, with the implementation of currently available cost-effective actions, energy use and emissions could be held constant or even decline in absolute terms.[13]

The scope for such action is immense. Across the commercial and residential sectors, new building heating efficiency measures, heating retrofits, efficiency standards for appliances and lighting, fuel switching, and the implementation of solar PV panels in urban areas could save 4.5 Gt of GHG CO_2 emissions annually by 2050, an amount which is approximately equivalent to the entire GHG emissions of the European Union in 2011,[14] at a collective net present value of more than US$6 trillion.[15]

Perhaps of even greater importance, such actions could yield a range of socio-economic impacts, both positive and potentially also negative. Owing to the fact that people spend, on average, 90% of their time inside, the impact of climate change mitigation measures on indoor air quality, building construction, heat and cold stress, and a variety of other factors could be substantial.[16] At the same time, mitigation measures have the potential to create employment, contribute to community development and reduce urban poverty.

The next section explores the current state of evidence around the socio-economic impacts of climate change mitigation measures in the commercial and residential building sectors. Analysis here relies on several high-level studies and the literature they cover, particularly Ürge-Vorsatz et al. (2009), WHO (2011), GEA (2012), Ürge-Vorsatz et al. (2014), Lucon et al. (2014), Von Stechow (2015) and Ürge-Vorsatz et al. (2016).[17]

Evidence is presented with individual sections for each pathway leading to a specific wider objective. The first section, for example, outlines the evidence for climate mitigation actions in commercial and residential buildings to improve public health through the pathway of indoor air pollution.

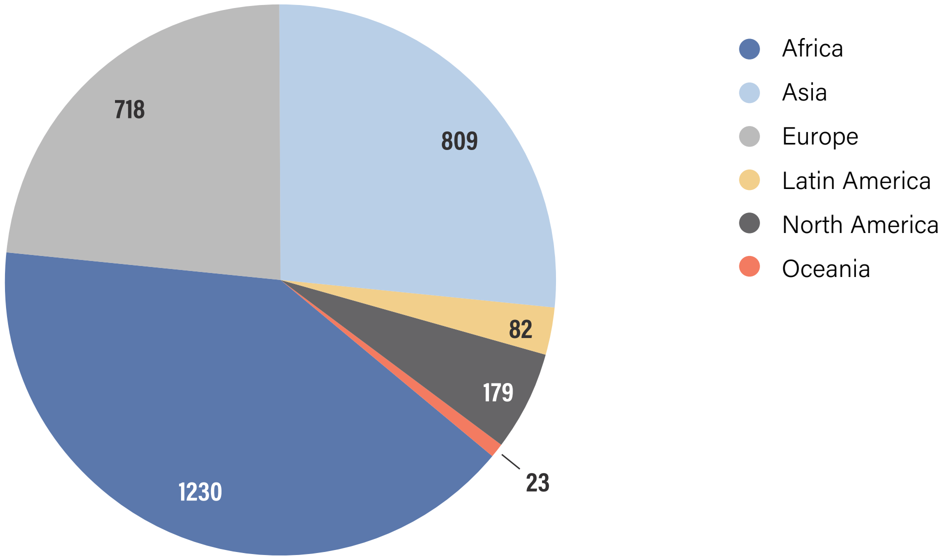
1.1 HEALTH CO-BENEFITS

Indoor air pollution

Globally, between 2.5 and 3 billion people live in households that rely on open fires of solid fuels (primary biomass and coal) for cooking, heating, and lighting.[18] Due to inefficient combustion, these fires produce excessive amounts of particulate and gaseous emissions, concentrations of which can be many times greater than the worst outdoor air quality readings. The health impacts of indoor cooking smoke include respiratory illnesses such as pneumonia, heart disease, lung cancer, chronic obstructive pulmonary disease (COPD), low birth weight, and asthma, and the impacts disproportionately affect women and children who are more often responsible for cooking and spend longer periods of time indoors.[19] In 2010, air pollution from indoor fires was responsible for 4 million deaths, almost entirely in least developed and developing nations.[20]

Figure 3

Population (millions) using solid fuels for cooking, heating, and lighting



Mitigation of indoor air pollution by improving the efficiency of indoor stoves, switching to cleaner burning fuels, and using less dangerous and polluting lighting options (among other interventions) can yield benefit for the climate, public health, and household energy bills. A vast literature has assessed indoor air pollution, ranging from global analysis[21] to studies of household interventions.[22] The World Health Organization (WHO) global indoor air pollution database contains 154 studies of indoor air quality covering 37 countries, including 30 studies in India, 16 in China, and 28 in African countries.[23] Approximately one-third of these studies address indoor air pollution in urban areas, and within this sample studies of urban centres in India and China comprise more than half of the total. Literature on indoor air pollution therefore covers a wide number of countries and contexts, including all areas of the world where the burden of disease from indoor air pollution is highest;[24] however, there is a bias, relative to the burden of disease, towards Indian and Chinese cities within studies of urban contexts.

A much smaller subset of literature has assessed the potential for mitigation measures and only a small number of studies have documented health improvements resulting from specific real-life interventions.[25] The majority of literature relies on theoretical models that connect changes in air pollution with disease rates, morbidity, and mortality. For example, Larsen (2014) relied on a dose-response model to estimate cases of various health ailments linked to indoor air pollution and values those cases based on cost estimates of disability-adjusted life years (DALYs) and value of statistical life (VSL) estimates.[26] Jeuland and Pattanayak (2012), working at the household level, used cost-of-illness (COI) estimates and VSL estimates to value a reduction of cases against a baseline.[27]

The scale of impacts across a range of interventions and contexts has been found to be very large. In terms of the direct economic case, across a wide range of possible interventions (various improved cook stove designs, solar lighting, improved charcoal, various fuel switching options), payback periods are found to range from less than two months to less than one year for the majority of interventions.[28] For example, a study in Kigali, Rwanda, found that a US$10 investment in an improved cook stove could save 1.6 tonnes of CO_2e and US$181 in fuel costs over a four-year lifetime, in addition to reducing indoor air pollution 90%.[29]

Literature that has valued the health benefits of these measures finds that they range in scale from two to nine times the value of energy savings, with benefit–cost ratios as high as 60.[30] If applied widely, the potential for the scale of health benefits is therefore massive. At a national level, Wilkinson (2010) calculated that 0.1–0.2 Mt of CO_2e and 12,500 DALYS could be saved each year for a population of 1 million people in India using clean cook stoves.[31] At a global level, Bruce (2006) found that an investment of approximately US$2 billion to improve indoor air quality resulted in between 700 and 79,500 healthy life years being added, depending on the region where the investment was made,[32] and Hutton (2007) found that halving the global population lacking access to clean fuels would be worth US$91 billion (2005 US dollars) in health benefits.[33]

While these results are impressive, a large set of contingencies complicate their policy implications . Changing fuel prices, technologies, baseline emission levels, other mitigation and policy actions, GDP and population growth rates, geographic and climatic conditions, and local cultural practices (among other factors) all impact on the level of uptake of indoor air quality mitigation measures, and the scale, and sometimes sign, of co-benefits. In some cases, important contingencies have been widely researched. Higher incomes and levels of education, for example, are closely associated with adoption of cleaner cooking and lighting options.[34]

In other cases, more research is required. Conducting a systematic review of 32 studies of improved cooking stove adoption, Lewis (2012) found that associations between cleaner cooking stove use and fuel prices were mixed, with non-significant and inconclusive associations between fuel choice and prices for coal, fuel wood, and cleaner fuels.[35] These results suggest that certain policy levers, such as changes to fuel subsidies and taxes, may not have desired effects. Similarly, access to credit facilities is regarded as a possible “game changer” due to the high upfront costs of some clean cooking technologies;[36] however, there is little empirical analysis to support this claim.[37] Further research is therefore needed to better understand these contingencies, particularly in Sub-Saharan Africa where the case study literature appears to be least developed relative to the impact of the indoor air pollution.

Outdoor air pollution

Fossil fuel combustion for heating, cooking, and lighting not only impacts on residents indoors, but also on local populations through outdoor air pollution. Indeed, it is estimated that 500,000 individuals lose their lives each year as a consequence of outdoor air pollution caused by indoor energy use.[38] Similar to indoor air pollution, outdoor air pollution from energy use in buildings has been connected with a range of respiratory illnesses and cancers, heart disease, and reduced quality of life.[39] Geographically, the impact of this pollution is concentrated in large cities in the developing world.[40] However, indoor energy use is a contributing factor to poor air quality across global urban areas, 97% of which do not meet WHO annual air quality limits.[41]

A number of studies have monetised the health benefits of energy efficiency measures in buildings[42] and the methodological approaches they take are similar to those used for indoor air pollution studies. Physical indicators estimated included the number of avoided cases of pneumonia, respiratory distress and other ailments, avoided hospital admissions, years of life lost; quality-adjusted life years and value of statistical life approaches were employed to produce monetary values.

Results from these studies demonstrate the potential for substantial physical and monetary impacts from energy efficiency measures in buildings across a number of countries and contexts. Levy (2016), for example, found that improved insulation in US homes would save 80 million tonnes of CO_2 from power plants, 30 million tonnes of CO_2e from indoor energy combustion and 320 deaths, or in monetary terms, US$12–390 per tonne of CO_2 saved.[43] Markandya et al. (2009) calculated that the health benefits of measures to reduce electricity use could be valued at US$2 (2010 US dollars) per tonne of CO_2 not emitted in the European Union, US$7 per tonne not emitted in China, and US$46 per tonne not emitted in India.[44] Chan et al. (2007) calculated that reducing electricity usage in China could have health benefits valued at as much as US$6 billion in 2020.[45] Across the literature, the scale of monetised health benefits resulting from building energy efficiency measures is reported to be approximately 8–22% of the value of energy savings in developed nations and significantly higher in developing nations where the burden of disease is higher.[46]

In addition to demonstrating the scale of potential health benefits in physical and monetary terms, these publications reveal important contingencies affecting the extent of health impacts from mitigation measures in buildings. Energy efficiency measures in Indian cities have the potential to yield relatively larger health benefits due to Indian electricity grids relying heavily on coal and operating at relatively low efficiencies, power stations operating relatively close to heavily populated areas, pollution levels from other sources producing a high base-level of emissions, and climatic factors preventing pollution from dissipating at certain times of year (among other factors).[47] In the United States and Europe, by contrast, electricity grids are less emissions intensive, operate at higher efficiency levels, are generally not as close to densely populated areas, and existing pollution levels are lower – although climatic conditions and topography do cause some cities to experience high pollution levels at certain times of the year. Existing technologies and infrastructure, combined with geography and the environmental context are therefore key determinants of the scale of outdoor health benefits from mitigation measures in buildings.

This literature also reveals some of the limitations of existing research. Most studies that had monetised benefits were focused on developed country contexts, where the potential for energy savings is arguably lowest and the costs the highest, and none of the studies identified were focused on urban areas in Africa or South-East Asia where some of the fastest rates of urbanisation are taking place. Analyses also focused on theoretical modelling rather than controlled trials. While this is understandable given the challenge and cost of conducting this type of research, the consequence is that we have a limited understanding of some of the cultural and behavioural factors that are likely to affect the success of interventions.

Indoor environmental quality

Poor heating and cooling systems, inadequate ventilation, and the use of certain building materials are contributing factors, in both developed and developing cities, to heat and cold stress, respiratory diseases, allergies, asthma, mental health problems, and an increased morbidity.[48] In addition, building defects can lead to excess energy use on cooling and heating. In temperate countries, estimates suggest that between 10% and 40% of winter deaths can be attributed to indoor temperatures,[49] and 45,000 deaths were attributed to a heatwave in Europe in 2003.[50] In developing country cities, impacts are significantly larger as poor building design leads to increased use of solid fuels for heating, cooking, and lighting, and these are responsible for more than 3 million deaths annually.[51] The impacts of poor indoor environmental quality (IEQ), while often accompanied by poor indoor and outdoor air quality (see sections 1.1.1 and 1.1.2), can also arise from, and be addressed, independently.

While a substantial body of qualitative literature makes the case that green building standards and other measures contribute to improved health and productivity,[52] a relatively smaller and more recent body of literature attempts to quantify these findings.[53] This literature demonstrates that the value of co-benefits from improved IEQ is not only substantial, but that in specific circumstances it can be worth multiples of the value of direct energy savings, which is the metric typically used as the primary rationale for these investments.[54]

Clinch and Healy (2001), for example, found that heating upgrades to the Irish residential building stock, including the value of health benefits, comfort benefits, and emissions reductions (SO_2, NO_x, CO_2 and PM_{10}), could be valued at 1.7 times the value of the direct energy savings.[55] Similarly, Chapman et al. (2009) found that the value of lost working days, admissions to hospital, and reduced CO_2 emissions saved from investments in insulation in low-income communities in New Zealand could be valued at 3.2 times the value of direct energy savings.[56] Across a large set of studies, the co-benefits of investments to improve indoor environmental conditions were valued at 0.22–74 times the value of the direct benefits, and benefit–cost ratios were found to be as high as 3.9.[57]

It should be noted, however, that the wider applicability of these results may be limited. The majority of studies targeted very specific communities, where the extent of fuel poverty and poor building standards was much greater than for the broader population.[58] Further, while a substantial literature on the option for improving indoor air quality in developing nations exists (see above), quantified literature on the IEQ benefits from investments in buildings is restricted to literature from a small number of developed country contexts. There is therefore a need for quantified research on IEQ, beyond the benefits of indoor air quality, particularly in developing nations because heat stress, rather than cold stress, is the key challenge in many developing contexts. It should also be noted that there is significant cross-over between indoor air quality benefits and indoor environmental quality benefits, although academic literature has tended to focus on developing countries for the former and developed countries for the latter.

Comparisons between different parts of the existing literature are also challenging due to the large number of overlapping health co-benefits assessed and the variety of methodological approaches employed. Studies in some cases rely on subjective measures of benefits, such as “comfort benefits”.[59] Some literature conducted ex post evaluations and estimated savings from specific health costs, for example from asthma attacks and prescription medications.[60] Others conducted ex ante studies and calculated monetised benefits using air quality data and willingness-to-pay estimates.[61] In some cases, only health co-benefits were monetised,[62] while in other cases subsidy outlays, air pollution, and reductions in carbon emissions were also monetised.[63]

The values that studies find for health and energy savings are also time and context specific. Contingencies affecting the scale of co-benefits from investments to improve IEQ include the socio-economic context, the local climate, the state of the existing building stock, and the level of planned intervention (shallow versus deep retrofit), and current energy prices. The socio-economic context can determine the extent that local inhabitants can afford to invest in buildings, and can also be associated with the health of inhabitants. Local climate, especially the extreme highs and lows faced by a region, can shape the potential of higher building standards. The state of the building stock and the level of the planned intervention can determine the scale of the potential change in indoor conditions, and energy prices affect the scale of direct benefits. Comparisons of studies are therefore useful for indicating the potential scale of the benefits, but context-specific analysis is needed to inform policy-making.

1.2 EMPLOYMENT AND THE GREEN ECONOMY

Employment

Investments in more energy-efficient or lower-carbon buildings are likely to require different skill sets, materials, and processes than conventional buildings, and to therefore have impacts on the labour market. In the literature search, 13 studies were identified that investigate the impact that investment in building standards and building efficiency can have on levels of employment. Across these studies, focusing only on literature that calculated net rather than gross employment creation (which led to the exclusion of four studies), each investment of US$1 million generated an average of 14 job years of employment (ranging from 0.25 to 35.5). Applying the figures in Gouldson et al. (2015), featured in the New Climate Economy 2015 analysis, which found that US$23.7 trillion would be needed in additional housing investment between 2015 and 2050, suggests that 331.8 million job years (range of 5.9 million to 841.3 million), could be created in urban areas by ambitious investments in low-carbon buildings.[64] However, this figure should be treated with caution as it is based on a small number of studies in a limited number of contexts.

It should be noted, however, that there is significant debate around the methodology used in these studies and their applicability to other contexts.[65] Most literature has calculated gross, rather than net, employment impacts, and has therefore ignored potential job losses in other industries and sectors. Analyses have also not considered the opportunity cost of investments. Green building standards may require more and better paid employees to build; however, if they are also more expensive, an equivalent or larger number of jobs could have been created through investment in other sectors.

Studies have also been relatively short term and there is a need for a better understanding of the long-term impacts of investments in green buildings. High-efficiency insulation may require greater employment during construction, but if deployed widely, could lead to reduced energy usage and, as a consequence, to job losses in the energy sector. Similarly, green buildings may last longer and require less maintenance than their conventional alternatives. While these may be positive impacts from the perspective of home owners, they impact on the total amount of long-term employment in the housing sector and are therefore worthy of consideration.

Finally, the existing literature on the employment impacts of lower-carbon buildings has focused almost entirely on European and North American contexts, where levels of economic development and labour market conditions are very different from developing contexts. More research, particularly in developing contexts, is therefore vitally needed for a better understanding of the employment impacts of green investments in buildings.

Methodological issues notwithstanding, current research provides a useful guide to the contingencies that determine the scale of employment impacts from investment in the housing sector. The type of retrofit (deep or shallow), aspects of the local labour market, the alternative (baseline) mode of construction, and the materials and methods of construction employed all play a significant role in the scale of employment impacts. Research also suggests that financing arrangements can be an important factor. Where financing arrangements can leverage capital and deploy funds that otherwise would have been idle, research suggests that both induced and net employment impacts can be increased.[66] Deciding between private and public funding options, loans, revolving funds and policy-induced methods of increasing investment is therefore an important consideration for policy-makers.

Productivity

By changing thermal conditions, lighting, humidity, and a range of other factors, energy-efficient buildings can have subtle but far-reaching impacts on the way we live our lives. In commercial buildings, improved insulation and upgraded heating, cooling, and lighting have been linked with reduced work days lost to respiratory illnesses, allergies, the flu, depression, and stress.[67] Singh et al. (2010), for example, found significant reductions in rates of absenteeism caused by illnesses and stress in workers who moved from conventional to green office buildings.[68] Across the existing literature identified, which it should be noted is based heavily on case studies, green buildings have been found to improve work productivity by 1–16%, with some literature even showing higher figures.[69]

In monetary terms, this means that the productivity benefits from investment in commercial buildings are among the largest of the co-benefits achievable from low-carbon investments, particularly in regions of the world where labour costs are high.[70] In a typical office building in a developed world city, salaries exceed energy and maintenance costs by a factor of 100 or more, and the construction costs of investments by a similar margin.[71] Investments that yield even small improvements in productivity can therefore be justified even where there are short-term energy, maintenance or construction costs.

In the residential sector, energy-efficient homes can also lead to improvements in the productivity of their inhabitants. Clean cook stoves and fuel-switching measures not only dramatically improve indoor air quality (section 1.1.1), but can also reduce the amount of time that needs to be devoted to fuel collection, freeing time for other activities.[72]

A number of caveats should be noted for policy-makers responding to these findings. First, the term “productivity” is defined loosely across the literature, and the benefits described here have a significant cross-over with benefits described in the section on health. The 1–16% improvement in productivity in commercial buildings, which is found across the literature, is therefore roughly inclusive of, rather than additional to, the benefits of improvements to IEQ, air quality, and an improved outdoor environment. Second, the existing literature is heavily based on case studies from the United States and Europe (with a small number of exceptions, such as Ravindu, 2016).[73] The wider applicability of findings is therefore limited.

These results also depend upon a number of contingencies, which are important for policy-makers to consider before applying the results to their local context. One of the most important is the baseline level of worker productivity and the baseline levels of indoor environmental conditions. Several of the studies that showed potentially very large productivity improvements from investments (such as Kats, 2003)[74] were based on investments in buildings with relatively poor ventilation systems, poor lighting, and faulty heating and cooling systems. In these cases, there was a large potential for improvement, but this is not likely to be the case for recently constructed buildings where best practices have been applied.

The scale of monetised benefits is also heavily dependent on local wage levels. This marks an important methodological difference between the value of health co-benefits calculated from these same investments, and their impact on productivity (in terms of workers’ contribution to GDP). The value of health impacts, based on the cost of hospital admissions or VSL estimates, can vary by orders of magnitude between developed and developing contexts, or can be relatively similar in value dependent on willingness-to-pay estimates, and assumptions around VSL in different regions. By contrast, the productivity of workers in terms of their wage levels can be several orders of magnitude apart between developed and emerging cities, and significantly different between the wealthiest and least wealthy cities in each country, and are relatively insensitive to changes in aspects of the methodology. Monetising the productivity impacts of investments in commercial and residential buildings is therefore likely to show dramatically different results depending on the local context.

1.3 POVERTY ALLEVIATION AND INEQUALITY

The benefits of low-carbon investments, whether monetised through energy savings or non-monetary benefits relating to social welfare (such as improved thermal comfort, air quality, lighting), are unlikely to be evenly distributed across populations. Estimates of the total impact of investments can therefore obscure important equity considerations.

In some cases, investments have a strong likelihood of benefiting vulnerable populations. For example, low socio-economic status, fuel/energy poverty, and poor building stock are often found alongside each other, particularly in specific regions such as Central and Eastern Europe, and this creates opportunities for synergies between targeted climate, energy, and social policies.[75] Similarly, investments in improved cooking stoves in low-income cities have a strong likelihood of benefiting not only low-income residents in general, but also women and children in particular as they face a disproportionate share of the burden of health impacts, and the time devoted to fuel collection.[76]

Even where programmes are not targeted towards specific populations, a large portion of benefits from some low-carbon investments in buildings can accrue to more vulnerable populations. Studies of national retrofit programmes in Hungary, Ireland, and the EU have found that 16–50% of total benefits would be in the form of improved health, thermal comfort, living conditions, and productivity for residents, although these were primarily studying residents with relatively low socio-economic standing.[77]

However, it is not the case that lower-income and vulnerable populations are necessarily the largest beneficiaries from investments in building retrofits. Policies for small-scale renewables in residential and commercial buildings can be highly regressive when they lead to higher energy prices; in developing cities, building standards can be designed without consideration for the needs of informal settlements, and in developed cities, without consideration for the limited financial means of low-income households; and investments in commercial buildings are likely to benefit office workers, but not members of the informal economy. Policy-makers therefore need to carefully consider the impacts of their policies, and the potential for synergies and conflicts between their programmes and other challenges in urban areas. Whether policies help or hurt vulnerable populations will depend on a host of factors, including the level of socio-economic inequality in a region, the scale (deep or shallow) of an intervention, and the financial design of an intervention.

1.4 CONCLUSIONS

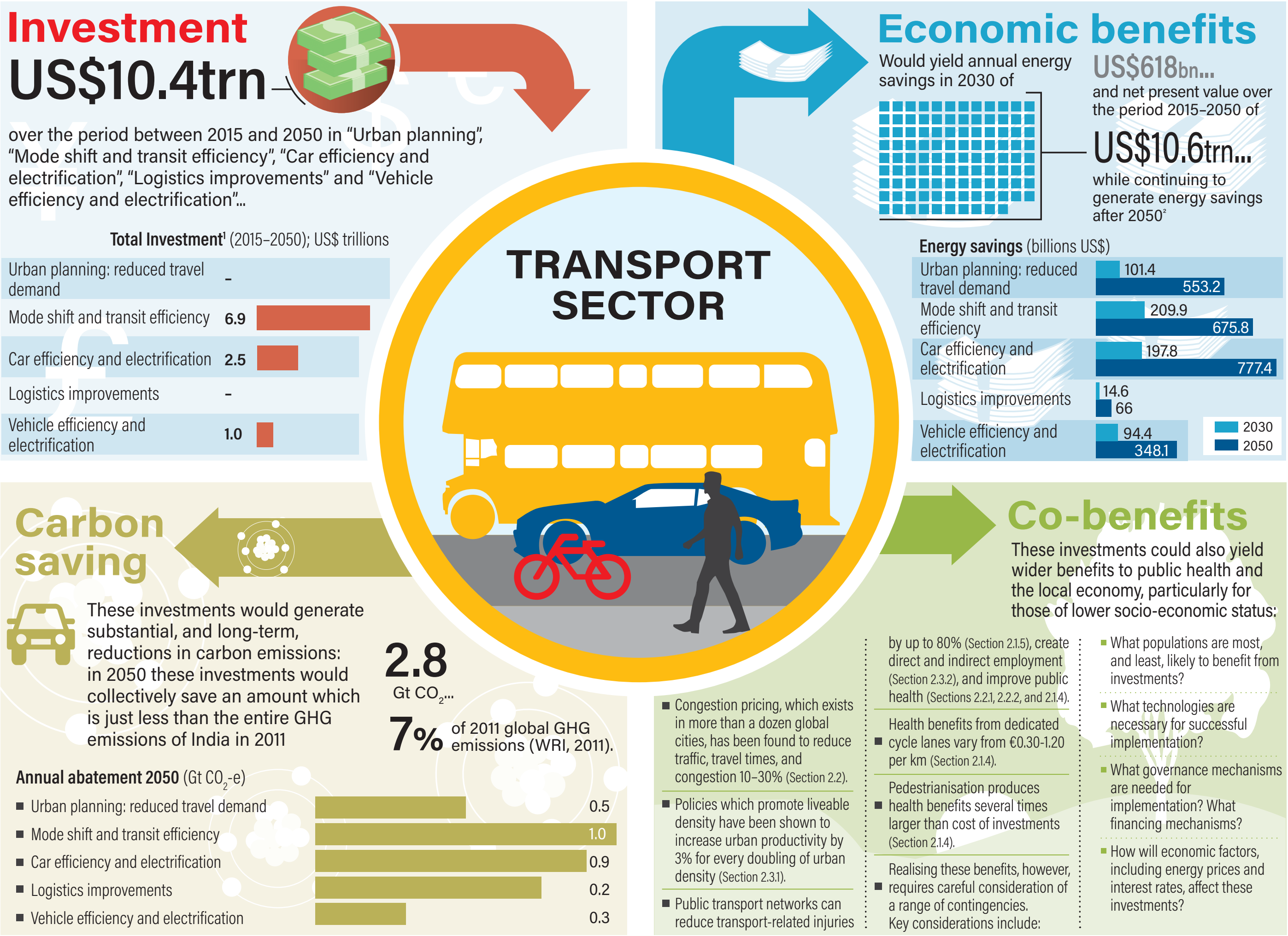
Some co-benefits of climate mitigation actions in the buildings sector have been widely researched and their value expressed in monetary terms. For example, indoor and outdoor air pollution have been studied extensively, as has the productivity impacts of energy efficiency investments in buildings. A number of studies have also investigated the employment impacts of climate change mitigation investments in buildings (at least in developed country contexts) and the impact on cold stress in temperate regions. The breadth of literature on these co-benefits is in part a reflection of their scale. Analysis by Ürge-Vorsatz (2014), for example, found that the combined monetised non-energy benefits of measures were one to two times the cost savings they produced, and a significant body of supporting literature confirms that monetised co-benefits can exceed the value of energy saved.[78]

Considering that Gouldson et al. (2015) suggested that the discounted energy savings from a large set of mitigation measures was US$6 trillion through to 2050, this suggests that the discounted value of monetisable co-benefits lies somewhere between US$6 trillion and US$12 trillion for these actions.[79] However, even this figure may understate the total co-benefits from mitigation actions in the buildings sector as it excludes co-benefits such as poverty alleviation, improved energy security, and reduced upstream environmental degradation that have not been included in this analysis or widely monetised across the literature.

At the same time, policy-makers should exercise caution in drawing broad-based conclusions from existing research. The majority of the current literature, and the vast majority of the literature that has monetised benefits, has focused on Western contexts, where healthcare costs are relatively high and pollution levels are relatively low. With a small number of exceptions,[80] studies have also focused on single cities or countries, which are not always representative cases, and few studies have quantified international or global co-benefits.

The existing literature has also tended to focus on single co-benefit types, such as benefits to health or employment, and ignored the potential for policies to support multiple objectives, or for multiple policies to have synergistic impacts. In most cases, this likely leads to a significant understatement of total benefits – but there is also scope for conflict between objectives. Measures to improve energy efficiency, for example, can raise housing prices and affect housing security, building heat envelope investments can contribute to sick-building syndrome, and employment created in the building sector can be at the cost of employment created in other sectors. There is therefore a need for comprehensive analysis that considers multiple co-benefits, in addition to the economic and carbon case for investments, and for such investments to be compared against policy alternatives. The opportunity for this kind of research is explored more fully in the discussion and conclusions section at the end of this report.

Figure 3
Transport Sector



Investment US$10.4trn over the period between 2015 and 2050 in "Urban planning", "Mode shift and transit efficiency", "Car efficiency and electrification", "Logistics improvements" and "Vehicle efficiency and electrification"...

Total Investment[1] (2015–2050); US$ trillions

Urban planning: reduced travel demand	-
Mode shift and transit efficiency	6.9
Car efficiency and electrification	2.5
Logistics improvements	-
Vehicle efficiency and electrification	1.0

Economic benefits Would yield annual energy savings in 2030 of US$618bn... and net present value over the period 2015–2050 of US$10.6trn... while continuing to generate energy savings after 2050[2]

Energy savings (billions US$)

	2030	2050
Urban planning: reduced travel demand	101.4	553.2
Mode shift and transit efficiency	209.9	675.8
Car efficiency and electrification	197.8	777.4
Logistics improvements	14.6	66
Vehicle efficiency and electrification	94.4	348.1

Carbon saving These investments would generate substantial, and long-term, reductions in carbon emissions: in 2050 these investments would collectively save an amount which is just less than the entire GHG emissions of India in 2011 2.8 Gt CO_2... 7% of 2011 global GHG emissions (WRI, 2011).

Annual abatement 2050 (Gt CO_2-e)

Urban planning: reduced travel demand	0.5
Mode shift and transit efficiency	1.0
Car efficiency and electrification	0.9
Logistics improvements	0.2
Vehicle efficiency and electrification	0.3

Co-benefits These investments could also yield wider benefits to public health and the local economy, particularly for those of lower socio-economic status:

- Congestion pricing, which exists in more than a dozen global cities, has been found to reduce traffic, travel times, and congestion 10–30% (Section 2.2).
- Policies which promote liveable density have been shown to increase urban productivity by 3% for every doubling of urban density (Section 2.3.1).
- Public transport networks can reduce transport-related injuries by up to 80% (Section 2.1.5), create direct and indirect employment (Section 2.3.2), and improve public health (Sections 2.2.1, 2.2.2, and 2.1.4).
- Health benefits from dedicated cycle lanes vary from €0.30-1.20 per km (Section 2.1.4).
- Pedestrianisation produces health benefits several times larger than cost of investments (Section 2.1.4).
- Realising these benefits, however, requires careful consideration of a range of contingencies. Key considerations include:
  - What populations are most, and least, likely to benefit from investments?
  - What technologies are necessary for successful implementation?
  - What governance mechanisms are needed for implementation? What financing mechanisms?
  - How will economic factors, including energy prices and interest rates, affect these investments?

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[1] *Based on the central scenario: energy prices rising 2.5% per year, 3% discount rate and base case learning curves (Sudmant et al. 2016).*

2. The transport sector

The transport sector accounted for 23% of global GHG emissions in 2010 and remains one of the fastest growing sources of global emissions, despite advances in vehicle efficiency.[81] Crucially, fossil fuels remain the dominant final energy source in transport, with oil accounting for over 90% of final energy demand.[82] Established transport networks and systems are costly and technically challenging to change once they are built,[83] leaving current design and planning trends difficult to alter. Recent analysis suggests that transport investments over the coming five years will substantially dictate the pathway of transport-related emissions for decades to come.[84]

Aggressive early action is therefore crucial if climate change is to be mitigated. A range of transport-related climate mitigation actions/policies can yield substantial economic benefits, specifically in: (1) compact urban planning and reducing passenger travel demand; (2) shifting passenger travel mode and expanding public transit; (3) improving passenger car efficiency and electrification; (4) improving freight logistics; and (5) improving freight vehicle efficiency and electrification. Investment in all those transport-related actions across the world's urban areas could save 2.8 Gt of GHG emissions annually by 2050. This is just less than the entire GHG emissions of India in 2011, or equivalent to 7% of 2011 global GHG emissions.[85] It could also yield direct net economic benefits between 2015 and 2050 of US$10.5 trillion.[86]

Adding to these direct benefits are the potential for positive impacts on public health. In 2015, the Lancet Commission on Health and Climate Change emphasised that the response to climate change could be "the greatest global health opportunity of the 21st century".[87] The health co-benefits of climate action in the transport sector can be realised through pathways of improved indoor and outdoor air quality, reduced exposure to noise, mitigation of the urban heat island effect, increased active travel and physical activity, reduced motor vehicle crashes, increased green space exposure, and reduced social exclusion and inequalities.[88] Additionally, there are economic and social benefits stemming from relieving congestion, reducing travel time and driver stress, increasing employment and productivity, reducing noise and improving mobility for the urban poor. In addition, there are also potential negative impacts, stemming from unforeseen impacts, opportunity costs, and conflicts between policies and measures.

Currently, the cost of transport externalities is very high, especially in rapidly developing urban areas. For example, the costs of motorised transport's congestion, air pollution, motor vehicle crashes, noise, and climate change in Beijing are between 7.5% and 15.0% of its GDP.[89] Rapid technological changes and volatility in energy prices, which radically alter the economic case for investments, make predictions and scenario comparisons challenging. Nonetheless, the literature demonstrates that a great opportunity exists for policy-makers to develop transport roadmaps that jointly achieve climate change, health, congestion, and economic objectives.

2.1 HEALTH CO-BENEFITS

Outdoor air pollution

The transport sector is responsible for high proportions of urban air pollution that could be reduced through targeted policies. Up to 30% of particulate air pollution in OECD cities worldwide, and as much as 60% in cities of the developing world, can be attributed to motor vehicle emissions.[90] In Beijing, for example, studies show that vehicles account for 46–58% of volatile organic carbon emissions, 6–22% of PM_{10} emissions and 31–35% of total NO_x emissions, including 74% of ground-level NO_x.[91] In India, a study of four megacities found that 20–50% of $PM_{2.5}$ could be attributed to vehicle emissions.[92] In Europe, the traffic contribution to urban PM concentrations ranges from 9–53% for PM_{10} and 9–66% for $PM_{2.5}$ with an average of 39% and 43% at traffic sites, respectively, and a higher range for NO_2, a more specific traffic marker, of over 80%.[93] Average concentrations of air pollutants are considerably higher at the road side compared with urban background locations, with average European ratios of 1.63 for NO_2 and 1.93 for NO_x,[94] and 1.14, 1.38, 1.23 and 1.42 respectively for $PM_{2.5}$, $PM_{2.5}$ absorbance (soot), PM_{10} and PMcoarse.[95]

The above pollutants are associated with a wide variety of negative health outcomes, including premature mortality,[96] and a wide spectrum of global disease, such as the onset of asthma, reduced cognitive function, lung cancer, diabetes, and obesity.[97] The World Bank estimated that at least 184,000 deaths in 2010 could be specifically attributed to transport-related air pollution, and the European Environmental Agency tagged air pollution as the single largest environmental health risk in Europe.[98]

With vehicle numbers projected to increase up to fourfold over the coming decades, both the volume and share of air pollutants from vehicles are set to rise substantially.[99] The costs associated with both premature mortality and selected illnesses, in OECD countries alone, was estimated at US$1.7 trillion in 2010, and over 50% of this cost (almost US$1 trillion) was attributable to road transport.[100] The OECD projects that the annual global cost associated only with premature mortality from outdoor air pollution will rise from US$3 trillion in 2015 to US$18–25 in 2060.[101] These costs are likely to be underestimated and disregard the costs associated with the above spectrum of disease.

Previous work has strongly advocated for an integrated approach to air quality and climate policies, which can improve population health.[102] The literature we identify and summarise next suggests that multiple climate policies targeting the transport sector have the potential to reduce transport-related air pollution and provide health benefits, although the investigated pathways leading to these benefits and the scale of the benefits varied. Land-use planning to reduce motorised passenger demand, improving transit efficiency, encouraging passenger modal shift away from the private car, improving passenger car efficiency and electrification, and improving freight logistics and efficiency are some of the measures policy-makers have at their disposal to improve air quality and protect/improve public health. It should also be noted that other measures, including the use of alternative and bio fuels,[103] after-treatment devices,[104] electric bikes,[105] and alternative bus and taxi technologies,[106] are relevant but were outside the scope of this review.

LAND-USE PLANNING

Urban planning to reduce passenger travel demand has been identified as a key measure that cities can adopt to improve air quality and public health and achieve significant economic savings.[107] Compact and mixed-use design of cities can lead to shorter access to work, school, and other activities, and therefore reduce the need for passenger car travel.[108] Reductions in passenger car travel demand are often accompanied by modal shifts towards more sustainable transport means, such as walking, cycling, and use of public transport (see section 2.1.4). Conversely, the rapid expansion of metropolitan areas, or urban sprawl, and the resulting un-mixed land use and low-density development patterns reinforce the need and convenience for extensive road networks and private car travel.[109]

Ewing (2008) found that high density can reduce vehicle kilometres per capita by 40%,[110] and comparisons of urban centres have found that dense, highly connected urban centres like Hong Kong produce only one-third of the carbon emissions per capita of European cities, while European cities produce only one-fifth of the carbon emissions of sprawling poorly connected cities like Houston.[111] Recent reviews and large-scale health impact assessments concluded that urban planning measures, unlike other transport policy instruments aimed at reducing traffic-related air pollution (e.g. freight management), have the potential to realise air quality improvements over the longer term, and provide additional benefits related to relieving congestion, improving the quality of places, and increasing a population’s physical activity levels, the latter associated with many health benefits.[112] Other demand regulation measures, such as increasing fuel prices, have also been tested and shown to provide exposure reductions.[113]

Many studies have provided quantification of the expected air quality and health benefits from such measures, although these were almost exclusively based on health impacts assessment modelling. For example, reducing the vehicle kilometres travelled by Chinese residents by 5% and 10% via increasing cycling, would lead to around 1.56% and 3.11% decrease in annual average concentrations of SO_2, and 1.40% and 2.80% decrease in NO_2, 3.09% and 6.18% in $PM_{2.5}$, and 2.93% and 5.86% in PM_{10}, respectively. If the reductions in demand were accompanied with a shift towards public transit, the estimated benefits were higher. The number of associated preventable deaths from air pollution-related disease per year were estimated to range from 568.96 thousand to 4515.95 thousand (depending on the scenario being tested), and these health improvements would save 3,433 to 27,337 billion yuan.[114] These figures are significantly larger than the total number of annual global deaths attributable to air pollution, according to the World Bank,[115] and should therefore be treated with caution. In particular, the authors apply a linear exposure response function, an assumption that may not be realistic over such a large change in air pollutant levels. At the same time, by investigating a large number of air pollutants across an aggressive scenario, the study authors identify that the World Bank figures for air pollution mortality are likely to represent a conservative estimate of the potential health impacts from investments in transport air pollution mitigation.

Grabow et al. (2012) suggested that the elimination of automobile round-trips ≤ 8 km in 11 metropolitan areas in the upper Midwestern United States would reduce $PM_{2.5}$ by 0.1 $\mu g/m^3$, and although summer ozone (O_3) would slightly increase in cities, it would decline regionally, resulting in net health benefits of US$4.94 billion per year (95% confidence interval (CI): US$0.2 billion, US$13.5 billion).[116] It should be noted that 25% of $PM_{2.5}$ and most O_3 benefits would occur to populations outside metropolitan areas. If 50% of the eliminated trips were made by bicycle, the health benefits would increase significantly due to increased levels of physical activity reducing mortality by 1,295 deaths per year (95% CI: 912, 1,636). The combined health benefits of improved air quality and physical activity were estimated to exceed US$8 billion per year in the study area.[117]

In a health impact assessment of six cities, land-use changes were modelled to reflect a compact city in which land-use density and diversity were increased and distances to public transport were reduced to drive a modal shift from private vehicles to walking, cycling, and public transport. The modelled compact city scenario resulted in health benefits for all cities (for diabetes, cardiovascular disease, and respiratory disease), with overall health gains of 420–826 DALYs per 100,000 population. However, for moderate to highly motorised cities, such as Melbourne, London, and Boston, the compact city scenario predicted a small increase in road trauma for cyclists and pedestrians (health loss of between 34 and 41 DALYs per 100,000 population).[118]

The scope of existing research on the impacts of urban planning and passenger car demand reductions is wide and spans European, American, Australian, and developing regions including Brazil, China, and India. No relevant studies conducted in other developing regions, such as Africa or the Middle East, were identified. The current literature is somewhat rough in terms of assigning the impacts to communities or regions, perhaps due to the health impact assessment methods widely adopted, as these are conducted at the population level.

The results presented are considered robust, as there was no study that made exceptional or unrealistic assumptions in its analysis, which might severely compromise the generalisability of its findings. Almost all studies in this category have adopted health impact assessment techniques to study the effect of hypothetical urban planning and demand interventions on air quality and health. In most instances, full-chain analyses were missing, that is traffic activity – vehicle emissions – air quality – exposure – health, perhaps due to the difficulties and complexities of such assessments and the absence of necessary data. Overall, quantitative evidence of post-implementation of measures in this category was lacking and impacts of hypothetical scenarios were modelled, instead of before and after intervention monitoring. In many cases, especially when the scope of analysis was bigger than a constrained community, as in all the studies we included, before and after intervention monitoring becomes very complex, expensive, and unfeasible, and therefore studies rely on health impact assessment modelling. Health impact assessment techniques are considered as robust tools to quantify potential impacts of interventions when these are not being measured. They are generally based on the best available scientific evidence, often sourcing exposure-response functions from systematic reviews and meta-analysis, and synthesising other information from all available sources in the study area. The utility and policy relevance of these tools, however, can be improved by complementing them with post-implementation monitoring, something that is largely missing in the current evidence base. Further, there is a need for more systemic assessment of the potential health impacts of interventions. For example, some studies considered the air quality improvements, but not the health and economic benefits stemming from the increased physical activity in their scenarios. Health benefits from physical activity may well exceed those from reductions in air pollution levels.[119]

The different scale of impacts in the different studies may be driven by several factors including social and land-use factors (such as the different bassline/current transport mode shares in the different cities), geographical factors (such as air pollution and exposure levels and population density), and technical factors relating to the research assessing the benefits (such as the selected exposure-response functions and different scenarios tested). There was evidence in the literature that the adverse health impacts and associated economic costs are estimated to decrease in line with reductions in air pollutant concentrations – that is, the health benefits increase as air pollution decreases.[120] This is in line with previous research showing that there is no safe threshold of air pollution, under which no health impacts would occur, and reinforces action aimed at sustained air pollution reductions in cities. One study highlighted the potential increases in urban O_3 levels due to the reductions of traffic-related $PM_{2.5}$, although O_3 declined regionally, and the overall outcome of the intervention was positive resulting in net health benefits of US$4.94 billion per year.[121] In another study, the well-established disproportionate traffic-related exposure levels were shown, highlighting important equity issues with transport-related exposures, which policy-makers need to consider when designing urban interventions.[122]

IMPROVING TRANSIT EFFICIENCY AND PASSENGER MODAL SHIFT

For rapidly growing cities, where infrastructure has yet to be built, and for cities where redevelopment is taking place, ideas such as compactness, connectivity, accessibility, and liveable density have emerged as an effective means of avoiding future emissions. The benefits of such an approach, whereby pedestrianisation, sustainable mass transport, and mixed land use are prioritised in urban planning, can yield substantial benefits for urban pollution and health outcomes. However, careful design is crucial to prevent unintended consequences. Where higher density is designed without transport options, or investments in transport do not sufficiently meet residents' needs, compact development can lead to congestion and higher levels of air pollution.[123]

Nieuwenhuijsen and Khreis (2016) evaluated radical concepts such as car-free cities, primarily driven by the need to reduce GHG emissions, and their potential impacts on public health.[124] The authors calculated great benefits in terms of reduction in not only air pollution (e.g. up to a 40% reduction in NO_2 levels on car-free days) but also noise and heat island effects, and potential increases in green space and physical activity, suggesting that more systemic approaches are needed to realise the full benefits beyond a narrow focus on one particular exposure. Three health impact assessments cited in this review estimated small air quality improvements and health benefits from the replacement of private car journeys by active or public transport.[125] For example, 76 annual deaths, 16 minor injuries, 0.14 major injuries, and 127 cases of diabetes, 44 of cardiovascular diseases, 30 of dementia, 11 of breast cancer, 3 of colon cancer, 7 of low birth weight, and 6 of preterm birth can be prevented each year, if 40% of long-duration car trips (where travellers leave their neighbourhood) were substituted by public transport and cycling.

Sabel et al. (2016) estimated that the introduction of a new metro in Thessaloniki, Greece, would reduce local deaths from air pollution by about 20%.[126] Xia et al. (2015) estimated that shifting 40% of vehicle kilometres travelled to alternative transport modes in Adelaide, South Australia, would reduce annual average $PM_{2.5}$ by a small margin of 0.4 $\mu g/m^3$, preventing 13 deaths a year and 118 DALYS.[127] Woodcock et al. (2009) conducted a health impact assessment of alternative transport scenarios in London and Delhi.[128] Both the use of lower-carbon-emission motor vehicles and an increase in active travel, and then a combination of the two scenarios, were tested. The increase in active travel and resulting less use of motor vehicles (i.e. modal shifts) had larger health benefits per million population (7,332 DALYs in London, and 12,516 in Delhi in one year) than the increased use of lower-emission motor vehicles (160 DALYs in London, and 1,696 in Delhi). The combination of active travel and lower-emission motor vehicles resulted in the largest health benefits (7,439 DALYs in London, 12,995 in Delhi). Most of the preventable premature deaths were estimated to result from increased physical activity, followed by the reduction of air pollution exposures.

Other passenger modal shift measures are more subtle and context specific. Yang et al. (2016) quantified the potential emission reductions of reducing the student ferrying (transport on short and regular trips) behaviour in Beijing.[129]

Daily, during the non-school seasons, HC, CO, NO_x, PM, and CO_2 emissions from the passenger car fleet were estimated to be reduced by 7.6%, 7.3%, 6.1%, 5.9% and 6.1% compared with those in the school season, respectively. In a health impacts assessment study, Rabl and de Nazelle (2012) modelled the mortality effects of switching from car to cycling or walking.[130] A driver who switches to cycling for a commute of 5 km (one way), five days a week, 46 weeks a year, would experience health benefits from the physical activity worth about €1,300 per year (US$1,450 in 2017 dollars), and in a large city (> 500,000) the value of the associated reduction of air pollution is in the order of €30 per year (US$33 in 2017 dollars). For the individual who makes the switch, the change in air pollution exposure and dose implies a loss of about €20 per year (US$22 in 2017 dollars) under the study's standard scenario but that is highly variable and could have the opposite sign. The results were similar for walking. The increased accident risk for cyclists was dependent on the local context.

As with the existing research on the impacts of urban planning, the scope of the research on the impacts of modal shifts and improving transit efficiency is wide. It spans European, Australian, and developing regions including China, India, and Mexico. No relevant studies were identified in America, Africa, or the Middle East. More attention has been given to the impacts for modal shifts when compared with improvements in transit efficiency. Again, the current literature is rough in terms of assigning the impacts to communities or finer regions of metropolitan areas, again perhaps due to the health impact assessment methods widely used. Reviews specifically addressing the impacts of modal shifts or transit efficiency on air quality and health outcomes were largely missing, although one wider review on car-free cities was relevant and included.[131] Almost all studies in this category adopted health impact assessment techniques to study the effect of modal shifts or transit efficiency on air quality and health. Overall, quantitative evidence of post-implementation of measures in this category was also lacking, and the impacts of hypothetical scenarios were modelled instead of before and after intervention monitoring, which would be complex, expensive, and unfeasible.

As with the land-use research, the differences in estimated benefits between studies are likely to be due to differences in social and land-use factors in the study areas, geographical factors, and technical factors specific to the analysis. There was evidence that the health benefits of air quality improvements through mode share shifts differed by region; for example, estimated benefits were higher in the more polluted Delhi when compared with London,[132] which is likely attributable to the linear model used to describe the exposure-response relationship. These results are clearly assumption specific, but are realistic as one would expect larger health benefits from air pollution reductions in the most polluted areas, and there is currently little data to suggest a non-(log) linear relationship between the exposure and the outcome. There was also evidence that a combination of policy measures, such as active travel and lower-emission motor vehicles in policy packages, rather than the use of individual measures, resulted in the largest health benefits.

Overall, our findings suggest that policy-makers could realise small urban air quality improvements and subsequent health benefits if they actively encourage a passenger modal shift from private vehicles towards more sustainable travel means, including walking, cycling, and clean public transit. Additionally, there are health benefits associated with an increase in physical activity levels, which may well exceed benefits from the air pollution reductions. The integration of modal shift policies within an urban planning framework is recommended as urban sprawl is a key trend causing job/housing and school/housing mismatch and subsequently long commuting distances, increasing private car demand and usage, and reducing active travel proportions. Further, as travelling attitudes and habits are often very deep-rooted and can be hard to change, comprehensive packages of urban and transport planning measures can play a transformative role by offering appealing alternatives.

In encouraging alternative travel means, policy-makers should consider the potential for unintended consequences from increased accident risk for cyclists and potential increases in individual air pollution exposures.[133] However, these consequences were shown to be extremely dependent on the local context, including the road safety conditions in the study area; for example, data for Paris and Amsterdam suggest that the loss due to fatal accidents after modal shifts is at least an order of magnitude smaller than the health benefit of the physical activity. On a population level, these risks were much smaller than the benefits attributed to overall reductions in air pollution, increased physical activity, and reduced motor vehicle crashes. These results are in line with more recent health impact assessments that show increases in physical activity and reductions in air pollution contribute the most to the 20% preventable deaths attributed to current urban and transport practices,[134] and that the health benefits of cycling well outweigh the risks associated with individual increases of air pollution exposure or motor vehicle crashes.[135] However, there is a need for an integrated policy framework that encourages modal shifts from the private car into active or public transport, but pays attention to the exposures of these shifting populations by providing designated routes, away from the roadside, and/or ensuring that these shifts are made at large scales sufficient to absolutely reduce air pollution levels (e.g. car-free policies) and improve safety and quality of space.

PASSENGER CAR EFFICIENCY AND/OR ELECTRIFICATION

A smaller number of studies investigated the air quality and health impacts of passenger car efficiency and/or electrification.[136] The prominent trend in this literature was the lack of full-chain health impact assessment and considerably less quantification of work.

Incentivising the electrification of passenger cars is often proposed as a sustainable approach to urban mobility and economic growth.[137] The literature suggests, however, that this may be a simplistic view and that electric vehicles may not result in assumed air quality and health benefits, unless uptake is optimistically large, and complemented by non-exhaust PM reduction measures. A state-of-the-art review by Timmers and Achten (2016) investigated the effects of fleet electrification on non-exhaust PM emissions, and found that total PM_{10} emissions from electric vehicles – originating from powerplant emissions – are likely to be higher than their non-electric counterparts, while a reduction in $PM_{2.5}$ emissions from electric vehicles is estimated to be negligible (1–3%).[138] Research on the health effects of non-exhaust PM is new and was not sufficiently explored in this review, but there are numerous studies, both epidemiological and toxicological, indicating distinct adverse health effects of non-exhaust PM H.[139]

Soret et al. (2014) estimated that fleet electrification can reduce total NO_x emissions by 11% and 17%, in Barcelona and Madrid respectively, only if 40% of all vehicles were substituted by electric vehicles (including two-wheelers, heavy-duty vehicles, buses, and light-duty vehicles).[140] Similar to Timmers and Achten's conclusions, the fleet electrification was found to have a limited impact on PM_{10} emissions (3–4% emissions reductions). No health impact assessment was conducted in this study.

Pathak and Shukla (2016) tested two potential transport scenarios for Ahmedabad, India, from 2010 to 2035.[141] The first was "business as usual" and the second was a low-carbon scenario constituting several climate change mitigation measures, including a modal shift towards non-motorised and public transport, fuel switch, reduced demand, energy efficiency, decarbonisation of electricity, and sustainable behaviour. The quantitative assessment of transport activity under business as usual was a four-fold increase in energy demand. The low-carbon scenario, besides improving energy security by reducing oil demand, was estimated to reduce NO_x by 74% and $PM_{2.5}$ by 83% from the passenger transport sector compared with business as usual in 2035. No health impact assessment was conducted in this study.

Xue et al. 2015 showed that, although increasing the proportion of new energy vehicles including hybrids, CNG, and electric vehicles will improve air quality in Xiamen, China, the greatest contribution to air pollution reduction comes from other policy scenarios.[142] These include alternative fuels and diesel truck decreases contributing to nearly 30% of air pollution reductions, followed by an option to control the intensity of private vehicles.

In a large-scale health impact assessment, Ji et al. (2012) modelled the health impacts of the use of conventional vehicles and electric vehicles in 34 major Chinese cities.[143] $PM_{2.5}$ emissions from electric cars were estimated to be higher than conventional gasoline vehicles, resulting in more preventable deaths, even after accounting for proximity to the emission sources. As a result, of the total excess deaths per year in Shanghai, nine were attributable to gasoline cars and 26 to electric cars. When compared with diesel cars, electric cars were shown to provide health benefits, yet the main reason behind these was not the reduction of total exhaust $PM_{2.5}$ emissions from electric cars, but the fact that most of these emissions occur at power plants, away from major population centres. There was evidence, however, that the urban use of electric vehicles will move exposures and adverse health impacts to rural, non-electric-car-users, who are potentially lower socio-economic populations.

The scope of existing research on the impacts of passenger car efficiency and electrification is limited, and is mostly focused on developing regions including China and India. The literature on non-exhaust PM emissions largely had a European and an American focus. No relevant studies were identified in Africa, and the current literature is rough in terms of assigning the impacts to communities or finer regions of metropolitan areas, as with the other categories. One study investigated the urban/rural differences in exposures and health impacts attributable to urban use of electric vehicles and noted such differences. In comparison with the literature identified in the previous categories, research on the impacts of passenger car efficiency and electric cars on air quality and public health is less advanced and includes less quantification and full-chain assessment. The main uncertainties are related to vehicle emission factors.

The literature on electrification is scarce, but some key points emerge. First, the air quality (and associated health benefits) of electric cars need more rigorous quantification, but current evidence suggests that these might be negligible (e.g. reductions in $PM_{2.5}$), or might even have an impact in the opposite direction (e.g. PM_{10}). There is emerging literature establishing the adverse health effects associated with traffic-related particulate matter, while the health effects associated with exhaust pollutants like NO_2 are more debated.[144] Second, the reduction of $PM_{2.5}$ emissions from electric vehicles is also likely to disappear as exhaust emission standards become stricter over time.[145] Particularly, the non-exhaust PM component of air pollution is expected to increase with the adaptation of electric vehicles, primarily driven by the increase in vehicle weight due to electrification (e.g. structural weights needed to accommodate larger batteries). While both emissions control regulation and electrification plans could lead to reductions in exhaust emissions, non-exhaust emissions from road vehicles remain unabated and need more consideration.[146] Some optimists expect battery technology to quickly improve, which would make electric vehicles lighter and therefore more energy efficient. Yet the overall trend over the last decade was a steady increase in vehicle weight in almost all segments.[147] Third, there was evidence that there may be air quality benefits of electric vehicles when compared with diesel vehicles, but this was not true when compared with gasoline vehicles. Improvements in gasoline technology may therefore also lead to important health benefits, yet the advancement of gasoline engines has received considerably less attention during the past 20 years, when Europe shifted its research capacity towards the diesel powertrain.[148]

The recent European diesel car boom demonstrates that climate action does not always have auxiliary health benefits, and can result in unintended consequences of deteriorating urban air quality and increasing the public health burden of air pollution, in addition to failing to achieve greenhouse gas savings initially promised/estimated.[149] Further, fossil fuels are still widely used in electricity generation and the use of coal, for example, constitutes 40% of global electricity generation.[150] The use of fossil fuels is causing significant premature mortality and morbidity, especially from respiratory and cardiovascular diseases and cancer,[151] adding to the health toll of electric vehicle use. The lack of progress with electricity decarbonisation is not promising and significantly limits the emission and air quality benefits of electric vehicles.[152] There is also little assessment of total life cycle, but some evidence that even the GHG impacts of electric vehicles are heavily dependent on use phase energy consumption and the electricity mix used for charging.[153]

FREIGHT POLICIES

Only three studies on the impacts of improved freight policies on air quality and health were identified, and these originated from the United States.[154] Lee et al. (2012) assessed the air quality and health impacts attributed to a clean truck programme in the Alameda corridor, USA, which progressively banned the older and most polluting trucks.[155] The truck replacement was estimated to have reduced NO_x and PM emissions by 48% and 55%, respectively, within a seven-year period. The health benefits from the reduction of $PM_{2.5}$ only was equivalent to US$428.2 million, but these estimates only incorporated two age groups (age 30–65, > 65), and two health endpoints (mortality and chronic bronchitis). To contextualise the results, the authors estimated that the payback period for replacing all drayage trucks in the study area is less than four years.

Sathaye et al. (2010) explored the air quality effects of a conventional freight logistics policy: that is, shifting the logistics operations to night-time hours. Due to the more stable/restrictive atmospheric boundary layer conditions during the night, the authors show that such a policy can increase the 24-hour air pollution concentrations in most locations in California, USA, and therefore worsen the daily human intake, or at best leave it unimproved.[156]

Finally, Bickford et al. (2013) reviewed studies that quantified the potential emissions and air quality benefits of shifting freight from truck to rail and then derived their own quantitative estimates in upper Midwestern United States.[157] Most studies reviewed (four out of five) reported net NO_x and PM emission reductions due to the truck to rail shift, yet the results and methods adopted varied widely. In their own quantification work, Bickford and colleagues estimated that truck to rail shift can reduce NO_2 and elemental carbon emissions in roadway grid cells by 18–28% and 15–16%, respectively, while the added rail activity can increase NO_2 and elemental carbon emissions along rail lines by 21–25% and 21–29%, respectively. The net change in NO_2 and elemental carbon concentrations was a monthly average reduction between 1.7% and 3.7% for NO_2, and a monthly average increase of 0.2% for elemental carbon. The implications to the populations exposed was not further discussed.

Despite diesel-fuelled freight vehicles being the largest motor vehicles contributors to air pollution within and between cities,[158] there is significantly less research on freight interventions to improve air quality and health outcomes, and these are exclusively from the United States. The research varied in terms of the methods used and included one full health impact assessment only. The main uncertainty is related to the emission factors used, which are likely to have underestimated the air quality benefits as these are generally optimistic and not reflective of real-world driving and conditions. The current evidence base suggests that the replacement of old trucks by newer, more efficient models can lead to significant air quality and health benefits, with savings exceeding the cost of investments. The effects of shifting freight from trucks to rail are unclear with suggestions of modest air quality benefits, but there was no health impact assessment conducted, which is essential considering the differences in populations exposed from freight or rail lines. Finally, although the policy of shifting fright operation to night hours is receiving more attention and promotion and is being viewed as beneficial for transport systems (e.g. congestion) and the environment, research suggests that such shifts may ultimately result in unintended adverse health impacts and increased air pollution exposures, due to the limited dispersion of pollutants during night hours.

There is clearly a need for more research regarding the effects of freight policies on air quality and public health but there is also current evidence that freight vehicles are a major contributor to local and regional air quality problems and that these can be mitigated by upgrading fright fleets and increasing their efficiency. The benefits of such strategies will clearly depend on the age and the efficiency of the baseline freight fleet. No studies investigating the likely air quality and health impacts of a reduction in freight vehicle kilometres or the overall numbers of freight journeys by, for example, more efficient delivery patterns, were identified, but such policies are also expected to deliver benefits as they reduce vehicle emissions.[159]

Indoor air pollution

Transport-related indoor air pollution is often overlooked, relative to outdoor air pollution. However, outdoor and indoor air pollution concentrations are correlated as there is considerable penetration of outdoor sources of pollution, including transport-related sources, into indoor environments. Unfortunately, an integrated assessment of indoor and outdoor air pollution exposures from the same sources is missing and no studies exploring the effects of transport policy interventions on indoor air pollution exposures and associated health impacts were found.

Nevertheless, several studies indicate the contribution of road transport to indoor air pollution levels and to the composition of air pollutants is substantial.[160] Studies that investigated the PM composition of outdoor and indoor microenvironments found that black smoke, a traffic exhaust marker, alongside other trace elements including V, Sn, Tl, and polycyclic aromatic hydrocarbons (PAH), have strong indoor–outdoor concentration correlations, indicating high concentrations from outdoor to indoor environments.[161]

One study that characterized the indoor–outdoor relationship of $PM_{2.5}$ in Beijing found that there is a strong correlation between indoor and outdoor $PM_{2.5}$ mass concentrations, and that the ambient data explained ≥ 84% variance of the indoor data.[162] Guo et al. (2010) similarly showed that $PM_{2.5}$ levels in an Australian primary school were mainly affected by the outdoor $PM_{2.5}$ ($r = 0.68$, $p < 0.01$).[163] Another study in Germany found that over 75% of the daily indoor $PM_{2.5}$ and black smoke variation could be explained by daily outdoor variation for those pollutants.[164] Similarly, in 100 surveyed schools across Europe, the average ratios of indoor and outdoor concentrations of NO_2, PM_{10} and benzene suggested that the main source of these pollutants were outdoor traffic sources.[165]

Health effects of indoor air pollution originating from traffic sources are similar to those of traffic-related outdoor air pollution (see section 2.1.1). Given that people spend up to 90% of their time in indoor environments, these exposures and their health effects ought to be explored more fully. The amount of air pollution penetrating indoors from outdoor sources will depend on factors such as the intensity of and proximity to outdoor sources such as major roadways or bust junctions, the building heights, the weather conditions such as the wind speed and direction and cloud cover, the presence of open windows, and ventilation systems.

Noise

The transport sector is responsible for high proportions of noise in urban areas that could be reduced through targeted policies. The levels of ambient noise are associated with the road network, junctions, traffic flows, speeds and loads, acoustics, and meteorological conditions in cities.[166] The L50 noise level (the noise level exceeded for 50% of the measurement period) is affected by traffic levels. It ranged from about 54 decibels (dB) in acoustic shadows in residential tertiary streets up to 74 dB on high-traffic roads.[167] Lee et al. (2014) found that the total number of vehicle counts explained a substantial amount of variation in measured ambient noise in Atlanta (78%), Los Angeles (58%), and New York City (62%).[168]

The health effects of traffic-related noise are increasingly becoming recognised. Ambient noise has been associated with a range of different adverse health outcomes,[169] including adverse reproductive outcomes,[170] all-cause premature mortality,[171] annoyance and sleep disturbance,[172] cardiovascular mortality and morbidity,[173] cognitive effects in children,[174] high blood pressure in children,[175] mental health and well-being,[176] stroke,[177] and type-2 diabetes.[178] Ambient noise can also cause stress and aggression.[179]

The burden of disease attributable to traffic-related noise may be equivalent to or exceed that of air pollution.[180] Mueller et al. (2016) estimated that around 600 premature deaths (4% of all deaths) could be avoided with a reduction of 10 dB in traffic-related noise exposures in Barcelona, a city with a population of around 1.6 million people.[181] Tobías et al. (2015) estimated that the reduction of traffic-related noise by only 1 dB(A) can prevent an annual mortality of 284 cardiovascular-related deaths and 184 respiratory-related deaths in adults ≥ 65 years old in Madrid, Spain.[182] These reductions are significant and are equal to the impacts associated with the reduction of $PM_{2.5}$ by 10 $\mu g/m^3$. Tainio (2015) estimated that air pollution, noise, and injuries attributable to local transport in Warsaw, Poland, were causing approximately 58,000 DALYs; 44% of which were due to air pollution and 46% to noise.[183] In conservative estimates, 1 million healthy life years every year are lost because of traffic-related noise, in the western part of Europe alone.[184] The cost of traffic noise in the EU22 was estimated to be at least €40 billion each year (US$45 billion, 2017 dollars), with 90% of these costs specifically caused by passenger cars and lorries. These were considered conservative estimates which were equivalent to 0.4% of total GDP.[185]

Although noise has significant effects on human health, the number of studies relating this to the specific policy measures we investigated is small, and these generally lack costed estimates.[186] There are other policy measures that are relevant but were outside the scope of this report. For example, Weis et al. (2015) suggested that the large-scale adoption of electric two wheelers could significantly reduce traffic noise.[187] The switch from fossil fuels to biodiesels was also suggested as another strategy to reduce vehicle noise emissions.[188]

Rabl and de Nazelle (2011) presented an estimate of the health impacts due to a shift from car to cycling or walking, by evaluating the four effects relating to changes in air pollution exposures and accident risk and citing costs for other impacts, especially noise and congestion.[189] A driver who switches to cycling for a commute of 5 km (one way), five days per week, 46 weeks per year, would experience health benefits from the reduction in noise worth about €1700 (US$1900, 2017 dollars). The results for walking (2.5 km) were similar. Applying these estimates to a specific example of a policy measure in Paris: the Velib bike-sharing system, the population benefits of the reduction in noise were estimated at €69.9 million per year (US$78 million, 2017 dollars).

The studies on noise are scarce and only cover a few cities in Europe and one in the United States. The studies used a health impact methodology and focused mainly on the effects of mode shift at the city level. The estimates for noise were crude and were not based on detailed modelling or measurement exercises. In all the studies, noise was not the main exposure under analysis. The studies were judged as robust but also used older estimates for costing that were almost 10 years old. The literature on the potential health impacts of noise is very limited and did not incorporate any scenario testing to quantify the health effects of specific policy measures or interventions.[190] There is a clear need to fill large gaps in the literature on the effects of urban planning, reduced passenger travel demand, vehicles efficiency and electrification, and freight logistics improvements on noise and associated health effects. There is also a need to provide health estimates under different scenarios.

However, policy-makers need to be aware that noise can have large adverse health impacts, which are comparable to those of air pollution (in the case of premature mortality), or may exceed those of air pollution (in the case of morbidity). Such impacts are currently not seriously considered in policy circles or in academic circles, as shown by the results of our searches and review. There was evidence in the literature that the scale of the positive impacts of traffic noise reduction measures may be limited by the scale of interventions, where local actions can have little effect due to, for example, motorway traffic not being subjected to local traffic reduction measures. This highlights the advantage of complementing local policies with national policies. Unintended consequences of traffic noise reduction measures include the potential for increases in motor vehicle crashes, because of non-detection. Various studies have suggested that electric cars or hybrid cars are 1–2 dB quieter than conventional cars, but that this may lead to increased accidents because of non-detection, especially to the blind and visually impaired.[191] For this reason, some countries such as the United States and Japan are considering minimum noise requirements for such vehicles, although this restricts the noise reduction advantages of electric vehicles.[192]

Physical activity

Over the past 70 years transport systems have been designed in a manner that emphasises the pre-eminence of motorised mobility, especially via the private car.[193] The number of vehicles, motor vehicle kilometres, road construction funding, and vehicle infrastructure priorities have all been on the rise in most developed countries, and developing countries are following similar pathways.[194] These trends not only affect current and future emissions from cities, but also rates of physical activity, and by extension, public health. Car use is associated with decreased physical activity,[195] and declining active travel is considered an important contributor to overall declines in physical activity and increases in sedentary behaviour.[196] At the same time, rates of chronic disease, cancer, dementia, mental health, and premature mortality are closely connected with levels of physical activity.[197]

Policy-makers have at their disposal a number of options that can simultaneously help to improve urban mobility, increase physical activity, and reduce carbon emissions. A global literature review indicates that the per kilometre health benefits of dedicated cycle lanes vary from €0.30 to €1.20 (US$.33–1.45, 2017 dollars).[198] Taken cumulatively across Europe, this could be €31–122 billion per year (US$35–136 billion, 2017 dollars). A study in New Zealand indicates that transforming urban roads over the next 40 years to be better suited to bicycle use would yield benefits that are 10–25 times greater than costs,[199] and a Norwegian cost–benefit analysis found that investment in cycling networks in three Norwegian cities would have benefits at least 4–5 times the cost of investment.[200]

Urban planning measures can also significantly affect travel choices and physical activity levels.[201] Sugiyama and colleagues (2012) systematically reviewed 46 quantitative studies examining the associations between walking and multiple built environment factors, including the presence and proximity of destinations and sidewalks, connectivity, aesthetics, traffic on, and safety of the walking routes.[202] Half of the studies came from North America, 11 from Australia, 8 from Europe, 3 from South America, and 1 from Japan. A total of 80% of the literature suggested that the presence and proximity of retail and service destinations are conducive to adults walking. Other factors such as the availability of sidewalks and well-connected streets were also found to facilitate active travel.

Additional reviews support the findings of Sugiyama and colleagues (2012). Day (2016) focused their review on 42 empirical studies conducted in China and similarly showed that active travel was most strongly associated with the proximity of non-residential locations.[203] The literature reviewed supported an association between land-use mix (proximal non-residential locations) and active travel in Chinese cities. Similarly, in a review of 65 studies of children from North America, Europe, Australia, and Asia, D'Haese et al. (2015) found that walkability, density, and accessibility were associated with active travel to school.[204] Additional studies finding supporting results include Buehler and Pucher (2012), Wong et al. (2011), Lee and Moudon (2004), and Cohen et al. (2006).[205]

In contrast, increased urban sprawl and longer distances between homes, retail locations and work locations, has been found to be associated with decreased physical activity and poor health indicators.[206] Salon (2016) showed that pedestrian and cyclist road use in urban census tracts is double that in suburban census tracts, which in turn is an order of magnitude greater than that in rural census tracts.[207] In a review synthesising studies, Saelens et al. (2003) showed that residents of high-walkable neighbourhoods reported two times more walking trips per week when compared with residents of low-walkable neighbourhoods (3.1 versus 1.4 trips).[208] Similarly, Rodríguez et al. (2006) showed that residents of walkable urban neighbourhoods made twice as many trips walking and cycling compared with residents of suburban neighbourhoods, logging 40–55 extra minutes of weekly physical activity.[209] These differences were mainly driven by utilitarian travel, rather than leisure travel.

The most effective approaches towards improving urban mobility and public health while reducing carbon emissions may come from integrated investments.[210] Urban planning that promotes compact and mixed land-use patterns and increased physical activity also makes transit more viable and efficient,[211] and contributes to increasing public transit demand.[212] Indeed, Buehler and Pucher (2012) found that, when coordinated in packages of other complementary policies (e.g. attractive fares, restrictions on car usage, etc.), compact cities can increase the likelihood of public transport use five times.[213] Residence proximity to transit is also a strong predictor of transit ridership; for example, a zone within 1,000 m of a subway station is likely to have a 7.7% higher transit mode share compared with zones further away.[214]

For policy-makers, these results should inform the approach taken to addressing physical activity and transport networks in cities, rather than specific investments. Compared with studies in the air pollution and noise categories, there was a higher level of heterogeneity between the methods of the studies in this category, which limits the usefulness of comparisons. In the health impact assessment studies, modelling assumptions and tested scenarios varied largely between studies, which may explain the wide range of effects and cost–benefit ratios described.[215] Other reasons that could explain the differences in the scale of the benefits estimated across the different studies include differences in social and cultural factors, such as the baseline physical activity levels and active travel mode shares in the different areas, and technical factors related to the study methods, such as the different exposure-response functions selected for the health impact assessments and the inconsistencies in defining active travel and measures of the built environment such as walkability, density, diversity, mixed land use, etc. Despite these differences, the literature consistently demonstrated positive effects of the investigated interventions on physical activity levels and associated health impacts where investigated.

Overall, policy-makers could realise significant health benefits if they actively promote compact and diverse cities, invest in public transit, and encourage a passenger modal shift from private vehicles towards walking and cycling. Unlike interventions that target individuals or specific population groups to increase their physical activity levels, making changes to the urban environment is a universal intervention that targets the whole population of the neighbourhood/area and therefore increases population-level physical activity, rather than the activity levels of individuals who are motivated and participate in tailored interventions. Further, changes in the urban environment are long lasting and are arguably permanent, while behaviour change campaigns and programmes are rarely maintained.[216] The benefits of higher urban densities go way beyond the climate and public health benefits we discuss and include increasing the potential for urban agriculture, which in turn reduces food miles and improves local food security, improving the housing choices for all residents, reducing social exclusion, increasing the opportunities for creative social interaction, reducing crime rates, improving cities' economic efficiency and employment opportunities, among others. There are, however, documented disadvantages of increasing density, which highlight the need for an integrated policy approach to overcome these potential negative consequences. These include exacerbating traffic congestion and parking problems, reducing an area's capacity to absorb rainfall, reducing green space and exacerbating air pollution, increases in noise, and negatively impacting the economic development of surrounding rural areas.

Motor vehicle crashes

Motor vehicle crashes are responsible for 1.3 million global deaths each year and over 78 million injuries.[217] For people under the age of 60, motor vehicle crashes rank among the top 10 causes of global deaths,[218] and are the number one global cause of death among those aged 15–29 years.[219] In OECD countries, road crashes are the single biggest cause of deaths in those aged 15–24 years.[220] Deaths from motor vehicle crashes exceed deaths from HIV/AIDS, tuberculosis, or malaria,[221] and are disproportionality distributed across the world's population: low-income and middle-income countries account for over 90% of the world's roads deaths despite only having 48% of the world's registered vehicles.[222] In low-income countries, the number of road deaths per 100,000 is 24,[223] which is similar to the level recorded in developed countries such as the Netherlands in the 1970s.[224] These figures are likely to increase with population growth, rising vehicle ownership rates, large-scale investment in road building, and trends in the car industry of moving new markets to low- and middle-income countries.[225]

In economic terms, road crashes are estimated to cost 1–5% of GDP in developing countries, undermining efforts to reduce poverty and developmental assistance.[226] In developed countries, the costs are similar. For example, the cost of road crashes was 1.7% of GDP in Australia in 2006,[227] 1.6% of GDP in the United States in 2010,[228] 2.6% of GDP in Belgium in 2002,[229] and 1.2–2.3% of GDP in the UK.[230] Worryingly, there is evidence from around the world that the number of motor vehicle crashes and road deaths has been increasing.[231]

Even within the same region/country, the impact of motor vehicle crashes on the population is disproportionately distributed. Numerous studies show that neighbourhoods of lower socio-economic status have higher motor vehicle crashes, especially for child pedestrian injuries.[232] Despite the high variability between regions, motor vehicle crashes are generally highest for vulnerable road users, most notably active travel commuters (pedestrians and cyclists), followed by public transport commuters, then car commuters.[233] Historically, most of the road safety interventions have focused on the safety of vehicle occupants.[234] Yet, 50% of the world's road traffic deaths occur among motorcyclists, pedestrians and cyclists, while 31% occur among car occupants (remaining is unknown).[235] There is, however, a “safety in numbers” effect, such that when the number of pedestrians and cyclists increases, the increase in the number of accidents involving them is smaller than proportional.[236] The impacts of motor vehicle crashes also extend beyond the direct road deaths and injuries. Concerns over road safety are cited as some of the most important issues underlying parents’ preferences for driving children to school, deterring active travel and restricting child play outdoors.[237] These trends further contribute to sedentary lifestyles and physical inactivity (see section 2.1.4).

Land-use planning to reduce motorised passenger demand, as well as improving transit efficiency and encouraging a critical mass of passenger modal shift away from the private car, are some of the measures policy-makers have at their disposal to improve road safety and protect/improve public health. These measures will be summarised next. There are other interventions beyond the scope of this report including traffic calming measures, which can reduce urban fuel use and motor vehicle crashes.[238]

In most contexts, increased traffic flows are associated with increased motor vehicle crashes.[239] Therefore, urban planning measures to reduce traffic and vehicle kilometres travelled (see section on 2.1.1) are likely to reduce road deaths and injuries.[240] More sustainable urban planning patterns accommodating walking, bicycling, and transit-friendly neighbourhoods are expected to lead to reduced passenger car demand and use, which in turn has been associated with reduced motor vehicle crashes.[241] Previous research has shown that traffic volumes and road densities are the main determinants of the frequency of motor vehicle crashes. Dumbaugh and Li (2011) estimated that each additional mile of thoroughfare is associated with a 9.3% increase in motor vehicle–pedestrian crashes.[242] A reduction of 30% in traffic volumes is associated with a 35% reduction in the number of pedestrians injured in motor vehicle crashes and a 50% reduction in the average risk of pedestrian collision.[243] Lowering traffic flows was linked to a decline in child pedestrian deaths in New Zealand,[244] and when achieved as part of the London congestion charging was linked to a substantial reduction in both the number of crashes and crash rates.[245] The London congestion charging zone was associated with 44 less motor vehicle crashes per month, which represented a 35% decline.

The literature, however, shows that different urban planning interventions established to reduce passenger car demand have different effects on road safety, perhaps mediated by the increase in active travel levels. In a systematic review of 85 quantitative studies investigating the effect of the built environment of childhood walking and pedestrian injuries, Rothman et al. (2013) found that higher road density and higher traffic speeds increase injury incidence and severity.[246] Land-use mix and proximity to services and facilities were also found to increase the incidence and severity of injuries but were associated with increased walking. The authors discussed that these urban environment characteristics may not be inherently dangerous, but rather may be markers for increased exposure to traffic in general. Two urban measures were consistently found associated with increased walking and a reduction in child pedestrian injuries, namely traffic calming and the diversity of land use including the presence of playgrounds, recreation parks, and open space. Further studies similarly showed that land-use mix and proximity to retail, although favourably promoting walking and cycling, are associated with increased crash risks in children and adults,[247] while the results from other studies were mixed.[248] Differently from the above studies and adjusting for pedestrian exposures, Ewing et al. (2003) found that all traffic fatalities and pedestrians’ fatalities decrease by 1.49% and 1.47%, respectively, with each 1% increase in a compactness index.[249] Godwin and Price (2016) argued that the distinct pattern of lower density of urban areas in the southeast USA is likely to be leading to rare and more dangerous walking and cycling activity resulting in decreased road safety.[250] Yeo et al. (2015) conducted a path analysis to examine the causal linkages between urban sprawl, vehicle miles travelled, and traffic fatalities, drawing on data from 147 urbanised areas in the United States.[251] In line with previous research,[252] the authors found that there was an indirect effect of urban sprawl on fatalities, which occurred through increases in vehicle miles travelled, alongside a more influential direct effect possibly occurring through increased traffic speeds and emergency medical service delays.

As for studies investigating the effects of passenger modal shifts on road safety, there was evidence of increased motor vehicle crashes risk, as motor vehicle passengers switch to active travel means, which tend to be more vulnerable. In a systematic review including 21 health impact assessment studies of passenger modal shift effects on traffic incidents, Mueller et al. (2015) reported that, with increases in active travel, 14 studies estimated an increase in motor vehicle crashes, six studies estimated a decrease in motor vehicle crashes, and one study estimated no change in motor vehicle crashes.[253] Only eight studies, however, accounted for the non-linear traffic incident risk attributed to increased safety because of the increased number of active travellers: the so called "safety in numbers" effect[254] (also overall the benefits of increased physical activity well outweighed the risk of motor vehicle crashes). Jacobsen (2003) showed a consistent inverse relation between the amount of walking and cycling and the likelihood of a pedestrian and cyclist being involved in a motor vehicle crash.[255] The author argued that a community doubling its walking can expect a 32% reduction in cycling injuries. In another review, Götschi et al. (2015) looked at studies that modelled the safety impacts of cycling, and showed that a modal shift from car travel to cycling is estimated to increase the number of cyclists' fatalities and seriously injured but that the benefits stemming from increases in physical activity well outweigh the risks.[256] For example, shifting a 10-km commute from car to bike will result in an average cost of €50 per person per year (US$56, 2017 dollars) from fatal crashes and an average saving of €1,300 per person per year (US$1450, 2017 dollars) from physical activity.[257] In line with other investigators,[258] Götschi et al. (2015) also concluded that impact modelling of cycling crash risks is highly case- and context-specific.[259] Also, the increases in cyclists' and pedestrians' fatalities and injuries following a mode shift from the car might be a representation of a period of increased vulnerable road users' collisions and injuries, which will cease/decrease when the cycling mode split approaches the 20% level.[260] From a different angle, Tainio et al. (2014) estimated the years lived disabled or injured for pedestrians, cyclists, and car occupants, and found that injured pedestrians and cyclists sustain 9.4 and 12.8 years lived disabled or injured, while car occupants sustain a higher value of 18.4 due to the severity of the injuries sustained.[261] The authors estimated that a person switching from car use to cycling in an urban area would, on average, have 40% less severe injuries.

Public transport networks have been found to be substantially safer than car travel, both for passengers and the public.[262] Research shows that cities with the highest share of mass transport users have the lowest share of traffic fatalities.[263] Cities built on a combination of transit and walking could also mitigate motor vehicle crashes. For comparison, between 2010 and 2014, the four largest Dutch cities – Amsterdam, The Hague, Rotterdam, and Utrecht (all with a very high bicycle modal share by international standards) – recorded 2.0 road deaths per 100,000 populations,[264] while Hong Kong and Paris, both cities centred on mass transit,[265] recorded 1.5 and 1.6 road deaths per 100,000 populations, respectively.[266] In a more recent analysis, public transit was shown to have one-tenth the per mile traffic casualty rate, when compared with car travel. The report showed that increasing public transit travel in a community is associated with decreasing crash rates, which results in public-transit-oriented communities being five times safer than car-oriented communities.[267]

As described above, the synthesised studies and reviews demonstrate that compact urban planning, reduced traffic flows and road densities, and improvements in public transit can improve road safety and reduce motor vehicle crashes. On the other hand, mixed land-use patterns and proximity to services and facilities, urban sprawl, and passenger modal shifts can increase motor vehicle crashes. Studies covered a wide variety of regions, including the United States, Australia, New Zealand, Canada, UK, India, Israel, and Europe. Studies from Africa were missing.

The increases in motor vehicle crashes with increasing mixed land use may be explained by the increasing walking or cycling population which become exposed to a well-established higher crash risk. Policies that encourage densification, mixed land use, and an increase in transit supply increase pedestrian and potentially cyclists' activity. With no supplementary safety strategies, these policies may indirectly increase motor vehicle crashes.[268] Similarly, compact areas with low-speed, but high-conflict traffic environments can increase crash exposures.[269] Policies that encourage modal shifts from the private car, although clearly demonstrating net public health benefits, can increase the risk of pedestrians and cyclists being involved in motor vehicle crashes. However, it should be noted that these results are highly context-specific, non-generalisable, and differ substantially depending on the study area (e.g. its motorisation levels, baseline active travel commuters, safety measures in place for pedestrians and cyclists). Furthermore, there are numerous methodological limitations that should be considered in this literature, including the fact that most studies do not account for the "safety in numbers" effect and the weaknesses in the indicators used to measure crashes (numerators) and corresponding exposures (denominators).[270]

Overall, our findings show that policy-makers would realise reductions in motor vehicle crashes if they reduce traffic volumes and road densities, increase the supply of mass transit, and specifically cater for the safety of vulnerable road users when encouraging modal shifts away from the private car. The impacts of compact cities also seemed beneficial although less consistent than the other policies. The evidence showing higher density or mixed land use associated with higher motor vehicle crashes can be misleading and mediated by the higher activity levels in those areas and potential modal shifts. In areas with higher population density and mixed land use, extra road safety measures are likely to be needed to mitigate the higher crash risk of active travellers.

Other environmental exposures: green space and urban heat islands effects

Urban heat islands are regions of urban areas where temperatures are significantly elevated due to human activities and changes to the environment, in particular reductions in green space.[271] These exposures have a combined effect on climate change and public health. Transport infrastructure including roads and parking areas contribute to the increases in temperature in urban areas via the so-called heat island effect. The urban heat island effect is observed where green, wooded, or open areas have been substituted by asphalt and concrete for infrastructure such as parking areas or roadways.[272] Besides traffic-related infrastructure, motor vehicles can also raise temperatures through tailpipe emissions (methane, nitrous oxide, carbon dioxide, and black carbon). Together with long-term climate change and re-radiation effects of dense urban structures, motor vehicles can amplify urban temperatures.[273] The EPA reported that the annual mean air temperature of a medium-size city of 1 million people or more can be 1.0–3.0°C higher than its surroundings, with differences up to 12°C in the evening time.[274] Transport and utilities also use significant amounts of land for infrastructure and right of way, which once was, or could arguably be used for, green and open space.[275] Green infrastructure, or green space, includes parks, gardens, green squares and cemeteries, hedges, trees, woodland, green roofs, green walls, and rivers and ponds within urban areas.[276]

There are well-established health effects from changes in local temperature and green space. Increases in temperatures cause premature mortality,[277] cardiorespiratory morbidity,[278] increases in the number of hospital admissions and use of health services,[279] preterm birth,[280] reduced lung function in children,[281] motor vehicle crashes,[282] and increases in children mortality and hospitalization.[283] Green space can mitigate the deleterious effects that urban environments have on health and has been associated with numerous beneficial health effects,[284] including decreased premature mortality and increased longevity,[285] reduced cardiovascular disease,[286] higher birth weight,[287] improved mental health,[288] improved people's self-reported general health,[289] improved sleep patterns,[290] recovery from illness,[291] reduced behavioural problems in children,[292] improved cognitive function in children,[293] increased social contacts,[294] and a better skin microbiome leading to reduced allergic disease.[295] Possible mechanisms for the health benefits of green space are due to increased physical activity and social interaction, psychological restoration and stress reduction, and importantly the mitigation of detrimental environmental exposures including air pollution, noise and heat.[296] Also, green space may mitigate the adverse effect of low socio-economic status on health.[297] A recent health impact assessment study in Barcelona showed that increasing green space in the city would avoid around 100 premature deaths annually.[298]

In addition to reducing heat island effects, increasing the quality and quantity of urban green space can also help urban areas to adapt to a changing climate. Regulating the urban environment with trees and natural spaces can mitigate climate-change-related events, including weather damage,[299] heatwaves,[300] and flooding.[301] Urban greenery and tree canopies can also directly combat climate change by sequestering and storing carbon.[302]

However, the case remains that green space is often limited in many urban areas and varies considerably between and within cities. European cities average around 18.6% green space while globally green space in cities can be as low as 1.9% and as high as 46%.[303] Urban tree canopy is also currently decreasing in most cities across the world due to densification, expansion, and increasing populations.[304] A few European cities have established greening campaigns partially to be replacing or reducing the space taken up by transport infrastructure.[305] However, the case is different in most developing countries, where unprecedented urbanisation is taking up natural spaces.[306]

In economic terms, there is compelling evidence to support greening cities. In work quantifying the health benefits of trees for 245 cities globally, McDonald et al. (2016) reported that, although the cost of temperature reductions varies significantly across neighbourhoods, the median cost of tree planting is less than every other climate change strategy considered except for cool-roof technologies.[307] An annual additional investment in trees of US$100 million globally would give an additional 77 million people a 1°C reduction in maximum temperatures on hot days, and 8 million additional people a large reduction in $PM_{2.5}$ (> 10 μg/m³), 47 million people a moderate reduction (> 5 μg/m³), and 68 million people a modest reduction (> 1 μg/m³).[308] McDonald et al. (2016) also estimated that, based on studies that functionally relate mortality to high temperature, the maximum possible tree planting in their case cities would reduce high temperature-related mortality by 2.4–5.6%, saving between 200 and 700 lives annually.[309] Additionally, tree planting would reduce electricity use and increase carbon sequestration. Similarly, Kardan et al. (2015) found that planting 10 more trees per city block in Toronto is equivalent to increasing the income of every household in that city block by more than US$10,000 annually, which provides results in a favourable cost–benefit ratio, as planting and maintenance of 10 urban trees costs between US$300 and US$5,000 annually.[310]

There are other co-benefits of greening cities. Investments in urban natural spaces can enhance a city's economic competitiveness, where aesthetic and beautiful places and quality of life are important for attracting and retaining a skilled workforce,[311] and may create green jobs and potentially increase tourism.[312] Urban parks can also function as biodiversity hotspots.[313] Urban green space can make active travel attractive and thereby encourage and support new, environmentally friendly behaviours,[314] and it was also found to be associated with a reduction in child pedestrian injuries.[315] Green spaces seem to benefit economically deprived urban communities more than others, contributing to mitigation of socio-economic inequalities,[316] another challenge policy-makers are faced with.

2.2 CONGESTION AND TIME

Time lost to traffic congestion reduces the number of hours available for economically and socially productive activities, significantly increases fuel expenditure, air pollution and the number of vehicle accidents, and reduces urban productivity and employment.[317] As a result, estimates of the cost of congestion in cities combine many of the co-benefits/co-costs associated with conventional urban transport.

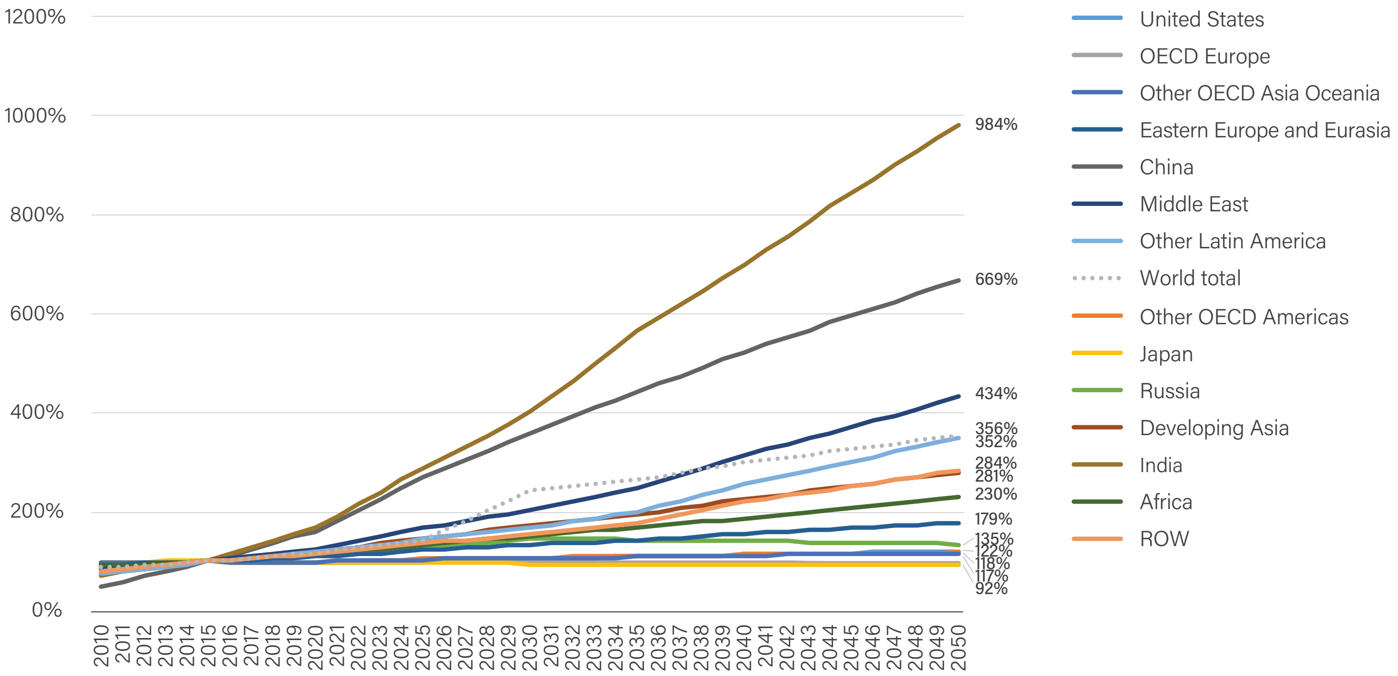
Recent research emphasises that the total costs of these impacts are substantial. Across 439 urban areas of the United States, the cost of lost time to congestion was estimated to exceed US$100 billion in 2009,[318] and US$124 billion in 2013.[319] In Europe, congestion in urban areas has been estimated to cost France US$23 billion, the UK US$20 billion, and Germany US$34 billion, each year.[320] In developing countries, where urban infrastructure is in many cases less extensive and urban densities are often higher, the cost of congestion is generally lower as a total figure but significantly higher as a proportion of GDP. In Sao Paulo, Brazil, for example, daily traffic jams reaching more than 350 km are estimated to cost US$120 billion each year in lost work hours, increased fuel consumption, and traffic accidents, which is nearly 8% of urban GDP,[321] and in Beijing, China, congestion has been estimated to cost as much as 5.3% of GDP.[322]

Table 2
Cost of congestion in urban areas (as a percentage of GDP)

Region	Cost of congestion (as % of GDP)
New York, USA[323]	1.1
Toronto, Canada[324]	1.1
London, UK[325]	1.5
São Paulo, Brazil[326]	7.8
Darak, Senegal[327]	3.4
Manila, Philippines[328]	4.0
Beijing, China[329]	3.3–5.3
Bangkok, Thailand[330]	1.0–6.0
Lima, Peru[331]	10.0
Cairo, Egypt[332]	4.0

Adding to the sense of urgency, vehicle growth in the developing world is fast outpacing the growth of paved infrastructure. Between 2010 and 2050 vehicle kilometres are expected to rise by 50–60% within the OECD and by 400–500% outside the OECD.[333] Global road infrastructure, however, is only expected to increase 60%.[334] As a consequence, congestion is anticipated to increase substantially. In China and India road occupancy levels, a measure of congestion, are expected to increase 2.5 and 6.5 times by 2050, while in Latin America, Africa, and the Middle East, occupancy levels are expected to increase more than 50%.[335]

Figure 5
Total vehicle kilometres by country indexed to 2015 based on business-as-usual trends



Research suggests that policy-makers have a number of options at their disposal to address congestion.[336] Congestion pricing – a travel demand policy where vehicles are charged for access to roadways at specific times – was first implemented in Singapore in 1975, and cities around the world have followed its example, achieving major reductions in congestion. In the first three years of its implementation, the London congestion charge reduced vehicle traffic by 16%, traffic delays by 26%, and journey times by 14%.[337] In Stockholm, traffic in the central business district was reduced by 22% and traffic delays by one-third.[338] In Milan, vehicle traffic was reduced by 21%, while in Singapore traffic remains 31% below 1988 levels.[339] Major cities currently considering or developing congestion charge programmes include New York, Beijing, and Bogotá.[340]

In addition to these impacts, congestion charging programmes have also shown to be an effective means of raising capital for further transport investments. Congestion charge programmes raise US$177 million in net revenue each year in London,[341] more than US$90 million in Stockholm,[342] US$125 million in Singapore, and more than US$20 million in Milan.[343] However, the distributional impacts of congestion pricing, with the poorest members of society potentially facing the largest financial burden and impact on their lives, needs to be considered in addition to the previously mentioned benefits.

Research indicates that improvements in public transit systems can complement measures that discourage private vehicle use, by providing residents with alternative transport options.[344] Bus rapid transit (BRT) systems have been successfully implemented across a range of developed and developing cities, including in Bogotá, Guangzhou, Lagos, Mexico City, Ahmadabad (India), and Johannesburg, South Africa, demonstrating the potential for reducing urban congestion.[345] For example, in Mexico City the Metrobus is attributed with reducing 110,000 tonnes of GHG emissions each year, improving particulate exposure to one-half or one-third of the previous level, reducing travel times by 40% and traffic accidents by 84%.[346] Whether such investments are cost-effective, however, depends on the local context, and in particular on the size of the city and transport system. Harford (2006), for example, using estimates of the reduction in congestion attributed to investments in public transport in 85 urban areas in the United States, found that benefit–cost ratios averaged 1.34, but were less than 1 in many urban areas.

Research also suggests that urban form can play a critical and reinforcing role in contributing to, or preventing, congestion, as a consequence of path dependence and 'locking in' in the development of both physical and institutional infrastructure.[347] Famously, a comparison is made between Barcelona, where a population of 2.8 million lives across 162 km^2 emitting 0.7 tonnes of CO_2 per capita from transport each year, and Atlanta, where a similar population lives across 25 times the areas and emits more than 10 times the carbon emissions from transport.[348] This issue is discussed further in section 2.3.1 on productivity.

The range of options available to policy-makers to address congestion illustrates the need for holistic responses, but also the need for actions to be tailored to specific urban contexts. In rapidly growing cities, rates of population growth and vehicle ownership are often driving factors in rising congestion.[349] In these cities, literature suggests that early attention to urban form and function can meaningfully address congestion and its associated costs before they become 'locked in'.[350] In cities experiencing slower population growth and level or declining rates of vehicle ownership, which is the case in many urban areas in the developed world, changes to urban form and function can be costly and time-consuming. Shifting to low-carbon transport networks therefore requires negotiating the need for fundamental changes to urban form and function, and the potential for a large set of innovative and complementary transport investments. These measures, which include congestion pricing and road pricing, investments in non-motorised transport measures, and public transport networks, frequently require sophisticated planning, and technical and management capabilities.[351] Finally, in cities where population and vehicle growth are high, but urban infrastructure has already been built, such as is the case in many of the world's mega-cities, more radical approaches may be needed.[352]

Basic characteristics of urban areas therefore provide some insight into the kinds of interventions that are needed. However, the success of any investment will also hinge on a range of additional factors, including aspects of the local economy (wages levels and economic growth rates), urban geography and topography, behavioural and social factors, technologies, and specific factors regarding the existing transport network. These factors are discussed further in other sections, and in the Discussion and conclusion section.

2.3 EMPLOYMENT AND THE GREEN ECONOMY

Productivity

The efficiency and accessibility of transport has wide-ranging impacts on local, regional, and global economies. The cost of travel (including expenditure of time and money) affects not only the flow of goods and services, but the pool of available workers and firms, and consequently the opportunities for knowledge-sharing, face-to-face interactions and the sharing of infrastructure and amenities.[353] The loss of these “agglomeration effects” or “urbanisation economies”, reduces productivity, wages, and output in the local economy.[354]

In value terms, the productivity losses that urban areas face as a result of poor transport networks have been found to be comparable with the direct losses associated with reduced work hours, increased fuel expenditure, and increased numbers of accidents (congestion losses), and to increase with city size. In Vancouver, Canada, for example, the loss of agglomeration economies due to congestion has been valued at between US$500 and US$1.2 billion; in Toronto, Canada, losses have been estimated at US$2.7 billion; and in New York, losses are estimated at US$4 billion.[355]

A large body of academic literature demonstrates that urban mobility is of central importance to agglomeration effects and urban productivity.[356] Literature on urban planning suggests that compact urban development, in part through its impact on travel distances and travel times, is strongly connected with higher productivity. Haughwout (2000), for example, found that a doubling of urban density was associated with a 6% increase in labour productivity in developed countries,[357] and Carlino and Hunt (2007) found that a doubling of employment density was associated with a 20% increase in patent intensity – a proxy for innovation and productivity growth.[358] Demonstrating the opportunity cost of reduced density, Hsieh and Moretti (2014) estimated that density-limiting policies in the largest US cities cost the economy approximately US$1 trillion annually, or 13% of output.[359] Across 10 studies which investigated the economy-wide urban productivity gains from urban agglomeration, elasticities were found to range from -0.007 to 0.084 with a mean of 0.03, implying that a doubling of urban agglomeration is expected to lead to a 3% increase in productivity.[i] [360]

Urban productivity is also enhanced by investments in urban transport networks, which reduce travel times and travel costs, and increase “effective density”.[361] Su and DeSalvo 2008, for example, found a strong relationship between support for urban public transit (through subsidies) and the extent of urban sprawl across 518 US urban areas.[362] Whether specific transport investments can have discernible impacts on urban productivity, and whether such impacts are causative or endogenous, remains subject to further inquiry, and some research has not been able to find any clear positive effect.[363] Where effects have been found, however, their scale is significant. In London, for example, a £15 billion pound investment in rail is expected to increase financial and business service employment density by 1.8% and 5.9% respectively.[364] Indirect evidence of productivity benefits from investments in urban transport can also be seen in property values,[365] and in the clustering of knowledge-based industries in dense and highly connected urban areas.[366]

Existing research thus provides a strong theoretical basis for measures that increase density and connectedness in urban areas to lead to improvements in productivity. A number of aspects of these results, however, bear further consideration. First, while literature finds positive agglomeration economies in most cases, it is not clear the extent to which these results can be assumed to apply widely. Studies have focused on large wealthy cities in the developed world (with a small number of exceptions, such as Au and Henderson, 2006[367]), where the push and pull factors for urbanisation are likely very different from those for cities in emerging and developing countries.[368] Indeed, cities

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[i] *Agglomeration is defined differently between studies with some looking at urban population density, some looking at employment density, and others looking at urban size.*

in Sub-Saharan Africa have seen rapid expansion with limited or negative economic growth over the last several decades.[369] The benefits of density and connectedness therefore depend on a host of other factors, including the provision of services, development of institutions of government, and investments in physical and institutional infrastructure, and in the absence of these, congestion, air pollution, and rising costs can lead to negative net economic impacts.[370] Further research in developing contexts is badly needed in order to understand these factors more fully.

Second, the scale of potential economic benefits varies significantly between studies. In part, this is a result of differences in study design. Studies used different types of data (panel and cross-sectional) and different geographic units, focused on different sectors, and covered different time periods, naturally leading to variation in results. In specific cases, the impact of these methodological choices was clear: studies that focused on industry and manufacturing productivity, for example (in contrast with studies that looked at economy-wide productivity) tended to show higher variation and higher average productivity impacts from agglomeration.[371] In other cases, the impact of study design is less clear, and further research investigating the impact of methodological decisions is needed.

The attributes of urban areas researched also played a significant role in affecting the scale and sign of agglomeration effects. Cities studied varied in terms of their size, economic makeup, rates of economic and population growth, and geography, to name only a few factors. Literature has addressed some of these questions, for example research has hypothesised an inverted U-shaped relationship between income and city size,[372] and specific urban sectors, particularly those that are knowledge-based, appear to benefit the greatest from agglomeration.[373] However, further analysis is needed, especially in rapidly developing cities in emerging economies, to provide a better understanding of the key characteristics that can indicate the potential for agglomeration economies.

Employment

A shift from private vehicle-oriented transport networks to low-carbon multimodal transit networks will have wide-ranging impacts on employment in urban areas. Multimodal networks may lead to fewer jobs in road construction, auto manufacturing, auto parts manufacturing, petrol distribution, and a variety of associated industries. At the same time, however, new jobs will be created to build and manage new transport networks and the vehicles which run on them.

A significant body of research suggests that direct investments in multimodal transit create relatively more employment than investment in conventional transport opportunities.[374] For example, a review of literature found that for each US$1 million invested, 11.4 jobs were generated by cycling projects, 9.9 jobs by pedestrian projects, and 7.8 jobs by road projects.[375] Research also suggests that measures of congestion can be linked with significant reductions in future employment growth in urban areas, while measures to improve mobility lead to employment growth. Hymel (2009), for example, found that for cities already facing high levels of congestion (such as Los Angeles) a 1% increase in congestion reduced employment growth by 0.4%,[376] while Sanchez, Shen and Peng (2004) and Yi (2006) found that high-functioning public transport networks are associated with higher labour force participation rates and higher rates of employment growth.[377]

In addition to generating direct employment, efficient and accessible transport networks raise employment by shifting consumption patterns and generating induced employment. Litman (2014) found that, in US cities with high-quality transit networks, residents typically spent approximately US$3,000 (12% of income) on transport, while residents of cities with poor networks spent approximately US$3,300 (14.9% of income).[378] Similarly, McCann (2000) found that households in auto-dependent communities in the United States spent US$8,500 per year, while those in cities with effective transport networks spent less than US$5500.[379] These savings in expenditure can generate additional employment if they are spent in sectors with a relatively higher labour intensity. For example, US$1 million spent on petrol or other vehicle expenses was estimated by Chmelynski (2008) to generate 12.8 to 13.7 jobs across the US economy, while the same expenditure across a typical bundle of goods purchased by a household generated 17.0 to 17.3 jobs, or 31.3 jobs if spent on public transport.[380] Reduced expenditure on petrol and vehicles, which is directed towards household goods or public transit, is therefore expected to increase the number of positions in these sectors.

While existing scholarship provides a structure for understanding the employment impacts of low-carbon investments in transport, a great deal of uncertainty remains. In this context, it is important to highlight that, while literature from both academic and grey sources show that there is potential for employment from green transport investments, academic literature highlights fundamental uncertainty around employment impacts,[381] while grey literature present the most optimistic scenarios.[382] Four uncertainties are important for policy-makers to consider.

First, existing literature has focused on the developed world, and particularly the United States. Existing literature may therefore not be relevant in developing contexts, especially because of the important role informal transport plays as a source of employment in developing cities.[383] Second, the higher labour intensity of some low-carbon transport investments implies lower labour productivity and suggests that the cost of producing an equivalent amount of electricity may be higher. This is increasingly not the case, however, and suggests that policy-makers may face an opportunity cost in terms of the potential employment impact of alternative investments. Third, although long-run employment may be higher, frictional unemployment may be created in the short term if there is a shift to low-carbon transport networks. Both academic and grey literature are relatively vague, and optimistic, about the scale of this frictional unemployment generated during the transition. Finally, the literature has not engaged significantly with the uncertain impact of technological changes. While new technologies could increase the demand for labour, driverless cars (as one example) also present the potential for substantial losses in employment.

2.4 POVERTY ALLEVIATION AND INEQUALITY

Investments in urban transport networks have the potential to disproportionately benefit vulnerable populations and the urban poor. In contrast with interventions that target individuals or specific population groups – as with investments in specific buildings or appliances – changes to urban networks benefit entire neighbourhoods, or even regions. Furthermore, in many cases, people from ethnic minorities and lower socio-economic classes spend relatively larger amounts of time commuting and are therefore more likely to see significant impacts on their lives.[384]

Benefits not only come in the form of improved mobility, but across the range of co-benefits connected with transport investments detailed above. Vulnerable populations often rely more heavily on non-motorised transit options and travel more dangerous commuting routes.[385] In addition, vulnerable populations are, in many cases, in relatively worse states of health compared with the general population, and as a result benefit disproportionately from interventions that improve air quality, or increase physical activity.[386] And the opportunities for transport investments have been found to be relatively large in developing contexts.[387] Transport investments can therefore mitigate health and safety inequalities as well as climate change under certain conditions.

However, it is dangerous to assume that investments in low-carbon transport necessarily provide benefits to vulnerable populations. Indeed, poorly designed transit networks can do just the opposite. Public transit can create new risks for users, particularly for women and for minorities,[388] and investments ill suited to the cultural context and the needs of different populations can produce adverse outcomes. In some East African nations, bicycling is considered inappropriate for women. In many nations, bicycling is thought of as a transport mode only for those who do not have a car. And in nearly all nations, bicycles are expensive compared with walking, and may be unaffordable for some members of society. An investment as seemingly innocuous as a bicycle lane can therefore overlook, and in some cases exacerbate, challenges faced by particular sections of society.

The gendered aspects of transport may be particularly underappreciated; indeed, it has been said that travel patterns are “one of the most clearly gendered aspects of life”.[389] Especially in developing countries, where fewer women have entered the formal economy, travel by women is more often outside of peak times, to a wider set of locations, and by a more diverse set of transport means. Travel by women is also more frequently made on foot.[390] As a consequence, women’s needs from transport networks are fundamentally different, valuing flexibility, coverage, reliability, and safety relatively highly, and transport by women is costlier and more restricted. Networks, however, are commonly developed by men for the needs of the male-dominated workforce of the formal economy, who travel on weekdays at peak hours between specific transport nodes.[391]

There is therefore a significant need for a systematic analysis of the relationships between low-carbon transport investments in cities and their impacts on vulnerable populations. Analysis by this study revealed only a very small number of articles focused on these aspects of low-carbon transport investments, underlining the need for further research.

2.5 CONCLUSIONS

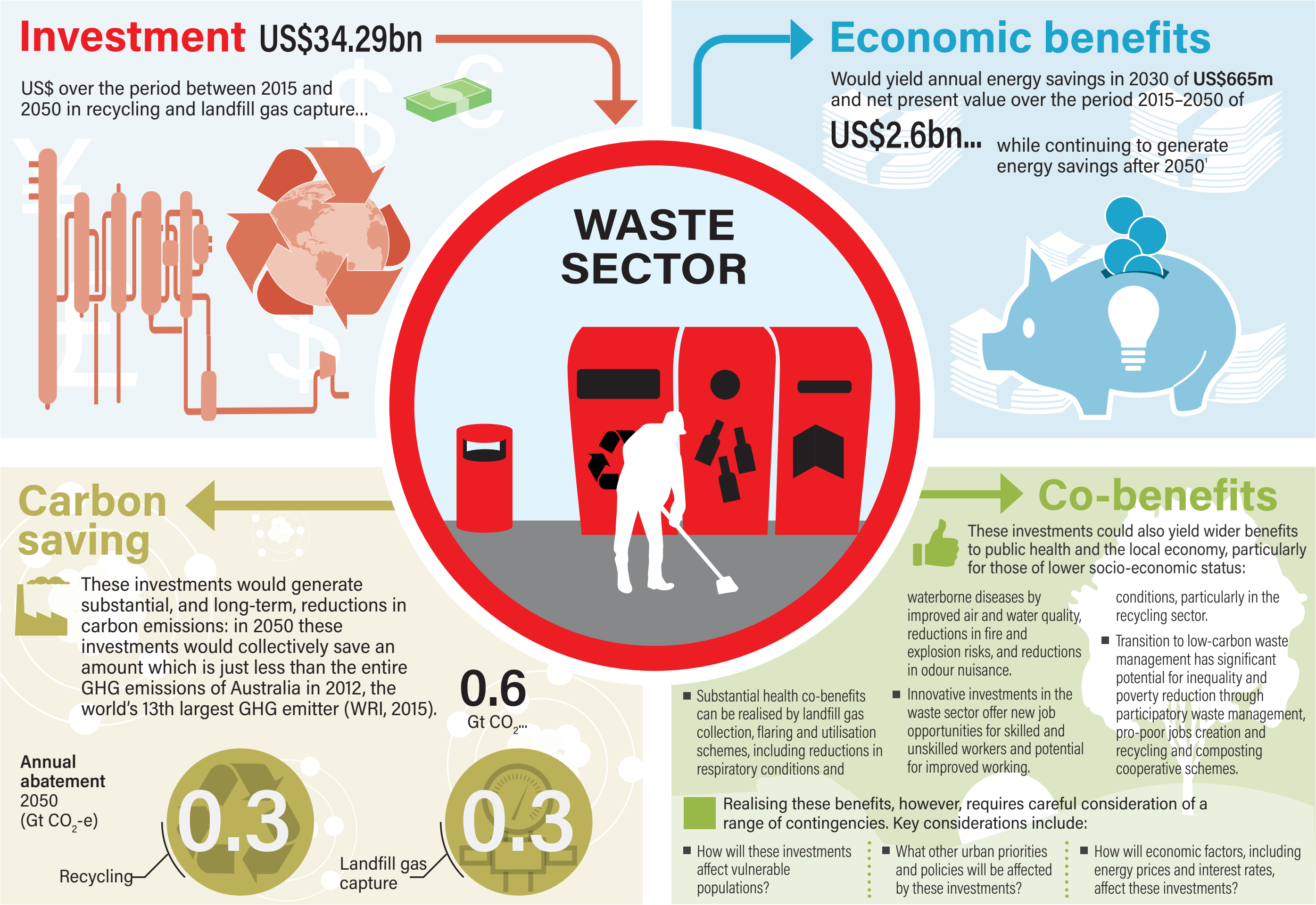
Some co-benefits of climate mitigation actions in the transport sector have been extensively researched, including improved outdoor air quality, increased physical activity, and reduced congestion and travel time. Others do not have such extensive evidence, including improved indoor air quality, reduced ambient noise, and motor vehicle crashes. Generally, there is a lack of costing estimates in the literature and few studies monetise the value of co-benefits. Overall, the climate actions explored in this work were almost always associated with positive health and economic co-benefits. The breadth of literature on these co-benefits is in part a reflection of their scale. For example, our review's findings suggest that the benefits from cycling investments can be as much as five times the cost and that switching the public from car to active travel modes walking and cycling would consistently result in a positive benefit to cost ratio associated ranging from 2 to 360 (median = 9).

Based on the literature, the most important co-benefits relate to impacts on physical activity. Investments in urban planning, public transit, and non-motorised transit infrastructure are some of the ways in which policy-makers can generate modal shift to cycling and walking, thereby increasing physical activity and improving health. The scale of impacts, across all co-benefits identified, depend on many factors.

Technical considerations related to the increases in vehicle weight due to electrification and the sources of electricity generation emerged as important factors that could have an impact on air quality improvements expected from fleet electrification and vehicle efficiency improvements. Geographical factors, such as baseline air pollution and exposure levels, and population density can also affect the scale of the co-benefits identified. The age and efficiency of current fleets has an effect on the cost-effectiveness of some of the proposed measures, such as taxi fleet or freight renovation. And positive impacts from increasing the diversity of land use may be offset by increases in active commuters who are at higher crash risks, if diversification policies are not accompanied by road safety measures and increasing the share of playgrounds, recreation, parks, and open space in urban areas. Integrated approaches are therefore critical for the development of transport policies that yield the largest benefits.

The existing literature covers a variety of countries and regions, lending more confidence to the individual study findings and conclusions (which were generally consistent). However, research in African regions is completely missing. The existing literature tends to focus on single co-benefit types, such as benefits to health or congestion, and ignores the potential for policies to support multiple objectives, or for multiple policies to have synergistic impacts. In most cases, this likely leads to significant understatement of total benefits; however, there is also an underappreciated scope for conflict between objectives. Measures to increase green space and improve air quality, for example, can raise housing prices and feasibly introduce an additional way by which wealthy neighbourhoods deviate and become more fragmented from poorer areas. Systematic approaches and working across sectors are recommended to avoid the flawed sector-centric planning and decision-making .[392]

Figure 6
Waste Sector



US$ over the period between 2015 and 2050 in recycling and landfill gas capture...

Would yield annual energy savings in 2030 of **US$665m** and net present value over the period 2015–2050 of **US$2.6bn...** while continuing to generate energy savings after 2050[1]

These investments would generate substantial, and long-term, reductions in carbon emissions: in 2050 these investments would collectively save an amount which is just less than the entire GHG emissions of Australia in 2012, the world's 13th largest GHG emitter (WRI, 2015).

These investments could also yield wider benefits to public health and the local economy, particularly for those of lower socio-economic status:

- Substantial health co-benefits can be realised by landfill gas collection, flaring and utilisation schemes, including reductions in respiratory conditions and waterborne diseases by improved air and water quality, reductions in fire and explosion risks, and reductions in odour nuisance.
- Innovative investments in the waste sector offer new job opportunities for skilled and unskilled workers and potential for improved working conditions, particularly in the recycling sector.
- Transition to low-carbon waste management has significant potential for inequality and poverty reduction through participatory waste management, pro-poor jobs creation and recycling and composting cooperative schemes.

Realising these benefits, however, requires careful consideration of a range of contingencies. Key considerations include:

- How will these investments affect vulnerable populations?
- What other urban priorities and policies will be affected by these investments?
- How will economic factors, including energy prices and interest rates, affect these investments?

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[1] *Based on the central scenario: energy prices rising 2.5% per year, 3% discount rate and base case learning curves (Sudmant et al. 2016)*

3. The waste sector

The waste management sector accounts for an estimated 3–5% of global anthropogenic emissions.[393] Although this might not be considered as significant as the contributions from other sectors such as transport and buildings, the waste sector is in a unique position to be at the forefront of global emissions reduction. Although relatively low levels of emissions are released through waste treatment and disposal, waste prevention and recovery (as secondary materials or energy) have the potential to avoid emissions in all other sectors of the economy, such as material extraction, mining, forestry, agriculture, transport, manufacturing, and energy generation.[394] It is also recognised that restricting resource use to more sustainable levels and applying resource efficiency can effectively reduce GHG emissions linked to climate change, as well as offer other benefits of an economic and social nature.[395]

The climate benefits from more sustainable waste management practices are significant, such as reduction in landfill gas emissions, reduction in natural materials extraction and manufacturing, replacement of virgin materials with recycled or recovered wastes, replacement of fossil fuel energy with energy from waste and carbon bound in soils through compost application.[396] A number of low-carbon measures can deliver these climate benefits, such as waste prevention, waste recovery, recycling, composting of organic waste, energy from waste, anaerobic digestion of waste with electricity and/or heat recovery, mechanical biological treatment (MBT), landfill gas utilisation or flaring.[397] The climate change mitigation potential of the waste sector in developing countries is three times higher than the one in developed countries;[398] this highlights the role of this sector for mitigation action in the developing world .[399]

Analysis in the New Climate Economy report 2015 demonstrated the scope for actions in the waste sector to reduce emissions from urban areas while generating economic returns.[400] Across global urban areas, implementation of recycling programmes and landfill gas capture between 2015 and 2050 would save US$665 million in 2030 and US$2.6 billion in 2050, paying back the entirety of the original investments made.[401] At the same time, these investments would save 0.6 Gt of CO_2e, an amount which is just less than the entire GHG emissions of Australia in 2012, the world's 13th largest GHG emitter.[402]

In addition to the significant climate benefits of low carbon waste management, research has provided an increasing volume of evidence of the economic and social co-benefits of such action, especially in cities.[403] Mayrhofer and Gupta (2016) explore the evolution of the concept of co-benefits in literature and highlight that interventions with development as a primary goal have climate co-benefits and, vice versa, strategies designed to tackle climate change have significant social impacts such as in health and employment. The research into co-benefits applies the terminology to a wide range of climate-related, economic,[404] environmental,[405] social,[406] and political[407] goals. However, there is still the need for robust measurement techniques to fully evaluate the co-benefits of waste prevention, landfill gas utilisation, and recycling to encourage and inform future action on low-carbon waste strategies.[408]

In the following sections, a review of the literature on the co-benefits of low-carbon waste management to health, employment and the green economy, and poverty alleviation is presented.

3.1 HEALTH CO-BENEFITS

Inadequate waste management has significant detrimental impacts to human health.[409] Hazardous substances and contaminants can travel through air, water, and soil from uncontrolled waste facilities to neighbouring communities, and cause substantial short-term and long-term health problems.[410] Pollution prevention regulations have been successful in protecting human health in most industrialised countries; however, in low- and middle-income countries risks to health from inadequate or inappropriate waste management practices are still present.[411] In the following paragraphs the main health co-benefits from two low-carbon interventions, namely landfill gas flaring and/or utilisation for energy generation, and recycling, are explored.

Outdoor air pollution

Outdoor air quality can be adversely affected by gas emissions that occur during waste decomposition. One of the most air-polluting waste management activities is landfilling.[412] The two main gases emitted by landfills are methane (CH_4) and carbon dioxide (CO_2); they are colourless and odourless gases that act as asphyxiants. The effects of exposure to these gases are well known: humans cannot breath air containing more than 10% carbon dioxide without losing consciousness, and high concentrations of methane can cause coma due to respiratory arrest.[413] In addition, methane is a flammable gas and is explosive in air concentrations of between 5% and 15% by volume. Landfill gas also includes trace gases of volatile organic compounds (VOCs) and gaseous compounds such as arsine and stibine, which can give rise to significant adverse health effects both acute and chronic if not managed properly.[414] Hydrogen sulphide (H_2S) is another landfill gas, which is colourless, flammable, and with a characteristic odour of rotten eggs. Exposure to high concentrations results in depression of the central nervous system, loss of consciousness, and respiratory paralysis.[415] Particulate matter (PM_{10}) in also present in landfill gas. Exposure to particles that can enter the respiratory system is known to be associated with a range of adverse effects on health, especially for people with pre-existing lung and heart disease, the elderly, and children, who are particularly sensitive to particulate air pollution.[416]

Epistemological studies investigating the rates of adverse birth outcomes or cancer cases around landfill sites in the UK have shown little or no evidence of increased risk for neighbouring communities.[417] However, this is not the case for uncontrolled waste disposal sites in developing countries, where the exposure to harmful substances from landfills is significantly higher, and environmental and health and safety regulations are not as stringent.[418]

Uncontrolled methane (CH_4) emissions from landfilling has been ranked as the third largest anthropogenic source of CH_4 emissions.[419] In addition to its impacts on climate change, methane also acts as an ozone precursor as it contributes to the formation of tropospheric ozone.[420] As a result, controlling methane emissions from landfills has significant benefits for reducing health risks associated with elevated tropospheric ozone concentrations.[421] The health co-benefits of methane-controlling measures, such as landfill gas utilisation and flaring, are of global significance. Research by Anenberg et al. (2012) concludes that measures reducing methane emissions can substantially benefit global public health and potentially reverse trends of air pollution-related mortality in Africa and South, West, and Central Asia.

A study by the UN-Habitat (2010)[422] reported that the incidence of pulmonary problems is 1.4 to 2.6 times higher in landfill workers than in the overall population. Respiratory disorders of waste workers result from inhaling particulate matter, bio-aerosols and VOCs during collection and disposal. Therefore, efficiently and safely collecting landfill gas for flaring and/or energy generation has the potential to significantly reduce the occurrence and prevalence of such respiratory disorders.

Although the health co-benefits of low-carbon waste management interventions, such as landfill gas flaring and/or utilisation, have been covered extensively, particularly in the cases of low- and middle-income countries, quantifying these benefits has been challenging.[423] These benefits are usually reported as the number of avoided deaths or health conditions relative to past experiences. The methodological difficulties in accurately and consistently quantifying such benefits are the reasons behind this gap in literature.[424]

Water quality

Water-soluble pollutants and hazardous substances from waste, landfills, and other waste facilities, if not controlled and treated appropriately, can enter the surface or groundwater, and subsequently be consumed by humans.[425] In uncontrolled landfills or open dumpsites where no physical barrier (e.g. liner) exists between the waste and the ground, leachate from decomposing waste is a major source of groundwater and soil contamination.[426] In engineering landfills with landfill gas collection systems, a liner is installed to act as a barrier between the waste and the surrounding ground, as well as a cap, to prevent landfill gas and leachate from escaping beyond the landfill perimeter.[427] Therefore, installing a landfill gas collection system in new landfill phases has the added benefit of minimising water pollution.

Landfill leachate can be extremely harmful to people, leading to acute and chronic health effects.[428] A study by the UN-Habitat (2010) reports that the relative risk of infections and parasites is three to six times higher for solid waste workers than for the control baseline populations, while acute diarrhoea occurs 10 times more often.[429] The same study reports that in Mexico the average life expectancy of waste workers is only 39 years, while the rest of the population reaches an average age of 69.[430]

In conclusion, although the main purpose of a landfill gas utilisation system is to collect landfill gas and generate energy, it offers the added benefit of minimising water pollution and thus prevents health risks linked to waterborne diseases and conditions.[431] These co-benefits can be substantial considering the severity of the health risks particularly in low- and middle-income countries.[432]

Odour

The environmental impacts associated with landfill gas range from explosion and fire risks, and harm to local flora and fauna, to stratospheric air pollution and global warming potential.[433] Impacts on human health and water quality are covered in the previous sections; in this section the co-benefits of landfill gas collection, flaring and/or combustion for energy recovery, in relation to odour control are discussed.

Table 3
Environmental impacts of landfill gas

Scale	Potential impact
Local	Explosion and fire Asphyxia Human health Odour nuisance Harm to flora and fauna
Regional	Photochemical air pollution Acidic precipitation
Global	Stratospheric ozone depletion Global warming potential

Adapted from Environment Agency, 2002.[434]

Trace compounds within landfill gas are responsible for many of the malodours associated with landfilling operations.[435] Odour causes local annoyance and the presence of odour is often linked to concerns about the impact of landfill gas emissions on human health.[436]

Malodorous species can have very low odour thresholds (i.e. the concentration of a compound in air that is just detectable to the human nose). Common odorants in landfill gas include hydrogen sulphide, organosulphur compounds such as methanethiol and dimethyl sulphide, carboxylic acids such as butanoic acid, aldehydes, and carbon disulphide.[437]

Odour from landfill gas can vary due to meteorological conditions, such as wind speed and direction, turbulence, air pressure and temperature changes, atmospheric humidity, precipitation, and solar radiation.[438] Depending on these environmental conditions, landfill gas odour can extend to over several kilometres from the site boundary. The emissions of landfill gas may need to be diluted several million times in order to render its odour undetectable. Still, calm conditions during cold periods are more likely to give rise to poor dilution and cause odour nuisance. Persistent odour can result in a number of impacts upon amenity and quality of life for neighbouring communities.[439]

The objective of control systems is to ensure that landfill gas does not pose a risk to human health or pollution to the environment.[440] The purpose of flaring is to dispose of the flammable constituents, particularly methane, safely and to control odour nuisance, health risks, and adverse environmental impacts.[441] The primary purpose of landfill gas combustion is energy recovery.[442] However, landfill gas collection prevents odorous gases from escaping into the atmosphere, and landfill gas flaring and combustion destroy several odorous gases in the process, acting as odour control mechanisms too.[443] As a result, landfill gas collection, flaring or utilisation has the co-benefit of reducing nuisance and adverse amenity impacts to neighbouring communities due to odour.

Due to the subjective nature of what constitutes "nuisance", the adverse impacts of landfill gas odour are descriptive and qualitative in literature.[444] There is a lack of studies that quantify or monetise the impact of landfill gas odour and as a result can also quantify the co-benefits of reducing odour nuisance through landfill gas collection, flaring and utilisation.[445]

3.2 EMPLOYMENT AND THE ECONOMY

Employment

The transition to a sustainable low-carbon economy has significant positive impacts to employment, although methodological challenges remain in quantifying these and producing evidence comparable across different sectors and countries.[446] Numerous studies in industrialised countries demonstrate that there are overall job gains compared with "business as usual" scenarios, job movements, and improved job quality in this transition. This knowledge can inform policies that enable a fair transition to a green economy; however, there are few comparable studies for developing countries.[447]

Green employment opportunities in the waste management sector are more common in industrialised countries, although examples emerge from developing countries especially in recycling.[448] In developing countries accounting for the jobs related to the waste management sector is highly challenging due to the heavy reliance on the informal recycling sector, such as waste pickers.[449] There also concerns about the rights, and health and safety of the workers in the waste sector, and of the nearby communities to waste management facilities, especially in developing countries.[450]

In the case of Bangladesh, waste management and recycling activities are promoting the concept of the "3Rs" (reduce, reuse, and recycle) and working to improve current hazardous and unsustainable waste management practices.[451] There are currently few core environmental jobs in the waste management and recycling sector, but these are growing at a very high rate.[452] It is estimated that Bangladesh has the potential for 212,753 jobs associated with core environment related or green jobs in the waste management sector.[453] These jobs are in plastic, lead batteries, metals and scrap recycling, ship-breaking, and composting of organic wastes. Composting organic waste, and plastic waste recycling account for the majority of waste management and recycling jobs, 90,000 jobs and 68,000 jobs respectively.[454]

Recycling offers increased job creation opportunities in industrialised countries too.[455] While waste collection and disposal in landfills creates one job per 1,000 tonnes of waste managed, the collection, processing, and manufacturing of products with recycled materials as feedstock creates six to 13 or more jobs per 1,000 tonnes, depending on the material.[456]

In Malaysia, it is estimated that 15,780 people were working in environmental jobs in the solid waste management sector in 2009.[457] In Spain, a study estimated that there were 530,947 green jobs in 2009, equivalent to 2.6% of Spain's working population; 140,343 of these were in the waste management sector.[458] In China, 52,000 people are engaging in facilities operation of pollution management, including waste recycling and recovery facilities.[459] The informal recycling sector employs approximately 20 million people worldwide, almost 50% of the labour force involved in waste management.[460] In Metro Manila, the informal recycling waste sector provides 10,105 jobs and the formal recycling sector 5,591 jobs.[461]

In the EU, core environmental industries in the fields of pollution management, waste collection and treatment, renewable energy and recycling have a combined turnover of over €300 billion and provide 3.5 million jobs.[462] In more detail, the recycling industry in the EU27 countries offered an estimated 1.8 million jobs in 2006.[463] Friends of the Earth (2010) estimate that if a target of 70% recycling was implemented in EU27 countries, 322,000 recycling jobs would be created, in addition to 160,900 new indirect jobs, and 80,400 induced jobs. The total potential is therefore estimated to be for more than 563,000 net new green jobs. In a similar scenario in the UK, if a 70% recycling target was set for municipal solid waste, 29,400 new direct jobs would be created in recycling, 14,700 indirect jobs in supply chains, and 7,300 induced jobs in the wider economy relative to 2006.[464]

In conclusion, intensifying recycling, composting, and waste recovery operations has the potential not only for significant carbon emissions reductions and economic benefits,[465] but also green jobs creation. However, any policy interventions towards such goals should also address workers' rights, and health and safety considerations.[466] Only then, existing practices could be transformed into truly "green" jobs in the waste sector. Research suggests that jobs in composting of organic waste, door-to-door collection of household waste, upstream scrap metal, aluminium and plastic recycling represent improvements over working conditions of scavengers at the landfills or dumping sites.[467] However, greater improvements are still required to ensure that jobs in waste management and recycling comply with the International Labour Organization's "decent work" conditions.[468] Introduction of green technologies in the waste sector are likely to involve unskilled and informal workers with limited occupational and social protection. For example, in developing countries, collection and recycling work is often performed by marginalised groups known as waste pickers or scavengers, including children, women, and the elderly.[469] Basic occupational health services and primary health care may play an important role in reducing inequity and promoting a just transition towards green economies.[470]

Productivity

The literature on waste management and productivity focuses on material use and natural resources efficiency.[471] These findings are not specific to cities, but they are relevant to urban productivity insofar as increased resource efficiency and recycling of finite natural materials is essential to "feeding" urban consumption and making it more sustainable.[472] Establishing a resource-efficient economy is essential in achieving green growth. Better resource productivity can increase economic productivity and sustain economic growth by securing sufficient material supply, investing in new technologies and innovation, and improving competitiveness.[473]

Resource productivity refers to "the effectiveness with which an economy uses materials extracted from natural resources (physical inputs) to generate economic value (monetary outputs)".[474] The OECD incorporates a welfare perspective in resource productivity by including a qualitative dimension such as the environmental impacts per unit of output produced with a given natural resource input. Resource productivity is closely linked to the concept of decoupling:

- *Relative decoupling* occurs when the ecological intensity per unit of economic output is declining. In this situation, resource impacts decline relative to the GDP, which could itself still be rising.[475]
- *Absolute decoupling* occurs when resource impacts decline in absolute terms. In this situation, resource efficiencies increase at least as fast as economic output does and continue to improve as the economy grows.[476]

Although the volume of materials being consumed worldwide is continuing to grow, there are some signs of (*relative)* decoupling from economic growth.[477] The global economy today generates 50% more economic value with 1 tonne of raw materials than it did in the 1980s, rising from US$0.70/kg (2005 US dollars and PPPs) in 1980 to US$1.05/kg by 2008.[478] In the same period, domestic material productivity of OECD countries improved by 70%, rising from US$1.00/kg to over US$1.70 USD/kg.[479] Solid waste generation by economic activity is growing in line with the rise in material consumption.[480] Valuable natural materials disposed as waste and not recovered represent a loss to the economy.[481] It is estimated that approximately one-fifth of the raw materials extracted worldwide ends up as waste.[482] Improvements in material productivity can be achieved with policy interventions and technological change to improve resource efficiency, waste recovery, and recycling.[483]

Improved resource efficiency by waste recovery and recycling can also play an important role in increasing industry's competitiveness in global markets.[484] According to research by Defra, the UK industry can increase its gross profits by 16% if they implement all potential waste, and low-cost water and energy savings.[485] Consequently, this will increase the industry's competitiveness in the global market. The metal manufacturing and chemicals/non-metallic mineral products industries have a noteworthy opportunity to more than double their profits through waste reduction and lean production savings, highlighting the opportunities for co-benefits from resource efficiency and waste management in the green economy.

Case studies from Brazil suggest that the novel models of waste pickers' integration in recycling cooperatives not only increased the quantity and quality of recyclables, but also improved the communities' productivity by increasing their income, their working conditions, and helped to keep children at school for longer because their families could afford to do so.[486]

3.3 POVERTY ALLEVIATION AND INEQUALITY

Provision of appropriate and sustainable solid waste management services can lead to significant improvements in living conditions for poor and marginalised groups.[487] These groups tend to be the ones forming the working force in the waste sector and the ones mostly affected by the negative impacts associated with waste facilities or unsanitary conditions.[488] However, for these benefits to materialise, the transition to low-carbon solid waste management needs to happen alongside "pro-poor" strategies such as participatory waste management approaches.[489] These can be particularly effective in inequality and poverty alleviation, as well as social inclusion in a developing country context.[490] Examples from Clean Development Mechanism (CDM) low-carbon waste management projects that have been unsuccessful in maximising these co-benefits are discussed below, as are positive examples from Brazil, India, and South Africa.

CDM projects have been heavily criticised over the lack of emphasis on sustainable development benefits, such as job creation for the poor, improvements in inclusion of marginalised groups, inequality reduction and poverty alleviation.[491] Although CDM projects in the waste sector have delivered against environmental targets, most have lacked ambition in promoting development targets.[492] This is due to the fact that CDM projects primarily favoured large-scale waste management schemes, such as landfill gas flaring and energy recovery.[493]

Gutberlet (2009, 2015) argues that although landfill gas utilisation or energy from waste schemes can deliver similar GHG emissions reduction, neither offer as many socio-economic benefits – especially in relation to job creation, inclusion, and poverty alleviation – as recycling cooperative schemes.[494] Fehr and Santos' (2009 observations from Brazil showed that the informal recyclers organised themselves in cooperatives, associations, or social enterprises.[495] These collective forms of organisation provided vital spaces for social inclusion and human development, by promoting meaningful work, increasing the workers' self-esteem, and improving their living and working conditions.[496] The outcome of that research was that participatory waste management represented an effective, labour-intense, anti-poverty strategy that could achieve inclusion, equity, eco-health, eco-efficiency, and sustainability.[497] Studies by Agarwal et al (2005 in India and Noel (2010) in Haiti also pointed out the segregation and gender disparities among the informal waste sector workers.[498] Schenck and Blaauw (2011) established the socio-economic profile of waste pickers in South Africa, highlighting the opportunities to alleviate poverty and better integrate waste pickers within society while improving the sustainability of the waste management system.[499]

3.4 CONCLUSIONS

More sustainable, low-carbon waste management offers substantial gains in relation to health, job creation and the green economy, inequality and poverty reduction. In scale, these co-benefits can be significant, and potentially more compelling than the direct economic case for such actions. Landfill gas collection, flaring and/or utilisation schemes can have very large impacts on health through reduction in respiratory conditions, and also through reductions in waterborne diseases. Recycling programmes can provide opportunities for employment for both skilled and unskilled workers. And transition to low-carbon waste management can have significant positive impacts on inequality and poverty through participatory waste management, pro-poor jobs creation, and recycling and composting cooperative schemes, particularly in a developing country context.

However, these benefits can be more challenging to quantify or monetise compared with their economic counterparts. Further, they are also context-specific as they are more dependent on geographical, political, economic, and cultural factors. For example, the inequality and poverty alleviation reduction co-benefit can be more pronounced in developing countries where the informal sector (i.e. waste pickers) plays a significant role in supplying the majority of recyclable materials to satisfy consumption needs in high-income, industrialised countries.

Green jobs generation can benefit both developed and developing countries but the nature of these jobs will vary between countries. Examples of green jobs in Europe include opportunities in design, consultancy, research, policy, and regulation, whereas in Asia they involve more labour-intensive, unskilled jobs, such as in factories extracting precious metals from electric and electronic waste, and sorting mixed wastes into high-quality recycling materials. Local geological and meteorological conditions also control the extent to which air and water pollution from inadequate waste management facilities, such as open dumps, can affect human health. Therefore, the positive health impacts of a landfill gas collection scheme will also depend on these conditions.

In conclusion, the co-benefits from low-carbon waste management depend to a high degree on external factors, namely the material, social, economic, geographic, and political contexts. Therefore, it is advisable that these co-benefits, and strategies promoting them, are reviewed on a case-specific basis.

Discussion and conclusions

The significance of the co-benefits of climate action is highlighted in nations' recently submitted Intended Nationally Determined Contributions (INDCs). India's INDC provides targets for clean energy generation and emissions intensity, ostensibly to address the rising cost of poor air quality, even without explicit targets for carbon emissions.[500] Brazil's INDC targets an end to illegal logging, reforestation, and an expansion of biofuels, in order to further conservation and development goals as well as climate objectives.[501] China's climate policy is led by energy efficiency programmes and embedded in a plan to realise a "new normal" form of development with the Chinese economy based more on services and consumption and less on heavy industry.[502]

These examples illustrate not only the fundamental connection between co-benefits and climate action, but the importance of co-benefits as a means of tying diverse national policy agendas to the common goal of reducing global emissions. In contrast with the benefits of mitigating climate change, which are future-oriented, relatively uncertain in scale, and global in nature, co-benefits are frequently near-term, relatively certain, and locally realised. Where such benefits are excludable, such as with savings in energy expenditure, a co-benefits framework identifies the need for private actions, and where such benefits are non-excludable, as with improved air quality, protection of biodiversity, and improved public safety, co-benefits identify the imperative of public action. A co-benefits framework is therefore a means of mainstreaming climate action at local and national levels,[503] and also a tool for formalising sustainable development objectives and finding their connection with climate action at regional and global levels.[504]

The links between co-benefits and a wide set of local and regional social, environmental, and economic challenges also provide insights into the governance of local climate action. Urban climate actions are not a means of impacting on other urban challenges, but can be the most effective means. Realising these actions, however, requires coordination horizontally between different departments and sections of government, and vertically between different levels of government. Realising urban climate action is therefore fundamentally a multi-level, multi-actor, and cross-sectoral governance challenge.

These insights are of particular importance regarding the recently developed Sustainable Development Goals. Under the 11th goal, Sustainable Cities and Communities, subgoal 11.1 targets adequate, safe, and affordable housing; subgoal 11.2 targets safe, affordable, and accessible transit; and subgoal 11.6 targets improvement in waste management. These are all areas where this review has found substantial overlap between the potential for climate action and the potential for urban co-benefits.

Analysis by this review reveals that for specific types of measures in specific circumstances, a co-benefits framework could strengthen the case for making investments, sometimes considerably. In the commercial and residential buildings sector, strong evidence exists to support a number of interventions. In developing urban areas, research shows that clean cook stoves and low carbon cooking options pay back quickly while providing life-changing health benefits. In urban centres in temperate regions, especially where the building stock is old and showing signs of deterioration, there is evidence that the total value of benefits from investments in insulation can be 10 times the value of energy savings. And in cities across the globe, analysis shows that green building standards have the potential not only to create jobs, but also to improve worker productivity by as much as 16%. The salaries of the jobs created can exceed energy and maintenance costs by a factor or 100 or more, and the construction costs of investments by a similar margin.[505] Applying the average figures for the number of jobs created per million of investment to analysis completed by the New Climate Economy in 2015[ii] suggests that 331.8 million job years (range of 5.9 million to 841.3 million) could be created in urban areas by ambitious investments in low-carbon buildings.[506]

In the transport sector, evidence reveals that bicycle lanes can provide benefits to public health and urban energy expenditure that amount to more than five times the cost of investments, and pedestrianisation can provide similar results. In cities with gridlocked streets, research shows that congestion pricing can reduce traffic, travel times, and congestion by 10–30%. In rapidly growing cities, liveable density – which ensures that residents' basic needs, such as access to energy, accessible transport, and employment, are met – can increase economic productivity. Research suggests that a doubling of density can increase labour productivity by 3%. Further, public transport investments can lead to direct and indirect employment, reduce congestion, reduce traffic-related injuries, facilitate liveable density, and provide synergies with active travel options.

In specific geographies and contexts, these opportunities are particularly compelling, but challenges need to be overcome. In rapidly growing and highly dense cities in East Asia and Latin America, commercial and residential buildings can be built to a low-carbon standard at little additional cost, but need to be made available to vulnerable populations to help bridge (rather than broaden) the gap between the informal and formal economy. In established Western cities, low-carbon transport networks will need to overcome technical and institutional lock-in to private vehicles. In developing cities in India and Africa, investments can turn waste into a source of energy and employment, but transitions need to be managed in order to prevent impacts on vulnerable populations. And in rapidly growing cities in East Africa and South Asia, low-carbon transport networks can be built in advance of rising car ownership, but require vast inputs of capital that are often beyond the capacity of local policy-makers.

The challenges needed to be overcome for the measures to be implemented, while substantial, are challenges of governance and politics rather than fundamental capacities, technology, or even economics. This review therefore demonstrates that avenues to address climate change in conjunction with other urban issues may be closer than we had realised. However, this analysis also reveals an urgent need for further research. Specifically, this analysis highlights nine limitations of existing research that need to be addressed:

[ii] *Gouldson et al. (2015), in the New Climate Economy report (2015), found that US$23.7 trillion would be needed in additional housing investment between 2015 and 2050.*

1. *The thematic focus of the evidence base is highly variable*. Some co-benefits have been heavily researched, and others have been largely overlooked. For example, the health benefits of a range of low-carbon actions have been described as "game changing" due to their scale,[507] but evidence on their impact on poverty is often absent.
2. *Evidence on the pathways that connect low-carbon actions with different co-benefits is highly variable*. Air pollution as a pathway to improved public health is widely described in literature, but other pathways, for instance on the distributional impacts of measures, have received significantly less attention.
3. *The geographical coverage of the evidence base is also highly variable*. Some regions have been heavily researched, but others are frequently overlooked. The majority of high-quality transport modelling, for example, has occurred in North America and Europe but there is a paucity of research on the value of reduced congestion, improved mobility, and other co-benefits from low-carbon transport investments in Sub-Saharan Africa and elsewhere.
4. *Methodologies are designed to highlight co-benefits, and often overlook the potential for co-costs*. In addition to contributing to a number of social, environmental, and public health challenges in cities, low-carbon options can create new challenges and exacerbate old ones. Methodologies need to be designed that consider both costs and benefits, and that can be adapted when unforeseen costs and benefits arise.
5. *The literature tends to estimate the potential benefits rather than evaluating the actual benefits*. Ex ante analysis is more common than ex post analysis, and there are almost no examples of literature that compare the two. This type of analysis is crucial for policy-making and for learning about how to implement low-carbon actions in ways that generate the greatest co-benefits.
6. *There is a lack of common methods, metrics, measures, and indicators*. The wide range of studies employ a similarly wide range of methods and approaches, and they attempt to evaluate co-benefits using a variety of different measures and indicators. Only a relatively small proportion of the co-benefits identified and analysed in the research have been monetised, and common frameworks for assessing non-monetary benefits are largely absent. This creates challenges for comparative assessments and for the transfer of good practice.
7. *There is an absence of integrated or systems-based research*, with most studies focusing on specific co-benefits. The potential for both conflicts and complementarities across larger numbers of impacts is therefore not assessed and there is little evidence on unexpected effects or unintended consequences, whether positive or negative.
8. *There is a lack of information on the dependence of results on specific sensitivities and contingencies*. There is frequently a lack of explicit discussion on the baselines and counterfactuals adopted or assumed in different assessments, and on the policy, institutional, social, economic, and environmental contexts for the low-carbon action-generating co-benefits. The absence of these factors makes it difficult or impossible to understand the factors that shape co-benefits in different contexts.
9. *There is a lack of global scale or internationally comparative research,* with a widespread tendency to focus on single cities or countries, with only a few exceptions.[508] From a bottom-up perspective, this may be because the results of case-based analysis cannot be aggregated due to the methodological inconsistencies and the lack of common metrics etc. From a top-down perspective, this may be because of the significance of the contextual contingencies and sensitivities that shape forms and levels of co-benefits.

Robust, methodologically consistent, integrated analysis – which can be applied across a variety of contexts and settings, gives explicit indication of limitations and sensitivities, and includes a broad set of costs and benefits – provides the strongest case for policy-makers. Realistically, the current evidence base rarely meets these requirements, and it is generally not at the level needed to allow policy-makers to adopt a co-benefits framework in their decision-making. Nonetheless, there are instances where the existing evidence base enhances the already strong case for policy or for investments in urban climate mitigation.

However, improved methodologies and an enhanced evidence base could accelerate the case for policy and investment, and help to overcome some of the challenges facing a low-carbon urban transition. An integrated socio-economic case could provide linkages between climate change and core policy areas, such as energy, finance, and economic development, whose coordination is needed for transformative actions. A co-benefits framework could also contribute to overcoming multi-level barriers to actions between local, regional, and national actors, and facilitate collaboration between public, private, and civic actors by revealing shared interests and common goals. Finally, a co-benefits approach could find new ways to unlock investment, redirect existing financial flows, and reveal the potential for new ways of financing and delivering change.

The task of the research community is to support these changes by improving the methodologies and evidence available to policy-makers and other decision-makers. We therefore advocate:

- The development and promotion of common frameworks, methods, indicators, and metrics for assessing the net co-benefits of climate action in cities.
- The incorporation of a fuller and more transparent/explicit analysis of the key contingencies and sensitivities shaping these net co-benefits.
- The adoption of a more systems-based approach that considers not only specific net co-benefits but also wider first, second, and third order impacts.
- The development of ex ante approaches that forecast potential and ex post approaches that evaluate actual net co-benefits, and the linking of them to facilitate learning and to help to close the gaps between intended and achieved outcomes.
- The application of this approach to thematic and geographical areas where there are significant gaps or weaknesses in the evidence base relating to net co-benefits.
- The adoption of a bottom-up approach that explores these issues in individual cities before considering the issues with the aggregation or extrapolation of findings to the national, regional, and global scales.
- Based on the above, the development of clearer, more consistent, and more compelling user-led language/narrative around the net co-benefits of climate action in cities.

APPENDIX 1

Table 4
Keywords used in literature searches for the buildings sector[iii]

Higher-level objective and pathways		Health			Employment and the green economy		Poverty alleviation and inequality
Target sector	Climate change mitigation policy measure	Indoor air pollution	Outdoor air pollution	Indoor environmental quality	Employment	Productivity	
Buildings	New building heating efficiency	“Building” “Heating” “Indo Air Pollution” “Health”	“Building” “Heating” “Air Pollution” “Health”	“Building” “Heating” “Hazardous Building Materials” “Mould” “Fungus” “Health” / “Building” “Heating” “Heat Stress” “Cold Stress” “Thermal Stress” “Health”	“Building” “Heating” “Employment”	“Building” “Heating” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Building” “Heating” “Poverty” “Social Exclusion” “Inequalities”
	Heating retrofits	“Heating Retrofit” “Indo Air Pollution” “Health”	“Heating Retrofit” “Air Pollution” “Health”	“Retrofit” “Hazardous Building Materials” “Mould” “Fungus” “Health” / “Heating Retrofit” “Heat Stress” “Cold Stress” “Thermal Stress” “Health”	“Heating Retrofit” “Employment”	“Heating Retrofit” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Heating Retrofit” “Poverty” “Social Exclusion” “Inequalities”
	Appliances and lighting	“Energy Efficiency” “Appliances” “Lighting” “Indo Air Pollution” “Health”	“Energy Efficient” “Appliances” “Lighting” “Air Pollution” “Health”	“Energy Efficient” “Appliances” “Lighting” “Hazardous Building Materials” “Mould” “Fungus” “Health” / “Energy Efficient” “Appliances” “Lighting” “Heat Stress” “Cold Stress” “Thermal Stress” “Health”	“Energy Efficient” “Appliances” “Lighting” “Employment”	“Energy Efficient” “Appliances” “Lighting” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Energy Efficient” “Appliances” “Lighting” “Poverty” “Social Exclusion” “Inequalities”
	Fuel switching/ solar PV	“Fuel Switching” “Buildings” “Indo Air Pollution” “Health”	“Fuel Switching” “Buildings” “Air Pollution” “Health”	“Fuel Switching” “Buildings” “Hazardous Building Materials” “Mould” “Fungus” “Health” / “Fuel Switching” “Buildings” “Heat Stress” “Cold Stress” “Thermal Stress” “Health”	“Fuel Switching” “Buildings” “Employment”	“Fuel Switching” “Buildings” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Fuel Switching” “Buildings” “Poverty” “Social Exclusion” “Inequalities”

[iii] *“AND” and “OR”.*

Table 5

Keywords used in literature searches for the transport sector

Higher-level objective and pathways		Health						Congestion and time	Employment and the green economy		Poverty alleviation and inequality
Target sector	Climate change mitigation policy measure	Indoor air pollution	Outdoor air pollution	Physical activity	Vehicle injuries or deaths	Noise	Green space and urban heat island effects		Employment	Productivity	
Transport	Urban planning and reduced passenger travel demand	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Indo Air Pollution” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Outdo Air Pollution” “Ambient Air Pollution” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Physical Activity” “Active Travel” “Active Transport” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Mot Vehicle Crashes” “Traffic Accidents” “Vehicle Injuries” “Road Deaths” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Ambient Noise” “Noise” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Green Space” “Heat Isl” “Green Infrastructure” “Biodiversity” “Health”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Travel Time” “Journey Time” “Congestion”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Transport Employment”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Urban Planning” “Travel Demand” “Transport Demand” “Traffic Demand” “Demand Management” “Poverty” “Social Exclusion” “Inequalities”
	Passenger mode shift and transit efficiency	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Indo Air Pollution” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Outdo Air Pollution” “Ambient Air Pollution” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Physical Activity” “Active Travel” “Active Transport” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Mot Vehicle Crashes” “Traffic Accidents” “Vehicle Injuries” “Road Deaths” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Ambient Noise” “Noise” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Green Space” “Green Infrastructure” “Biodiversity” “Heat Isl” “Health”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Travel Time” “Journey Time” “Congestion”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Transport Employment”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Mode Choice” “Mode Shift” “Transit Efficiency” “Public Transport Efficiency” “Poverty” “Social Exclusion” “Inequalities”
	Passenger car efficiency and electrification	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Indo Air Pollution” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Outdo Air Pollution” “Ambient Air Pollution” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Physical Activity” “Active Travel” “Active Transport” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Mot Vehicle Crashes” “Traffic Accidents” “Vehicle Injuries” “Road Deaths” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Ambient Noise” “Noise” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Green Space” “Green Infrastructure” “Heat Isl” “Biodiversity” “Health”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Travel Time” “Journey Time” “Congestion”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Transport Employment”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Economic Productivity” “Agglomeration Effects” “Gdp Growth” “Congestion”	“Private Vehicle” “Private Car” “Passenger Car” “Efficiency” “Electrification” “Poverty” “Social Exclusion” “Inequalities”
	Freight logistics improvements	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Indo Air Pollution” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Outdo Air Pollution” “Ambient Air Pollution” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Physical Activity” “Active Travel” “Active Transport” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Mot Vehicle Crashes” “Traffic Accidents” “Vehicle Injuries” “Road Deaths” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Ambient Noise” “Noise” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Green Space” “Green Infrastructure” “Biodiversity” “Heat Isl” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Travel Time” “Journey Time” “Congestion”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Transport Employment”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Poverty” “Social Exclusion” “Inequalities”
	Freight vehicle efficiency and electrification	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Indo Air Pollution” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Outdo Air Pollution” “Ambient Air Pollution” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Physical Activity” “Active Travel” “Active Transport” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Mot Vehicle Crashes” “Traffic Accidents” “Vehicle Injuries” “Road Deaths” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Ambient Noise” “Noise” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Green Space” “Green Infrastructure” “Biodiversity” “Heat Isl” “Health”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Travel Time” “Journey Time” “Congestion”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Transport Employment”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Freight Vehicle” “Freight Fleet” “Efficiency” “Electrification” “Poverty” “Social Exclusion” “Inequalities”

Table 6

Keywords used in literature searches for the waste sector

Higher-level objective and pathways		**Health**				**Employment and the green economy**		**Poverty alleviation and inequality**
Target sector	Climate change mitigation policy measure	Indoor air pollution	Outdoor air pollution	Water quality	Odour	Employment	Productivity	
Waste	Recycling	“Recycling” “Indo Air Pollution” “Health”	“Recycling” “Air Pollution” “Health”	“Recycling” “Water” “Health”	“Recycling” “Odour “Health” X	“Recycling” “Waste Employment”	“Recycling” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Recycling” “Reuse” “Poverty” “Social Exclusion” “Inequalities”
	Landfill gas capture	“Lfill Gas Capture” “Indo Air Pollution” “Health”	“Lfill Gas Capture” “Air Pollution” “Health”	“Lfill Gas Capture” “Water” “Health”	“Lfill Gas Capture” “Odour” “Health”	“Lfill Gas Capture” “Waste Employment”	“Lfill Gas Capture” “Economic Productivity” “Agglomeration Effects” “Gdp Growth”	“Lfill” “Lfill Gas Capture” “Open Dumps” “Poverty” “Social Exclusion” “Inequalities”

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ABOUT THE COALITION FOR URBAN TRANSITIONS

The Coalition for Urban Transitions - launched in 2016 at the Climate Leaders' Summit in New York - is a major new international initiative to support decision makers to unlock the power of cities for enhanced national economic, social, and environmental performance, including reducing the risk of climate change. The Coalition provides an independent, evidence based approach for thinking about 'well managed' urban transitions to ensure that the growth of urban areas, and the accompanying process of economic, social, and environmental transformation, maximises benefits for people and the planet.

The initiative is jointly managed by the **C40 Cities Climate Leadership Group (C40)** and **World Resources Institute (WRI) Ross Center for Sustainable Cities.** Members include over 20 major institutions spanning five continents, including research institutions, city networks, international organizations, infrastructure providers, and strategic advisory companies. The initiative will be overseen by a Global Urban Leadership Group to steer and champion the work.

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