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Urban Planning to Enable a 1.5°C Scenario

Editors

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Article

The City of the Future

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Abstract
Limiting global warming to 1.5 °C will require rapid decarbonisation of the world's electricity and transport systems. This must occur against a background of continuing urbanisation and the shift to the information economy. While replacement of fossil fuels in electricity generation is underway, urban transport is currently dominated by petrol and diesel-powered vehicles. The City of the Future will need to be built around a different transport and urban paradigm. This article argues that the new model will be a polycentric city linked by fast electric rail, with local access based on autonomous "community"-owned electric cars and buses supplemented by bicycles, electric bikes and scooters, with all electricity generated from renewables. Less space will be wasted on roads and parking, enabling higher accessibility yet more usable public open space. Building the cities of the future will require national governments to accelerate local initiatives through appropriate policy settings and strategic investment. The precise way in which individual cities move into the future will vary, and the article illustrates how the transformation could work for Australian cities, like Sydney, currently some of the most car dependent in the world, using new financial and city partnerships.

Keywords
1.5 °C agenda; decarbonisation; future city; information and communication technology; public space; transport

Issue
This article is part of the issue "Urban Planning to Enable a 1.5 °C Scenario", edited by Peter Newman (Curtin University, Australia), Aromar Revi (Indian Institute for Human Settlements, India) and Amir Bazaz (Indian Institute for Human Settlements, India).

1. Introduction

With more than 50% of the world's population living in cities, and urban areas now accounting for more than 70% of global CO2 emissions and creating more than 80% of the world's GDP, solutions to global warming will inevitably involve cities reducing their greenhouse "footprints" (IPCC, 2014a). This will apply both to the long-established cities and to the rapidly expanding cities such as in Asia, the Middle East and Africa (Moriarty & Honnery, 2013). A key component of this will be reduced CO2 emissions from urban transport, which is currently dominated by private cars using fossil fuels. This will require a transformation of our transport sector away from so much reliance on cars and away from reliance on oil towards electrically powered vehicles and systems, powered by renewable energy (Newman, Beatley, & Boyer, 2017).

The timescale for this transformation is very short. Indications from the IPCC AR5 Report (IPCC, 2014a) are that we have at best four decades to substantially reduce greenhouse emissions from all sources. The IPCC 1.5 °C agenda is now suggesting we will need an even faster transition. This article is attempting to overview how cities will need to manage this transition to the City of the Future which features the removal of all fossil fuels in the passenger transport arena.

The move to renewable energy in the generation of electricity is now underway in earnest (Newman, 2017a), and there are indications that global coal consumption has peaked and started to decline (IEA, 2017a). In contrast, emissions from the transport sector and use of oil-based fuels continues to rise though at a reduced rate at a global level and in many cities and nations it is now decoupling from economic growth (Newman, 2017b).

There are a number of indications that trends in the transport sector are beginning to change:

- Per-capita car usage in many cities and countries is now falling, and there is a growing trend to reduced car dependent urban forms with a growth in transit and active transport modes, which have much lower emissions per passenger-kilometre (Goodwin & van Dender, 2013; Mittal, Dai, & Shukla, 2016; Newman & Kenworthy, 2015);
- Electric cars are beginning to gain market share and are poised to replace petrol and diesel-powered cars over the coming decades. Provided their electric energy is derived from renewables, this promises a substantial reduction in emissions (IEA, 2016);
- Self-drive or autonomous vehicle technology is also emerging rapidly. This provides an option to re-think the current paradigm of urban transport, which is based on privately owned automobiles and which has grown to dominate most of the world's cities, especially since 1950 (Carlin, Rader, & Rucks, 2015). However as discussed later, unthinking application of autonomous vehicle technology to simply replace current vehicles on a one-for-one basis will not produce significant benefits except in the area of safety.

This article looks at how these emerging trends could combine to generate a radical transformation not only of transport technologies and travel behaviour, but of the way we build and live in our cities. It suggests that the growing need for urban accessibility can be solved by a combination of:

- The emergence of a poly-nucleated urban form, combining a strong city centre with strong sub-centres, allowing accessibility to be maximised but travel minimised;
- Increased investment in high capacity electric rail transport links for trips to urban centres and for longer distance travel in urban areas, with a concomitant reduction in investment in general purpose roads and freeways;
- The large-scale replacement of private automobiles by jointly-owned and operated self-drive vehicles, which combined with bicycles and small scale electric scooters and cycles could cater for dispersed travel as well as feeder trips to centres and public transport nodes.

The article examines how these trends could emerge, their potential benefits, and how they could be encouraged by appropriate policies at national, state and local level. It then looks in detail at how they could apply in Australian cities using Sydney as a case study; currently Australian cities are amongst the most car-dependent and transport emissions intensive in the world and they are also experiencing rapid population growth which enables them to demonstrate rapid transformation.

The article looks at the history of urban transport and how it is now changing suggesting a new urban paradigm is emerging; these trends are used to create what could be The City of the Future and how it can be imagined to help with the 1.5 °C agenda.

2. Brief History of Urban Transport

Whilst there have been many changes in technology in the last few centuries, especially in fields such as information technology, medicine or manufacturing, it is a curious fact that the technologies which currently dominate urban transport are all essentially products of the 19th century—the tram, train and especially the car (Newman, Kosonen, & Kenworthy, 2016). Whilst modern versions of these modes are more developed in many ways such as safety and comfort, they are little changed in the key characteristics (capacity, effective speed), which determine how they accommodate urban travel and also how they shape our cities (Newman & Kenworthy, 2015, 1999).

In contrast, all of these modes represented a major leap forward over previous transport technologies (walking, horse drawn vehicles) when they were first introduced. Indeed, in many respects our current transport systems have gone backwards in recent years. Cars and freeways which can only handle around 3,000 passengers per lane per hour have come to dominate longer distance travel over rail-based solutions, which can handle ten times that movement in the same space. Meanwhile the very success of the car has led to rising traffic congestion, and with it slower speeds, both for the cars themselves and for any other vehicles (trucks, buses, trams, bicycles) caught up in the congestion. Thus urban efficiency as a whole has declined, notwithstanding the apparent improvement in personal mobility.

2.1. The First Rail Age

Prior to the industrial revolution, most urban travel was by foot, with typical walking speeds of 3–4 km/hr. The rich could afford horse-drawn travel options, allowing those speeds to be tripled. Bicycles also for a time provided quite an increase in personal mobility. But it was the train and the electric tram which first revolutionised urban travel, and they transformed cities from Europe to America to Australia in the late 19th century.

The radical increase in speed made possible by these modes, combined with their high capacity, meant that public transport came to dominate urban travel patterns in many major cities around the world within a few decades. While every city has its own unique history, geography, topography and urban economy, these technologies were applied almost universally in medium–sized or larger cities, and tended to have similar impacts. "New World" cities were much younger and in most cases smaller and lower density than their European counterparts when these technologies arrived. Nevertheless, electric trams (and electric inter-urbans) became commonplace across the new cities of North America and Australia. Sydney developed one of the world's largest and most heavily used tram networks, as well as a substantial suburban electric rail network by the 1930s, despite having only a few thousand inhabitants when the technologies were first invented. Similarly, more populous cities like Paris, Berlin and New York all introduced underground electric metro systems in the decades following the introduction of the first such system in London.

The railways in particular allowed cities to expand rapidly in their geographical areas. In European cities, this sometimes meant leaping across the old walls within which they had been confined for centuries. In other cases, long tentacles of development followed the railways out into the countryside, with the rich escaping the pollution and crime in the inner cities and commuting into the city for work or business. This was the precursor to the widespread "dormitory" suburbs which spread rapidly (but in all directions) with the rise of the car and freeway after 1950. In all these cities the 19th century rail innovations and urban development went hand-in-hand and were created by entrepreneurs who established partnerships with city governments (Newman, Davies-Slate, & Jones, 2017).

Another impact of the first rail age was on city centres. The ability to bring large numbers of people to the centre reinforced the parallel development of the skyscraper in those cities which did not have height limits. Chicago is perhaps the quintessential example, often seen as the home of the skyscraper, but also the biggest rail hub in the US and the fastest growing city in the world in the late 19th century.

In cities like London, Paris or Tokyo which were already densely settled over a large area before the first rail age, networks of rail lines covered a large part of the inner urban area, and the city centre was more spread-out. This was reinforced by height limits (in the case of Tokyo because of earthquake risk). These cities tended to have a number of privately owned rail systems, mostly built on the surface, each with their own city terminus. These in turn were connected by underground or metro systems, like London's "Circle Line".

At the metropolitan scale, most rail systems resembled radial networks. A few cities however, such as Berlin or Moscow, developed "ring metros" to complement their radial networks. The inner urban areas were often criss-crossed with metro and/or light rail networks.

While the development of cities in the first rail age is well understood, the key aspects to focus on here are that:

- The basic transport technologies spread very rapidly around the world;
- Each city utilised the technologies somewhat differently, based on their previous history, geography, economy and culture;
- Rail systems both spread housing development along the rail corridors and reinforced a range of urban centres, particularly the Central Business District, for commerce;
- The high capacity of rail systems allowed them to dominate urban travel (measured in passenger-kilometres) and to allow those cities which had strong economies to expand rapidly in population;
- The predominance of urban public transport was an equalising force in society once fares dropped to the levels affordable by the working class, increasing accessibility and allowing people to travel further. This in turn facilitated increasing specialization of the workforce.

2.2. The Car and Freeway Age

The first half of the 20th century saw the consolidation of the first rail age but also the rise of the automobile age, especially in the US where mass-produced cars allowed ownership to spread rapidly. The Depression and two World Wars slowed the process, but the car age started in earnest after 1950. The car offered two-dimensional, door-to-door flexibility, which quickly made trams that shared road space with cars, obsolete. Rail-based systems, however, were more resilient, having higher speeds and their own rights of way. A few cities retained their trams and and have since built on them as a major feature of their economic and social life (see Figure 1).

As car ownership and use expanded, land uses began to react. The car allowed low density suburbs to fill in the gaps between the rail corridors, but also reduced the primacy of the traditional city centre in terms of accessibility. Employment and other services found cheaper land in the suburbs and a general process of decentralisation began. Shops and other activities did coalesce into retail malls and office and industrial parks but in many cities these were surrounded by car parks and inaccessible by good quality public transport. Buses replaced trams in many cities but failed to halt the decline of public transport and in many cases exacerbated it. However, the rapid rise in cars produced a massive rise in road congestion, especially for cities with over one million inhabitants. The answer for a while appeared to be the urban motorway. US cities took this furthest, building on the Interstate Highway system, but many other cities from Seoul to Singapore to Sydney built networks of elevated or in some cases underground roads.

As with the first rail age, the responses by individual cities to the car differed. Most cities embraced the idea of the motorway, and their building programs were only limited by the availability of resources. In some cities

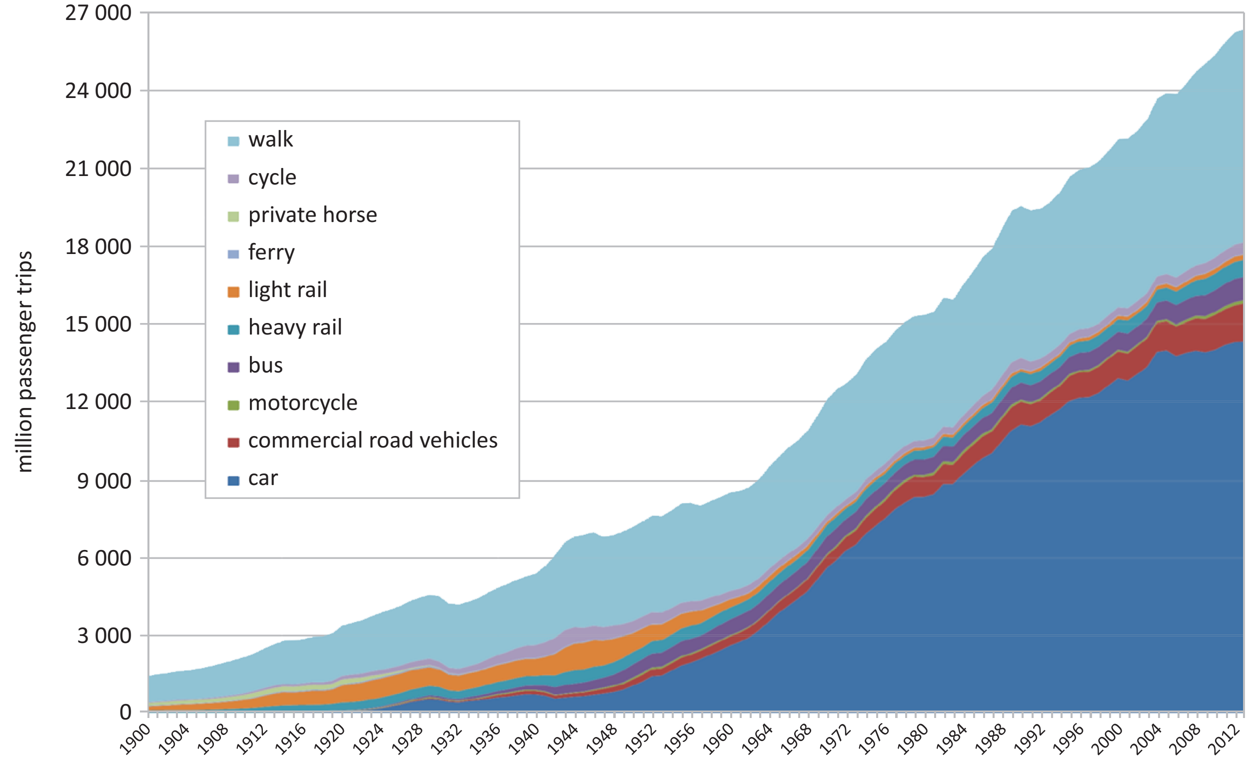


Figure 1. Metropolitan passenger trips in australia's capital cities, 1900–2013. Source: Bureau of Infrastructure Transport and Regional Economics (BITRE, 2014). Notes: Includes total annual passenger tips (for years ending 30 June) within all State and Territory capital cities, across all available transport modes (including rough estimates of non-motorised travel). Values for 'light rail' include estimates for the Sydney Monorail (as well as for early horse-drawn or steam trams). Values for 'bus' cover: all motor vehicles with 10 or more seats (i.e. charter/hire buses and other private buses/minibuses, in addition to UPT route buses), including the use of trolley-buses; as well as horse-drawn buses for early years. Values for 'private horse' include carriage and saddle horses, but not those used for horse-buses and horse-trams—which are included in the relevant mass transit modes. Values for 'commercial road vehicles' related to non-freight use of such vehicles (primarily due to travel by light commercial vehicles such as utilities and panel vans).

however, there was strong opposition to motorways from environmentalists, the public or from affected residents in the path of the freeways (Bratzel, 1999; Stone, 2014). In Sydney for example a series of protest movements involving unions, residents and others managed to halt inner city freeway development for twenty years. When it finally returned, it was in the form of largely underground toll-ways.

By 2000, cities in the developed world were firmly car-dominated, with a few exceptions such as Tokyo, which had high densities and the world's most heavily utilised urban rail system. Figure 1 (BITRE, 2014) shows, for example, the trends in trips by different modes in Australian capital cities, from 1900 to 2012. In the developing world, car ownership was not yet within the reach of the public, but was still seen as aspirational.

Nevertheless, there are significant differences between cities, even within the same country or with similar income levels, as to their reliance on different transport modes or their urban form. Singapore for example has far lower car use and far higher public transport use per capita than US cities with similar or lower income levels. Sydney has significantly less car use than other Australian cities; New York is completely different to the rest of the US, accounting for a massive 60% of all heavy rail use across the entire country. History, geography, politics and other factors can make a difference.

2.3. The Second Rail Age

A major change began to occur however around the turn of the 20th century which has been called "the second rail age" (Newman, Glazebrook, & Kenworthy, 2013). Per-capita car usage, which had climbed inexorably for fifty years, began to decline in some places. By 2005, the trend was becoming more widespread—after that year for example, all Australian capital cities began to experience the "peak car" phenomenon (Newman & Kenworthy, 2015). The phenomenon has now been demonstrated in China (Gao & Newman, 2018).

The cities began to change their priorities with urban regeneration growing faster than urban sprawl and a strong reaction to the building of freeways. These protests have grown in more recent years with 22 cities now removing freeways and major political shifts in cities being created around the need to change priorities away from high capacity roads (Gaynor, Newman, & Jennings, 2017; Newman & Kenworthy, 2015).

About the same time, public transport, which had in many cities been static or in decline for decades, began to rise rapidly. And City, Regional and National Governments have begun changing their investment strategies:

- In the US for example, there are now some 28 light rail systems in place, most built since 2000. Ridership on all forms of urban rail transport (heavy rail, commuter rail and light rail) has risen much more rapidly than population, although bus ridership has stalled or fallen in the last two decades (See Figure 2);
- In Europe, light rail has also made a revival, particularly in countries such as France and Spain, while major new underground rail systems have been built or are under construction in many older cities from Athens to Paris to London. See Figure 2 on UK rail growth;
- Rail, including automated metros, is in fact expanding rapidly around the world, but most notably in Asia, and in particular China, where 52 cities have built metro systems and some light rail systems. Major rail systems are now being built in Latin America, the Middle East, Africa and Australasia as well. Rail passenger kms have grown 46% between 2002 and 2015 when they had plateaued or declined for most of the previous 5 decades; high speed rail has grown over 6 times (IEA & UIC, 2016);
- Sydney is currently investing $40 billion in transport infrastructure, half on metro and light rail systems and half on a massive Toll-way system called West Connex. But the travel data points the way: last year there was a 11% increase in patronage on the rail network, while car usage is growing at only around 2% pa or in per capita terms it is in decline;
- 22 cities such as Seoul and San Francisco have actually removed urban freeways (the latter following an earthquake) and Paris is now closing some motorways along the Seine. Road pricing has also been introduced in cities like London, Oslo, Singapore and Stockholm (Newman & Kenworthy, 2015).

Illustrations of the second rail age are provided in Figure 2 (for the UK) and Figure 3 (for the US). In the case of Australia, Figure 4 shows the dominance of the original tram systems up until about 1950, the rapid decline in public transport use (particularly tram usage, as most tram systems were closed) until about 1980, and the recovery in public transport use, particularly on rail, since then.

The reason for this “second rail revolution” appears to be related to the declining speed of traffic and increased speed of urban rail which has been able to go around, over and under the growing traffic problems of cities on every continent (Newman & Kenworthy, 2015). There are also a range of good public policy reasons for this shift in priorities to electric urban rail.

2.4. The Urban Form Associated with Transport

The literature on how transport technologies have shaped cities is extensive (Anas, Arnott, & Small, 1998; Batty & Longley, 1994; Frey, 1999; Lynch, 1981; Newman & Kenworthy, 1989, 1999, 2015). The data show the old walking cities losing density in population and jobs as the

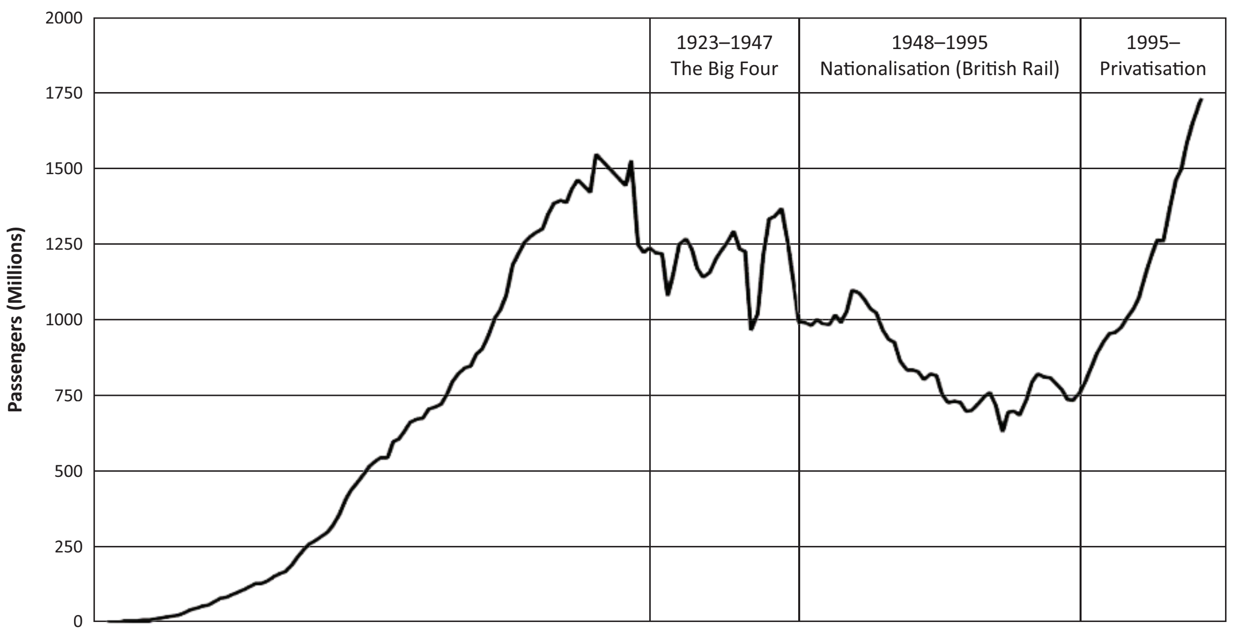


Figure 2. The growth in UK rail showing the first age and now the second age of rail. Source: Data sourced from Association of Train Operating Companies and the Office of Rail Regulation, UK, at Wikimedia Commons (2018).

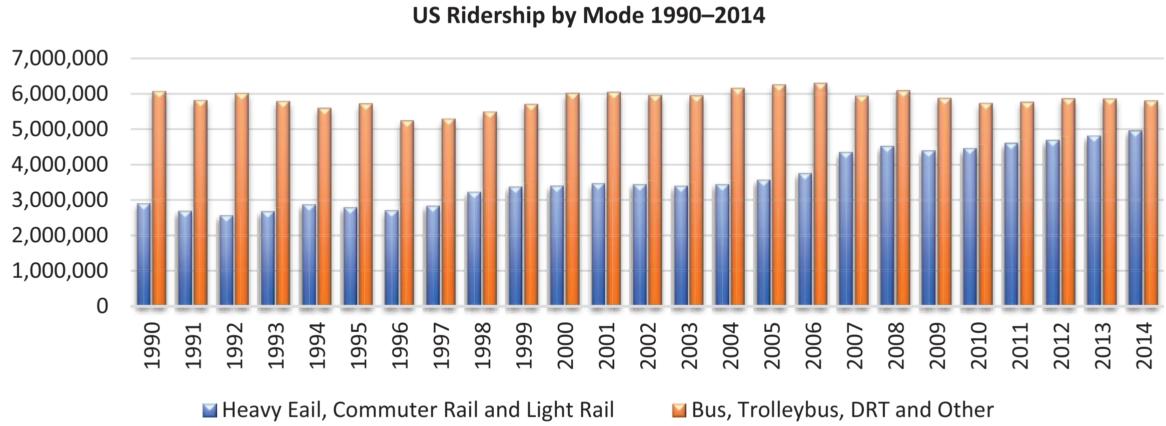


Figure 3. Rail and bus patronage in the Unites States, 1990–2014. Source: American Public Transport Association (APTA, 2016).

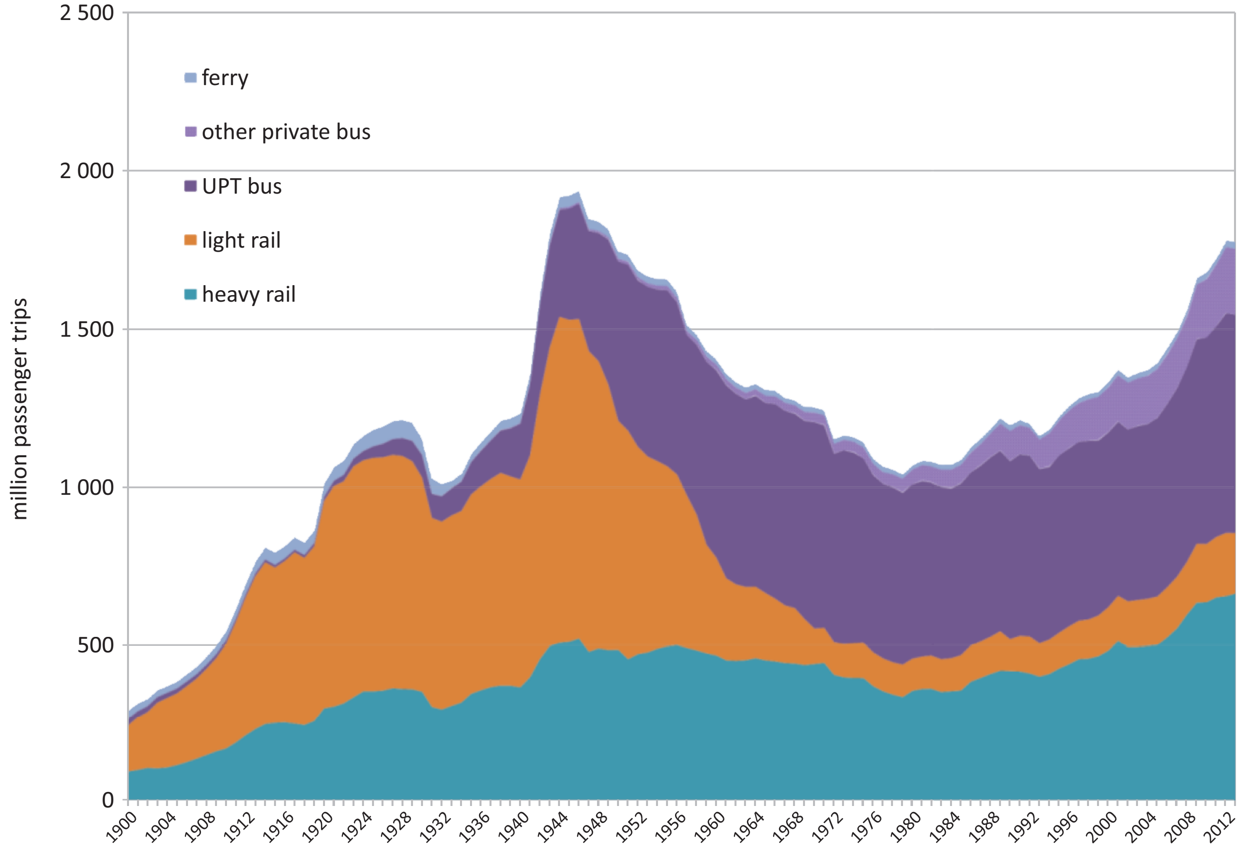


Figure 4. Urban public transport trips in Australian capital cities, 1900–2013. Source: BITRE, 2014. Notes: Includes total annual passenger tips (for years ending 30 June) within all State and Territory capital cities, across all mass transit (including rough estimates of horse-drawn vehicles). Values for 'light rail' include estimates for the Sydney Monorail (as well as for early horse-drawn or steam trams). Values for 'UPT bus' cover all route/school bus services, including the use of trolley-buses and horse-drawn vehicles for early years. Values for 'other private bus' are very approximate allowances for such vehicles, giving the roughly estimated contribution of charter/hire buses (and other non-UPT buses/minibuses).

tram and train spread the city out into a polycentric form, then the density reduced further as cars dispersed the city very rapidly. Now, densities are rising as the polynuclear urban form is again being favoured by renewed priority in rail systems and the increasing value of the old walking city centres with knowledge economy activity (Newman & Kenworthy, 2015; Matan & Newman, 2017).

3. The Climate Challenge

The IPCC Fifth Assessment Report (IPCC, 2014b) indicates that transport accounted for 14% of global Greenhouse Gas emissions in 2010, with 95% of transport energy coming from oil. This compares with 25% for electricity and heat production, 23% for agriculture, forestry and land use, 18% for industry, 12% for other and 8% for buildings. In fact, the full share attributable to transport would be higher, as some electricity is used for transport and some share of manufacturing is used to build transport vehicles and infrastructure.

Globally there is evidence that coal consumption has begun to decline slightly, after a decade or more of rapid increases. However, oil and gas consumption has been rising for the last five years as a result of the revolution in drilling techniques in the US (IEA, 2017a). See Figure 5.

While renewable energy in electricity generation, especially wind and solar, is now increasing and beginning to displace coal and gas, energy consumption and emissions for transport continue to rise. For urban passenger transport, there are marked differences in energy efficiency, and hence emissions, between different modes (Figure 6), with passenger rail over six times more efficient than cars, and buses three times more efficient (IEA, 2017b).

The focus on cities to help shape the response to global warming has been growing, particularly with organizations like C40, ICLEI and 100 Resilient Cities showing that cities must lead this transition to remove fossil fuels (C40, 2017). Many cities are now showing that they can remove fossil fuels much quicker than their national commitments (Kramers et al., 2013; Newman, Beatley, & Boyer, 2017). In every city which is planning to remove fossil fuels the strategy is to build a renewable electricity system and then electrify the transport system. Such planning builds on a number of emerging trends.

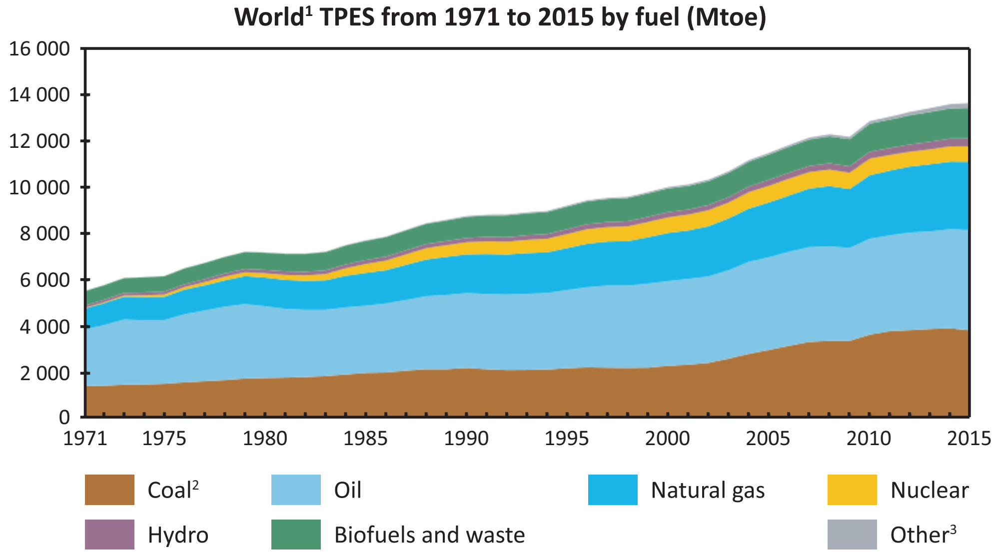


Figure 5. Global fossil fuel consumption. Source: International Energy Agency (IEA, 2017a).

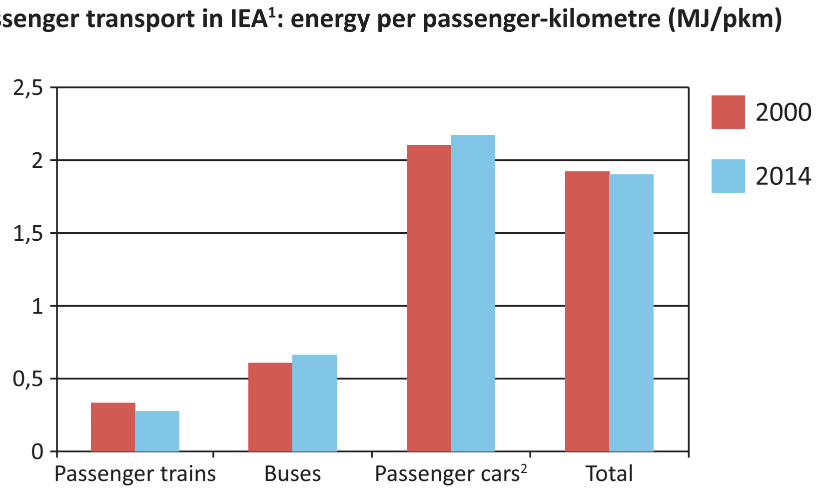


Figure 6. Energy efficiency by mode for passenger transport. Source: International Energy Agency (IEA, 2017b). Notes: 1. Refers to the 19 IEA countries for which data are available for most end-uses: Australia, Austria, Canada, Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, New Zealand, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States. 2. Passenger cars include cars, sport utility vehicles and personal trucks.

4. Emerging Trends

Some of the key emerging trends which will affect how cities and their transport systems evolve in future are outlined below.

4.1. Peak Car

As noted earlier, per capita car use is now in decline in many cities and countries, and in a few cities absolute volumes of traffic are also declining. This phenomenon has been identified for some time by academics (Goodwin & van Dender, 2013; Newman & Kenworthy, 2011) but is now becoming apparent to mainstream media (Rapier, 2017). Recent research (Sivak, 2017) confirms that vehicle ownership per capita in the US peaked in 2006, and per capita kilometres driven per person peaked in 2004, although both have rebounded slightly since their lows of 2012–13.

The reasons for this are many, and include:

- The declining utility of cars in many urban areas as a result of high levels of traffic congestion and the high costs of parking;
- The trend back to city centres and inner-city areas both for business and for residential use leading to rises in density that favours non-car modes of transport;
- Changes in behaviour, particularly by millenials, many of whom no longer bother to get drivers' licences;
- Improvements in alternatives to the private car, including mass transit, car sharing, improved taxi services such as "Uber" and bike share schemes.

This has occurred despite falling costs for purchasing new vehicles with the entry of competitive firms based in Korea and now China, and relatively low prices for fuel. All these trends were associated with increased use of smart phones and social media which are enabling people to make choices based on simple and rapid communications. As shown below this is likely to continue to grow with smart technology shaping transport and land use systems very directly (Newman, 2016).

4.2. Electric Vehicles

Electric cars, trams and trains have been available for over a century, the former using early batteries, and the latter using overhead or third rail systems for providing electrical power.

While electric power for rail based transport became increasingly common in the 20th century, electric cars proved uncompetitive with gasoline powered cars due to the limited energy densities of early lead-acid batteries. However, developments in battery technology and pressures to reduce urban pollution and greenhouse gas emissions is leading to a "second coming" for the electric car. Whilst hybrid and full-electric vehicles only made up about 4% of world automobile sales in 2016, sales in 2016 grew by 60% on a year earlier (see Figure 6) and there were an estimated 2 million electric cars on the road by 2016. EV's are beginning to become common where suitable government policies make them attractive—for example in Norway, where high taxes on regular cars and incentives for electric cars saw the latter achieve 30% of sales of new cars in 2016.

As sales of electric cars increase (Figure 7), so their costs have begun to fall, and many car companies are now planning to introduce new models. VW is introducing a number of new lower cost electric car models, Mercedes has accelerated plans for new electric vehicles to challenge Tesla (Shankleman, 2017) while Volvo has even announced it will phase out internal combustion powered cars by 2021. City governments have also begun providing incentives for electric cars and Paris has announced it will ban internal combustion cars by 2030 (G. Smith, 2017). The IEA indicates that 10 governments,

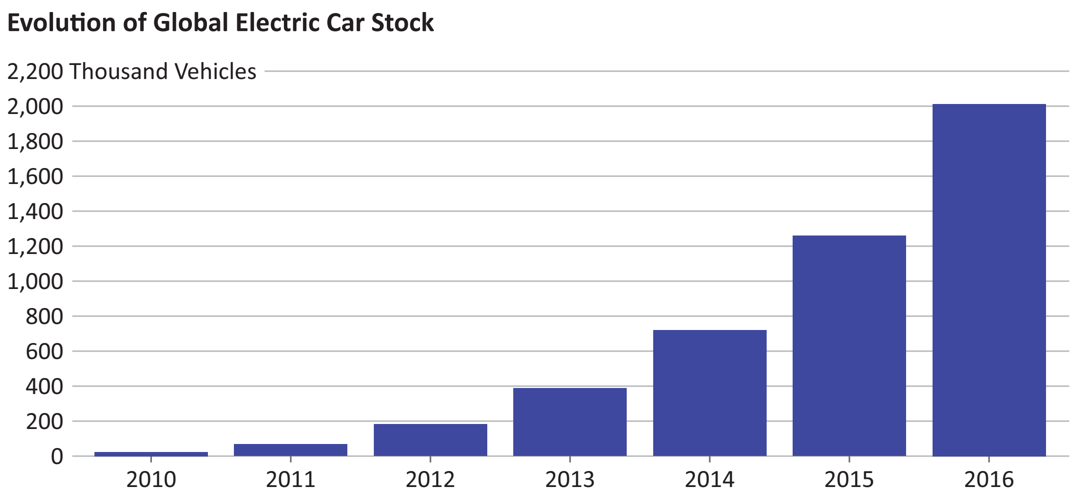


Figure 7. Growth of electric cars has begun to take off. Source: International Energy Agency (IEA, 2016).

including China, France, Germany, the UK and US, will set a goal of 30% market share for battery powered cars, buses, trucks and vans by 2030.

The Li-ion battery has now been mass produced, mostly in China, and has become the cheapest form of batteries for use in EV's (Nykvist & Nilsson, 2015). Concerns about the source of Lithium have eased as most Lithium now comes from Western Australia where eight new mines have shown how widespread supplies of crustal Lithium can be refined for batteries. Recycling of Lithium and the other batteries does not seem to have the issues of Lead Acid batteries (Shi, Chen, & Chen, 2018). Other batteries have different scientific advantages but for the next few decades of city building the Li-ion battery is likely to dominate and make solar households and businesses as well as solar transport a reality.

Whilst electric cars will significantly reduce local air pollution, their contribution to reducing greenhouse gas emissions depends on the source of their electrical energy. In countries such as France, with a high share of nuclear and renewable energy, replacement of petrol and diesel cars by electric cars will produce an immediate drop in transport-related greenhouse emissions. In countries like Australia, where 80% of electricity is currently coal-fired, there will be lower greenhouse benefits though even here it would be less. However, the shift to renewable energy has accelerated with dramatic growth rates in roof top solar (Green & Newman, 2017; Newman, 2017a) and so the electric car revolution will eventually produce major reductions in greenhouse gas emissions.

4.3. Autonomous Vehicles

Another major technological change in transport is also underway—the development of autonomous or "driverless' vehicles. Companies such as Google are already driving such vehicles on regular streets around America to test their safety features. Singapore has trialled autonomous taxis and various trials of autonomous buses are underway including in Perth and Sydney. In the case of Sydney, an autonomous shuttle bus trial is underway at Olympic Park, being conducted jointly by the NSW Government, the National Roads and Motoring Association, the Sydney Olympic Park Authority and a number of private companies (Transport for NSW, 2018). Initially the shuttle bus will operate on dedicated routes, and later it will begin operating on public streets.

Autonomous (driverless) technology is also being applied to larger scale mass transit systems (see Figure 8). There are already a large number of driverless metro trains installed around the world, with a recent report benchmarking 25 systems (Wavestone, 2017). The International Railway Journal (IRJ) reports UITP estimates that the number of kilometres of driverless metros will ex-

Autonomous taxi, Singapore.

Autonomous shuttle bus, Sydney Olympic Park.

Driverless metros are becoming common more and more.

"Trackless" Tram being tested in China. The guidance system will allow future driverless operation.

Figure 8. Autonomous vehicles are on the way. Sources: Wavestone (2017), Transport for NSW (2018), Birginshaw (2017) and A. Smith (2017).

pand from under 790 in 2016 to 2,200 by 2025 (Birginshaw, 2017). In addition, China has announced a new rubber-tired guided electric tram system which is being used in either driverless or driver mode and has the charcteristics of a light rail in terms of capacity, speed and potential ability to attract urban development (A. Smith, 2017).

Studies in the UK have estimated that the eventual replacement of conventional cars by driverless ones will result in a significant improvement in road safety, although the timeline for full autonomy in complex urban environments is likely to take some decades. However, if we simply replace privately owned vehicles with privately owned driverless vehicles, this will do little to reduce road congestion or parking requirements, or to make our cities more liveable.

However, if "communally" owned, a driverless vehicle could replace eight or more private vehicles, particularly if operated in a "continuous multihire" mode and if used to provide feeder services to rail and other mass transit systems or nearby activity centres. A single such vehicle could, for example collect two to five people, drive them to a rail station for the morning commute, then return empty to collect three or four more loads of commuters in the morning peak period. At the destination end autonomous vehicles could deliver commuters to offices or other facilities which were beyond the walking catchment of the station (destinations such as offices and shops are usually more concentrated than origins such as houses, with a higher proportion of people able to walk to them).

Thus, for example, one light rail vehicle plus a fleet of perhaps 15 autonomous vehicle shuttles (10 at the origin end and 5 at the destination end) could effectively replace 100 long-distance private car commuting trips (with a similar number in the reverse direction in the evening, plus additional avoided trips during the rest of the day). Figure 9 shows how this changes urban form.

This "last mile" service could substantially reduce the need for long distance trips by private cars, often with low car-occupancy (an average 1.2 passengers per vehicle is typical in most cities) which is the most energy and space intensive form of transport. This in turn could substantially reduce both road congestion (improving the efficiency of commercial vehicles) and the need for more road capacity, especially motorways.

In this context, the space saving attributes of mass transit over car-based systems is crucial. Arterial roads and motorways carry only around 1,000–2,000 vehicles per lane per hour (1,500–3,000 passengers), whereas light rail, suburban rail and metros typically carry 3,000–30,000 passengers per lane/track per hour, and are thus up to 10 times more space efficient (Newman & Kenworthy, 2015).

Shifting a significant share of current automobile-based travel partially to mass transit will require additional capacity on urban rail and bus systems. However the scale of increase may not be as large as expected, given that there is significant spare capacity on such systems during off-peak periods, to smaller sub-centres and in counter-peak directions. In addition the mass transit mode shares to the city centres in peak periods is already very high in many cities. For example Sydney, which is a car-dependent city, nevertheless has an 80% public transport mode share for trips to the central business district in the morning peak.

Parking is another often hidden cost of our current car-based systems. In Sydney, it has been estimated that car parking occupies at least 100 sq. km. of land, worth in the order of $100 billion if put to other uses (land values in Sydney have recently reached $1,000/m^2).

In addition, the use of autonomous shuttles to feed rail or other mass transit can widen the catchment areas of the transit system, making them more economic in lower density suburban areas, or in cities where activities are highly dispersed.

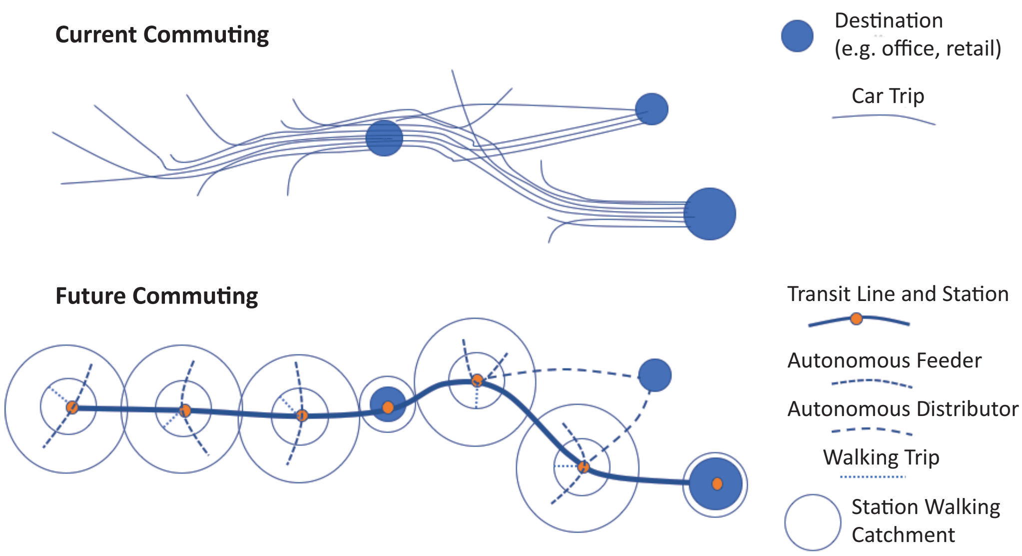


Figure 9. "Current" versus "future" commuting. Source: authors' own graphic.

The future transport technologies are likely to be combinations of electric fast rail down high speed corridors plus electric light rail (or trackless trams) in lower speed corridors like inner areas, all building up substantial dense centres around stations as shown in Figure 9; into these centres the AV–EV technologies can feed in their last mile and first mile passengers as well as cycling and walking. In each of these centres electric charging from solar energy can provide zero carbon fuel for all the electric vehicles through rapid recharging points; the whole local solar and local transport system can be managed by a Citizen Utility using blockchain technology (Green & Newman, 2017). Such an urban vision is unfolding rapidly before our eyes.

4.4. Population Growth, the Information Economy and Urban Structure

Cities have existed for at least 8,000 years, but it is only very recently that more than half of the world's population have lived in them. The process of urbanisation began in earnest in the UK with the industrial revolution, moved to other European countries and North America and is continuing now in China, India, Indonesia and other developing economies, especially in Africa.

This process has fuelled and been fuelled by a rapid increase in energy consumption, accompanied by rising living standards, the development of high-rise buildings and the growth in automobile ownership. In many places cars have taken over streets previously dominated by pedestrians and cyclists. Cities have also expanded in size, increasing trip lengths beyond what is feasible for non-motorised transport.

However, the patterns of urbanisation and city structure have not been uniform between cities and countries. In Europe, cities have continued to be built at relatively high densities, although there has been some "suburban sprawl" on the city outskirts. However, many European cities have retained the strong public transport orientation which accompanied their early development phase at the end of the 19th and beginning of the 20th centuries (Figure 10).

In contrast, most "new world" cities have experienced most of their urban growth in the age of the automobile—from 1920 to 2000. Accordingly, they have been built at very low densities and with extensive motorways and parking but limited public transport networks (Figure 10). However some of these cities (for example the State capital cities in Australia and many cities in the south or west of the United States) continue to experience rapid population growth. This provides opportunities for densifying these cities, especially along rail corridors or around emerging sub-centres as is already occurring in cities such as Sydney as discussed earlier.

At a global level, the focus of urbanisation is now on countries in Asia, the Middle East and Africa. This third phase of urbanisation is producing high-density cities which nevertheless cover large areas and house 10 million or more inhabitants. In many of these cities, there has been a rapid rise in car ownership and use alongside significant investment in metros and other public transport (Figure 11). In China for example, Beijing and Shanghai have built metro systems in just thirty years which now dwarf the traditional metros of European cities and associated with this they are now showing peak car as both urban rail and electric bikes are growing rapidly (Gao & Newman, 2018).

The urban structure of different cities also varies. European cities typically have 30% or more of their total employment in the central area, supported by strong radial public transport systems. US cities typically have only around 10% of their total employment in the "city centre", but with a significant share of jobs located in sub centers and "edge cities", often located at the intersection of radial and circumferential motorway systems (Karanfilovski & Stone, 2015). The mega cities of Asia tend to have multiple centres of economic activity like Singapore which has 22 sub centers (Newman & Matan, 2013).

However in almost every city the urban planners are looking to reduce automobile dependence through a

London is adding high rise buildings to an already dense urban core.

Outskirts of Washington DC illustrates car-oriented urban development.

Figure 10. Urban development contrasts.

Shanghai's metro network.

CITY	PATRONAGE (Billion)	LENGTH (Km)	STATIONS
Beijing	3.4	527	319
Shanghai	2.8	548	337
Seoul	2.6	332	311
Tokyo	3.3		179
Moscow	2.5	328	196
Mexico City	1.6	228	195
New York		373	468
Paris	1.5		303
London	1.3	402	270
Madrid		294	301
Guangzhou	2.3	240	
Nanjing		224	
Hong Kong	1.7		

Source: http://www.citymetric.com/transport/what-largest-metro-system-world-1361

World's busiest metro systems.

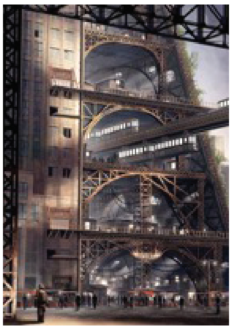
Figure 11. The emergence of the metro in the new mega cities of Asia. Source: Travel China (n.d.).

combination of improved transit and a polynuclear urban form focussing on rail stations (Newman & Kenworthy, 2015). This is being done not just for transport and energy reasons but also for the multiple benefits in social, economic and environmental factors that this can bring. Thus the 1.5 ºC agenda with its zero carbon goal as well as the need to fulfil the Sustainable Development Goals, is likely to see more focus on this kind of urban planning.

5. The City of the Future

There have been many futuristic scenarios for how cities will change and what transport systems we will use to get around them. Visions from the 19th century and early 20th century often featured electric trains or even gigantic steam engines (Figure 12) while later 20th century visions frequently include personal transport from cars to personal flying machines.

Many of these "visions" came from architects and others with only superficial knowledge of the economics of different transport technologies or modes. Many also envisaged high-rise cities patterned after New York. Indeed some extremely tall buildings are emerging, and new developments such as flexible lifts which can move sideways as well as vertically, may change building economics.



19th century visions of the future city focused on multi-level cities and mass transit.

20th century visions of the future focused on individualised transport systems.

Figure 12. Past visions of the City of the Future.

At the same time, as discussed earlier, cities are now becoming denser again after the period of urban sprawl in the late 20th century. This will reduce per capita travel requirements but requires efficient high-capacity modes if high levels of congestion are to be avoided. This is a major motivation behind the second rail age.

It now seems likely that many cities will continue to increase in both population and density, but that it is unlikely that "vertical" cities, "underwater" cities or other more fanciful constructs will replace the basic pattern of individual buildings connected by road and public transport networks. Urban fabrics last for many generations based around walking, transit and the automobile and they are likely to be the main combinations for many generations into the future, perhaps with even more walking urban fabric and transit urban fabric (Newman et al., 2016). Even the idea of the "non place urban realm" where all work and social interaction was done through electronic communications, has not emerged; instead the knowledge economy has facilitated "face-to-face" interactions in urban centers and has fed the regeneration of older urban fabric designed around walkability (Matan & Newman, 2017; Newman & Kenworthy, 2015). What can change however is the more precise urban structures within cities and the shares of transport undertaken by different modes and the role that new technologies are likely to play in shaping this City of the Future as set out in this article. But the trends are still likely to grow out of the functional arrangements of how cities facilitate commerce and provide social opportunities, thus ensuring that in the City of the Future the ancient walking city, the 19th and early 20th century transit city, and the modern automobile city are recognised, respected and regenerated by the new urban development processes (Newman et al., 2016). The new technologies discussed below are indeed enabling such recognition and rejuvenation.

Economic forces are likely to mean continued clustering of activities both to reduce transport costs and because of basic human social needs. Despite well over 100 years of the telephone, and thirty years of the internet, people still value face-to-face communication. Communications technology has not led to a displacement of travel—it appears to be a complement rather than a substitute. However the new use of ICT is to create smart control systems that offer a city much more than entertainment but a more efficient and sustainable transport system.

The long car-based commutes to work common in many cities now need not always be the norm. These derive from the unfortunate combination of the spread-out city and the growing specialisation of the labour force. While the rise of the car favoured the former, the rise of the information economy ironically favours greater clustering of activities into centres—as evidenced by the emergence of the suburban "office park" and satellite city centres in many cities, as well as the revitalisation of the traditional central business districts and inner urban areas (Thomson, Newton, & Newman, 2016).

This points to a City of the Future based on the emerging transport technologies highlighted in the previous section and on the emerging information economy with increasingly specialised business and human service sector jobs. This city is likely to have:

- An *increased concentration of jobs, residents and other activities* in both the traditional CBD, along old transit corridors, and in satellite cities and sub-centres clustered around intensive rail systems. These centres will be accessible from the local areas by walking, cycling, and small scale electric vehicles, and from the wider metropolitan region by the combination of local access modes and mass transit;
- All modes will be *electric* and their power will be *renewable*. Local management of electric power, integrated with local shared mobility systems, will emerge;
- Increasing densities for housing in all parts of the city, especially around stations, but with more open space and *less urban "sprawl"*;
- A concomitant *decline in the share of "dispersed" activities*, which will fail to achieve the economies of scale and scope possible with clustering;
- *New and expanded mass transit* systems providing better access to the CBD and sub centres with higher speed and capacity based around autonomous technology; subsequent reductions in road capacity and road infrastructure spending followed by some dismantling of freeways;
- The *replacement of many private automobile* trips by the combination of local access modes, mass transit and shared-use autonomous vehicles;
- A marked *reduction in overall traffic volumes* on the road network. This will allow some road-space to be re-allocated from cars to either trucks and commercial vehicles (which may also be driverless in some cases) or to bicycles, scooters other small personal mobility devices and to more intensive urban activity;
- A significant *reduction in parking*. This space can be re-allocated to higher uses, including additional commercial, office, retail, housing, public open space or other uses such as 'parklets' that facilitate local businesses;
- The changes in transport and land use will *improve accessibility, reduce the individual, social and environmental costs of travel and improve housing affordability*.

6. Case Study: Transformation of Sydney

What could the City of the Future look like? To explore that question, we examine an Australian city, Sydney, which is a medium sized city (on the world scale) in terms of population, but which is still very car dominated.

Sydney is Australia's largest city, with a population in 2016 of 4.6 million. It is also one of the world's fastest growing cities, with population increasing by 25% over the last twenty years.

Founded in 1788, Sydney grew rapidly in the first railway age, developing around an expanding tram and suburban rail network. Indeed, Sydney's trams moved more people in 1944 than all current light rail systems in the US put together. While the trams were replaced from the 1950's with buses, a large suburban rail system survived, which has over 200 stations, 2,000 double-deck rail carriages, and carried 360 million passengers in 2016.

Sydney was slower than most US cities to develop urban motorways, in part because of community opposition. However, between about 1970 and 2010 Sydney developed an extensive toll-way network, much of it in tunnels. During the same period, public transport investment was minimal. As a result, car travel came to dominate travel patterns by the turn of the century.

Forecasts by the Bureau of Transport Statistics a few years ago suggested that private car travel would continue to dominate urban travel patterns, notwithstanding the trend back to mass transit since 2005 noted earlier.

However, after forty years of neglect, Sydney is now also investing A$20 billion in its rail and public transport systems. Major projects are outlined below:

- A new 24 km automated metro line is under construction to the North-Western suburbs and will open in 2019, a second extension through the CBD to the south-western suburbs is also under construction and is due to open by 2024, and a third metro line has been announced and is currently being planned for completion by the late 2020s;
- The existing large-scale "suburban rail" system, which includes a small underground section in the city centre, is also being upgraded with additional rollingstock and improved services;
- The Inner West light rail line was extended a few years ago, with patronage quadrupling to 10 million passengers. A new CBD and South-East light rail line is now under construction, also to be opened in 2019—it will feature the longest trams in the world and is likely to carry at least 50 million passengers annually from its opening. A third light rail system has been announced for Parramatta, due to open by 2024–2025;
- The bus system has been modernised and frequencies increased with metro buses, and a major new busway is planned for the Northern Beaches;
- A second ferry terminal in the CBD has been recently opened with additional ferries being added to the fleet.

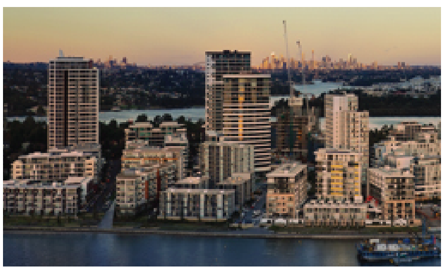
In addition, Sydney finally implemented its "OPAL" smartcard ticketing system in 2012, making travel by public transport much more convenient, especially for multimode trips. As a result, public transport patronage has increased by over 30% in the last six years, and the rate of increase has recently accelerated.

Indeed, as noted in a recent report by the Auditor-General, train patronage increased by nearly 11% in 2015/6, bus patronage by 12% and light rail patronage by 60%, compared with a year earlier (see Table 1).

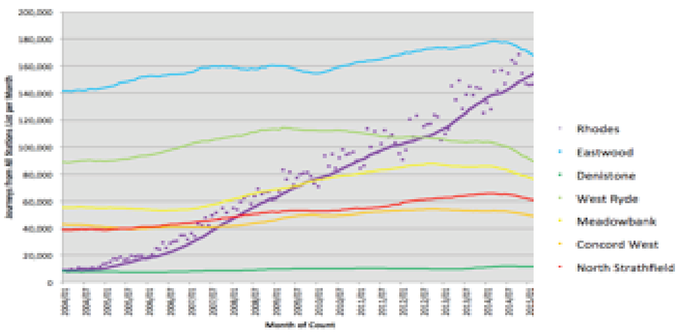
Another factor behind the rapid rise in public transport usage has been higher density development around existing public transport nodes. Figure 13 below shows

Table 1. Public transport patronage in Sydney (millions) 2009–2010 to 2015–2016. Source: Transport for NSW (2017).

Year	**2009/10**	**2010/11**	**2012/13**	**2013/14**	**2014/15**	**2014/15**	**2015/16**
Rail	289	294	302	306	312	326	361
Bus	210	214	219	220	224	257	290
Light rail	3	3	4	4	4	6	10
Ferry	14	15	15	15	16	15	15
Total	516	525	540	545	556	604	676
2009/10 BAS	**100%**	**102%**	**105%**	**106%**	**108%**	**117%**	**131%**



High rise development at Rhodes.



Boardings at Rhodes and neighbouring stations.

Figure 13. Impact of transit-orientated development on patronage. Source: Transport for NSW (2017).

one example—high rise units around Rhodes station, about half way between the CBD and the growing second CBD of Parramatta. Figure 13 shows the rapid growth in patronage at Rhodes station, which has increased 16-fold in a decade to over 5,000 boardings per day.

With the upgrades to rail, light rail, bus and ferry either under construction, or announced and in detailed planning, the authors estimate that Sydney's public transport patronage could potentially double in the next fifteen years to almost 1.3 billion passengers by 2030 (see Figure 14).

While this would be impressive, it would still leave Sydney as a relatively car-dependent city in 2030. However, with further investment in mass transit over the subsequent 25 years, and with the intelligent use of autonomous vehicle technology, Sydney could be a very different city by 2056. If these kinds of growth trends were the basis of urban growth it would be possible to essentially phase out oil from Sydney's passenger transport system.

The State Government has recently updated its transport plan for Sydney and extended it to a "vision" for 2056 (see Figure 15). This vision assumes Sydney will evolve into a region of 8 million population, with three connected sub-regions, the Eastern City centred on the traditional CBD, a Central Sydney based on Parramatta, and a Western City based on the opportunities around the Second Sydney Airport together with further devel-

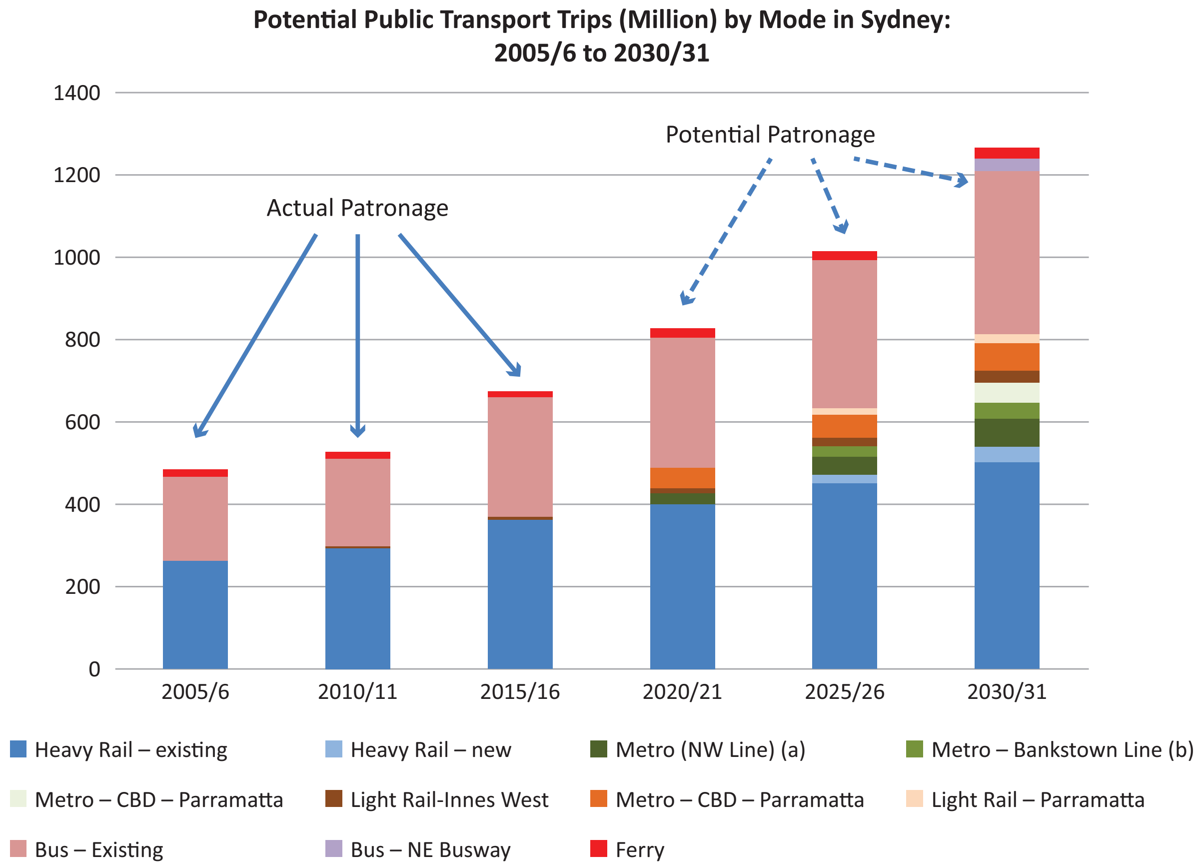
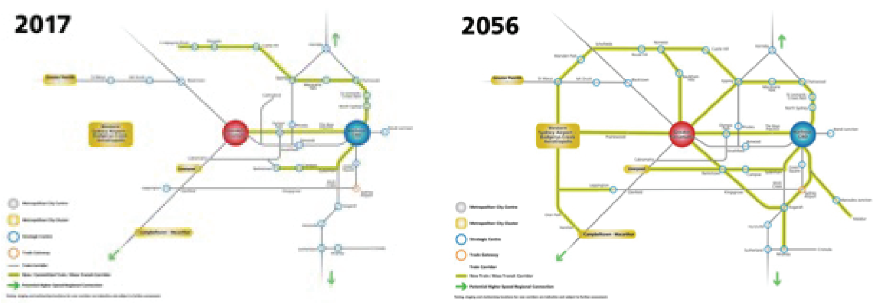


Figure 14. Actual and potential public transport patronage growth in Sydney: 2005–2006 to 2030–2031. Source: Transport for NSW (2017).



Sydney's mass transit system. Left: existing and committed links; right: vision for 2056.

Figure 15. Current and potential future mass transit system for Sydney. Source: Transport for NSW (2017).

opment at sub-centres including Penrith, Blacktown and Campbelltown. Each city would have a range of heavy rail, metro and light rail links, and the three centres would be located along the Metro West project, currently in planning. In addition, the 2056 vision assumed development of autonomous vehicles, which in conjunction with mass transit, will replace many private car trips.

A somewhat modified proposal for 2056 by the authors below shows how freight as well as high speed rail, together with a more extensive light rail network, could further enhance this vision.

Figure 17 shows the amount and shares of travel in Sydney in 2056 by different modes which would be possible under such a scenario. This assumes that over the next forty years:

- Population grows by 60% (average componund growth rate of 1.2% pa) to 7.5 million;
- Average Trip length decreases by 10% (with better distribution of employment etc);
- Total Travel (Passenger-kms) on Mass transit quadruples by 2055/56, with an average compound growth of 3.6% pa over the next 40 years;
- 20% of private car trips shift to shared-use autonomous vehicles and mass transit by then.

Under this scenario, total CO2 emissions from urban passenger transport could be almost eliminated, assuming by 2056 that 100% of all electricity in the Eastern Australian Grid is generated from solar, wind, hydro, geothermal or other forms of renewable energy, and that 90%

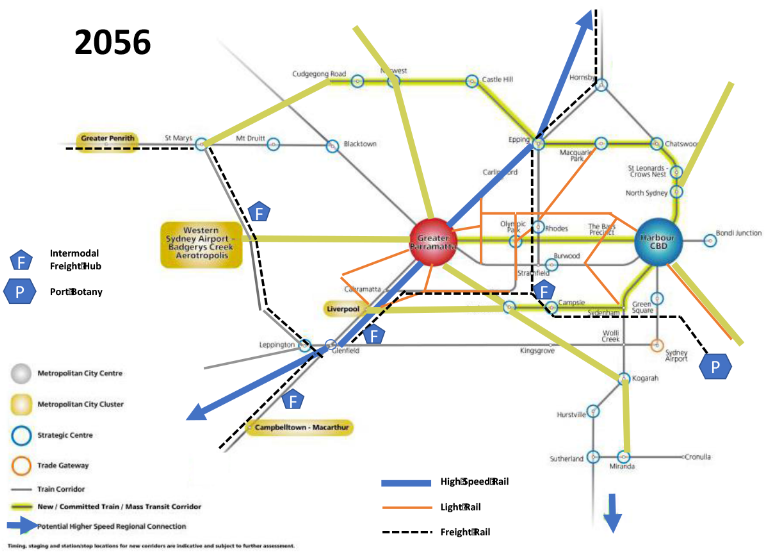


Figure 16. Modified potential future mass transit system for Sydney. Source: Transport for NSW (2017) and authors.

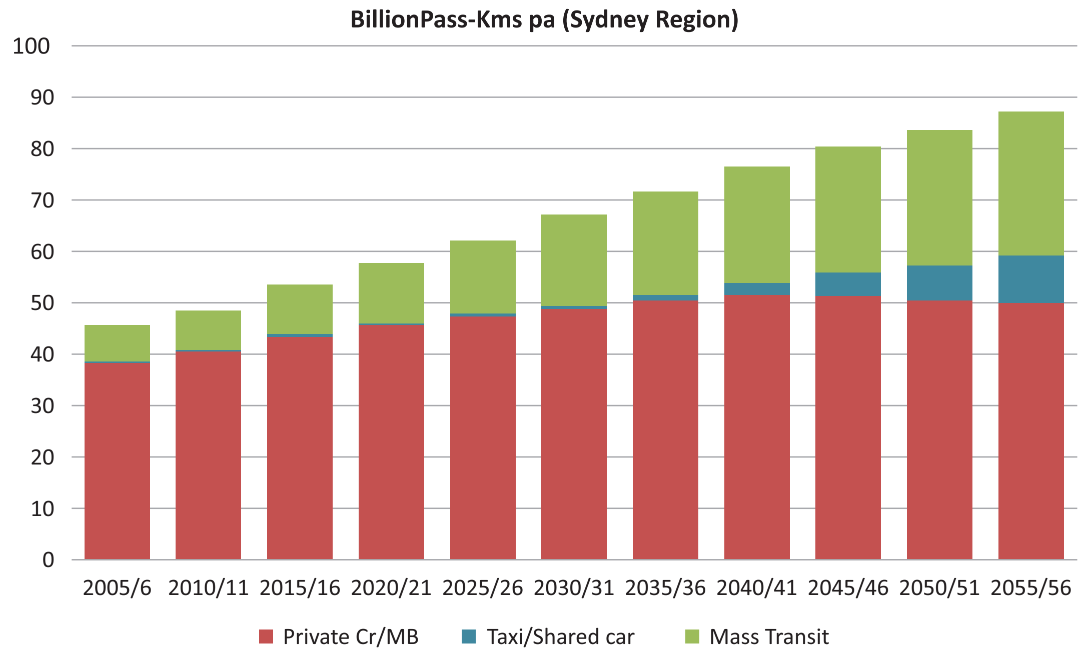


Figure 17. Potential future trends in travel in the Sydney region. Source: Transport for NSW (2017) and authors.

of all cars, buses and taxis are electrically powered by then. In addition, total private car traffic would level off after about 2030, notwithstanding the continuing population growth, suggesting no need for additional urban freeways beyond those currently under construction.

7. Making It Happen: How Government Can Act

Cities are built by a combination of public and private investment. But while the private sector is essential, the public sector plays a crucial role in determining the shape and overall liveability of the city for its inhabitants.

The previous discussion has outlined how we can transform our cities. How can governments encourage this transformation? The following are suggested:

- Slow or stop investment in urban motorways (Gaynor et al., 2017);
- Accelerate investment in mass transit systems, especially electric rail-based systems, including through new partnerships with the private sector (Newman et al., 2017);
- Encourage integrated development around rail stations and other key transit nodes and discourage further development remote from rail corridors;
- Provide walkable town centres and safe cycle-ways for local travel, including access routes to town centres, schools and transit hubs;
- Encourage the development of companies or nonprofit community organisations which can be Citizen Utilities as well as own and operate fleets of shared local mobility services, autonomous electric cars and small electric buses to act as feeders to transit hubs from areas outside the walking catchments;
- Enable the rapid general introduction of electric vehicles, both cars, buses and e-bikes with recharging facilities based on solar energy;
- Gradually introduce road pricing and parking policies to encourage people to reduce their private car ownership and use and help pay for infrastructure;
- Accelerate the transition from coal and gas-fired electricity to renewable energy, especially rooftop solar in all new residential and commercial urban developments, especially new green transit oriented developments;
- Facilitate the involvement of new governance along corridors of sub centres based on alternative funding and financing of electric rail systems and associated transit oriented developments through new urban partnerships.

The integration of all these policies into urban planning and development is possible if governments at all levels set up partnerships with private financing (especially superannuation companies looking for long term investments), developers (who understand markets and innovation in urban development) and communities (who know what they want for their precincts and neighbourhoods for the long term). This kind of partnership which integrates rather than does urban development based on separate silos of professional practice and sectoral advice, has been rapidly growing across the world (Clark & Clark, 2014; Newman, 2016). This is particularly important for the kind of urban developments outlined here for the City of the Future and new ways of bringing the partnerships together are being created that use private funding to help with the big capital costs of transit building (Newman, Davies-Slate, & Jones, 2017)

In Australia, the new partnerships are being called City Deals following the approach taken by the UK but with more specific requirements to enable:

- Partnerships with three levels of government that set out the plan for the City Deal;
- Community support for the projects;
- Private involvement in the financing through integration of land development and transit, backed up with some funding from local and state government and a risk guarantee from the national government.

The outcomes of the City Deals need to show transformational urban development with clear provision of affordable housing and sustainability objectives including the commitments to decarbonizing development. Such City Deals put urban planning firmly on the national agenda and demonstrate how the City of the Future can be created.

8. Conclusions

For the last 60 years, motorways were seen in many cities as essential tools to "unblock" the arteries of the city. But experience has shown that without matching investment in mass transit, and policies to manage car use, this only led to unconstrained urban sprawl and a range of environmental, health and other side effects.

One of these is the growing contribution of transport, especially car use, to global warming. Even without this threat, the motorway model of urban development has been seen to fail. The added pressure to deal with climate change provides an opportunity to re-envision how our cities and their transport systems can be built to improve environmental, social and economic outcomes.

The key is to use new technologies intelligently, building organically on the urban fabric of the past, and to see the privately owned and operated car as a luxury we no longer need or can afford. Cars certainly have their place and their two-dimensional flexibility will always make them an attractive and in some cases efficient option for cross-suburban travel. But they are not ideal for travel to centres or places of high concentrations of activities. For that, mass transit has shown it is the preferred solution supported by high quality and walking and cycling infrastructure to support intensive urbanism in centres. At the same time, the transition from privately owned petrol or diesel cars to community owned autonomous electric vehicles, as well as to bicycles and small electric vehicles, in combination with much greater use of mass transit, provides a unique opportunity for citizens to reclaim their cities from the dominance of the car. The City of the Future is likely to have an electricity system that is totally renewably powered and a passenger transport system that is completely electric. Nothing short of this is required given the climate crisis we face. It is also a city with significant attractions for social and economic opportunities that cities have provided for centuries and which they will need to provide for the future.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Financing Indian Urban Rail through Land Development: Case Studies and Implications for the Accelerated Reduction in Oil Associated with 1.5 °C

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Abstract

Urban travel demand and oil dependence need dramatic change to achieve the 1.5 °C degree target especially with the electrification of all land-based passenger transport and the decarbonizing of electric power. In this article we investigate the transition of 'oil-based automobile dependence' to 'urban rail plus renewable energy' to cater for transport demand in Indian cities. India is perceived to be a key driver of global oil demand in coming decades due to the potential increase in car use driven by a fast growing national average income. However, it is possible that India could surprise the world by aggressively pursuing an electrified transit agenda within and between cities and associated supporting local transport with electric vehicles, together with renewable power to fuel this transport. The changes will require two innovations that this article focuses on. First, innovative financing of urban and intercity rail through land-based finances as funding and financing of such projects has been a global challenge. Second, enabling Indian cities to rapidly adopt solar energy for all its electrified transport systems over oil plus car dependence. The article suggests that Indian cities may contribute substantially to the 1.5 °C agenda as both policies appear to be working.

Keywords

Keywords: 1.5 °C agenda; cities; climate change; India; renewables; substantially; urban rail; urban travel

Issue

This article is part of the issue "Urban Planning to Enable a 1.5 °C Scenario", edited by Peter Newman (Curtin University, Australia), Aromar Revi (Indian Institute for Human Settlements, India) and Amir Bazaz (Indian Institute for Human Settlements, India).

1. Introduction

Urban travel is the largest source of global transport related greenhouse emissions as well as associated issues such as air pollution. This is due to the urban travel being oil based and automobile dependent (Rode et al., 2014; Van Audenhove, Korniichuk, Dauby, & Pourbaix, 2014). The Intergovernmental Panel on Climate Change, chapter on Transportation (Sims et al., 2014), notes that reduction in transport sector emissions is critical to achieve the future climate change goal such as the 1.5 °C target suggested as the preferable limit to be addressed under the Paris Agreement. Electrification of all land-based passenger transport and the decarbonizing of electric power will be required to help achieve the 1.5 °C target; this has been clearly stated as the necessary and fundamental change needed in all urban systems and has been agreed to by the nations of the world in the Paris Agreement. This article will try to show urban rail can play a significant part in this transition due to its ability to replace car use and its ability to create new funding opportunities through rail-oriented land development due to land value uplift.

Urban rail has shown its potential to simultaneously electrify transport and help reduce the occurrence of automobile dependence. Urban rail can also help increase economic development in cities as urban rail facilitates the creation of dense urban centres with walking and transit urban fabric that are known to help with new economy jobs and other social, economic and environmental outcomes (Matan & Newman, 2016; Newman, Kosonen, & Kenworthy, 2016). One example from Glaeser and Xiong (2017) is of the Chicago stockyard where people and businesses have clustered around the associated rail stations. Such clusters attract additional business and lead to innovation due to the proximity of people and access to a large labour resource (Glaeser & Xiong, 2017). Knowledge economy jobs are particularly attracted to such transit-oriented centres of activity (Newman & Kenworthy, 2015; Yigitcanlar, 2010). Also, the energy intensity of rail transport is only about 15% of that of traditional cars, 50% of electric vehicles and 50% of buses (Lu, 2015). The major difference in the climate change debate is that urban rail is already mostly electric and therefore can be based quickly on renewable power. Thus, infrastructure investments that encourage rail may therefore lead to significant emission reductions in cities (Hoen et al., 2017).

If urban planning is to help with the 1.5 °C agenda it would need to facilitate the transition from oil-based automobile dependence to renewable electrified rail transit though this may not be a simple or linear process, especially in emerging cities like in India. This article will look at whether the process is underway in Indian cities where considerable momentum to remain in an oil-based transport system has been the agenda for many decades. The article begins by looking at the overall picture in India with respect to fossil fuels and economic growth in comparison to other nations before examining the first Indian cities that have attempted to begin to build electric rail mass transit systems and use more solar in their systems.

The process of decoupling economic growth from use of fossil fuels is at the heart of the 1.5 °C agenda. This process is already underway and the data on decoupling growth in wealth from growth in fossil fuels is now clearly showing not just a relative decoupling but an absolute decoupling globally and in most developed nations and cities (Newman, 2017a, 2017b; Newman, Beatley, & Boyer, 2017). See Figure 1a on Denmark, which is perhaps a leader in the developed world though most European nations are similar and even America and Australia are now moving down this path.

However, the decoupling in China (Figure 1b) and India (Figure 1c) now becomes the key focus for global policy as their coupled growth can easily make the 1.5 °C target impossible for the world due to their size and their leadership in the emerging world. The decoupling in China is led by strong top down policies and bottom-up demand in their major cities which has led to rapid declines in coal and oil growth (Gao & Newman, 2017). But India is less obviously decoupling and seems more poised to go either way; it is relatively decoupling and thus is demonstrating potential to go into absolute decoupling of wealth from coal and oil but could just continue growing also. Which outcome is likely is the underlying motivation behind this article.

This article will look at India and its growing cities to see whether a similar rapid decoupling trajectory can happen and whether the seeds for this transition are already present. The article will discuss the case of how Indian cities can contribute to the 1.5 °C target through its rapid growth in electric urban rail and its commitment to solar. The transition is being formally expressed as: from 'oil-based automobile dependence' to 'urban rail plus renewable energy' whilst continuing to cater for transport demand in Indian cities. The changes will require two innovations that the article focuses on. First innovative financing of urban and intercity rail through land based private investment as funding of such projects has been a global challenge and is one India is now taking on. Second, enabling Indian cities to rapidly adopt solar energy for all its electrified transport systems rather than fossil fuel based. The article further briefly discusses electric vehicles (EV), collaborative consumption and urban planning implications that would contribute to the future ability of Indian cities to contribute to the 1.5 °C agenda.

2. India's Urban Transport Demand and Oil

Urbanization is essential for driving economic growth (Glaeser, 2011). India is set to witness rapid urbanization in the next four decades with accompanying economic growth. India's urban population is projected to increase from 377 million in 2011 to 600 million by 2031. This would mean India will have 87 cities over a million population by 2031 from the 50 in 2011. The predicted urbanization and economic growth in India would possibly be the largest national urban transformation of the 21st century (Ahluwalia, 2011; Ahluwalia, Kanbur, & Mohanty, 2014; Heilig, 2012; WBG, 2017).

India is predicted to play a key role in future oil demand growth due to increased car ownership driven by high income growth. While the proposed oil consumption has been anticipated by the Organization of the Petroleum Exporting Countries it would however result in financial and environmental adversity for India and would be a significant setback in assisting achieve the Paris Agreement. Financially it will be a problem as India imports over 75% of its total crude oil resulting in energy security, trade deficit and foreign exchange issues. Environmentally it is an issue due to air pollution that has been a significant public health issue in all major Indian cities. Traffic congestion, noise and associated externalities are attached to the predicted automobile increase as well. It is also essential for Indian cities to avoid oil-based automobile dependence in order to fulfil their Paris Agreement and make progressive steps towards the 1.5 °C target (International Energy Agency, 2015; Van Moerkerk & Crijns-Graus, 2016).

Private vehicles in Indian cities are dominated by two-wheelers and cars. Two-wheelers are the dominant private mode with over five times the number of two-wheelers than cars in 2015.[1] High dependence on private

[1] The mode shift from two-wheelers to transit has higher probabilities than car that help in the growth of transit, especially rail based.

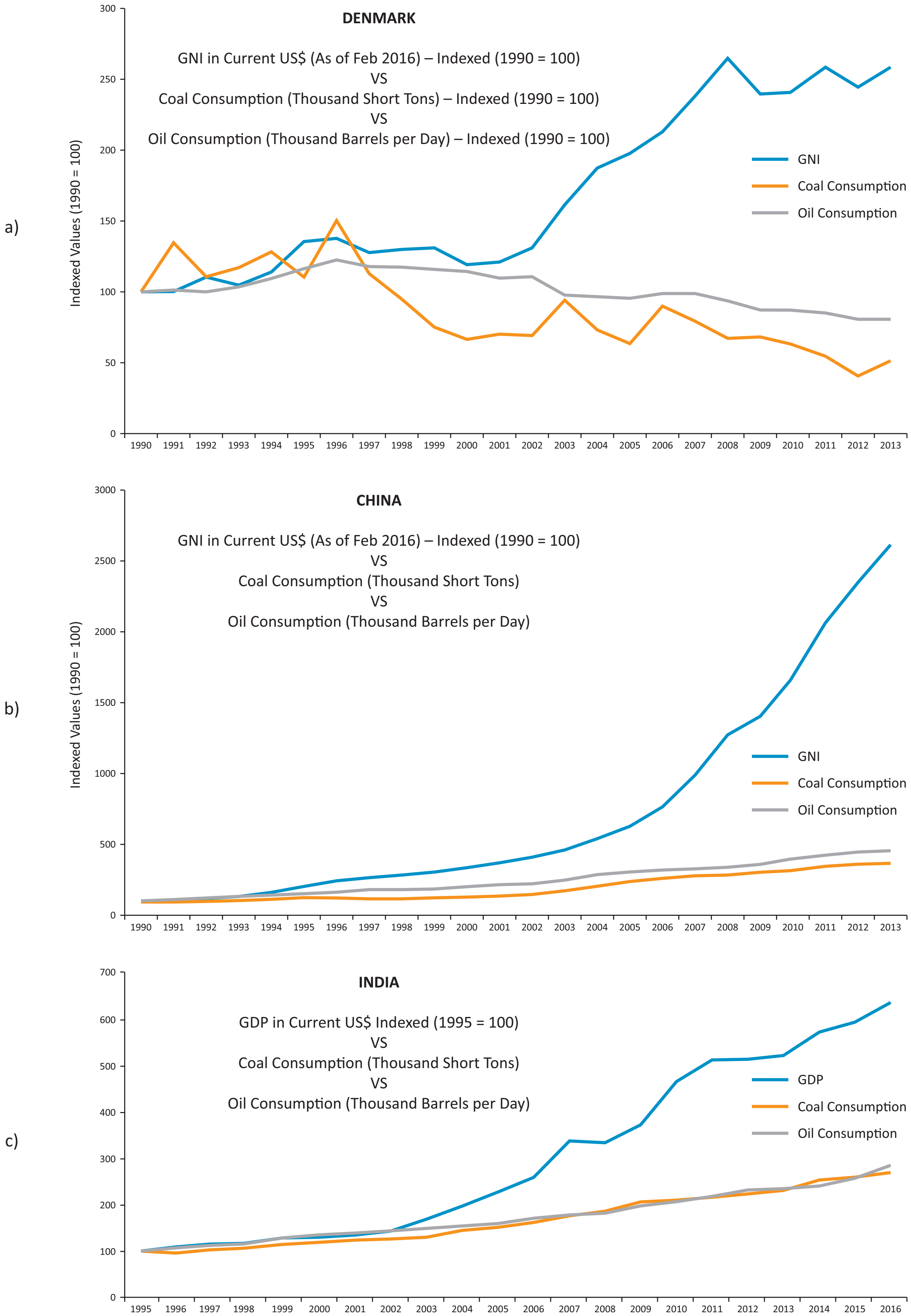

Figure 1. Decoupling wealth from coal and oil in Demark (a), China (b) and India (c). Note: GNI stands for Gross national income, which is almost equivalent to GDP but is more available in terms of data. Source: Compiled by author based on data sourced from CEID (2017), United States of America Energy Information Administration (EIA, 2016), Ministry of Petroleum & Natural Gas (2017), Newman (2017b), OPEC (2016) and The Worldbank Group (WBG, 2016).

vehicles has happened in the last two decades with a subsequent decline in public transport share but not totals as every available mode has been crowded with people during the rapid growth of Indian cities. 85% of the total private vehicles registered in India has happened between the years 1991 to 2011. The private vehicle growth rate has been over 10% annually which is one of the highest globally; however, India is still low in-terms of per capita vehicle ownership on a global scale.[2] The growth rate has been largest associated with high increases in income (Ahluwalia, 2017; Dhar & Shukla, 2015; Goel, Mohan, Guttikunda, & Tiwari, 2016).

Goel et al. (2016) show that registered vehicles in India are highly overestimated; they suggest that the actual number of in-use vehicles compared to officially registered is out by over 120%. The findings of Goel et al. (2016) indicates that the wealth increase leading to vehicle ownership may not essentially mean the increase of private vehicle km in Indian cities. To understand this further I have plotted historic growth rates in Figure 2 of the gross domestic product, oil consumption, car registration and road length in India.

Figure 2 indicates that there has been exponential growth of car registration even more than the GDP growth. But this has not resulted in road length increase or increased oil consumption levels. This is consistent with the earlier Figure 1c which shows wealth is being relatively decoupled from oil. The big question is whether this can be turned into an absolute decline in oil.

2.1. Automobile Saturation in Indian Cities?

At a macro level (from Figure 2) it seems that Indian cities have intrinsic features that could be acting as a 'soft power'[3] to hinder the growth of vehicle kilometre travelled as compared to car registration. One possible factor is limited road space in Indian cities as like many emerging cities they are historically walking cities with all that associated fabric in density and mixed use (Newman et al., 2016).

As per the Census of India (2011) about 24% of the population work from home,[4] 23% walk to work, 13% bike to work, 19% use public transport, 4% use a car and 17% use two-wheelers to go to work in Indian cities. A quarter of commuters travel less than 1 km and another third travel between two and five km. This travel pattern shows that the majority of workers do not use any motorized mode to travel to work and travel short distances—reflecting the dense walking fabric and mixed land use in Indian cities (Rode et al., 2014; Tiwari, Jain, & Rao, 2016). Thus, Indian cities need to invest significantly to improve and build their walking and cycling infrastructure which is in poor condition and do not even cover major transit/road corridors in order to improve walking fabric (Ministry of Urban Development, 2013). An increase in walking and cycling mode share is critical for achieving climate changes goals in cities and as mentioned before in this article urban rail can facilitate this increase due to its ability to replace car use and its ability to

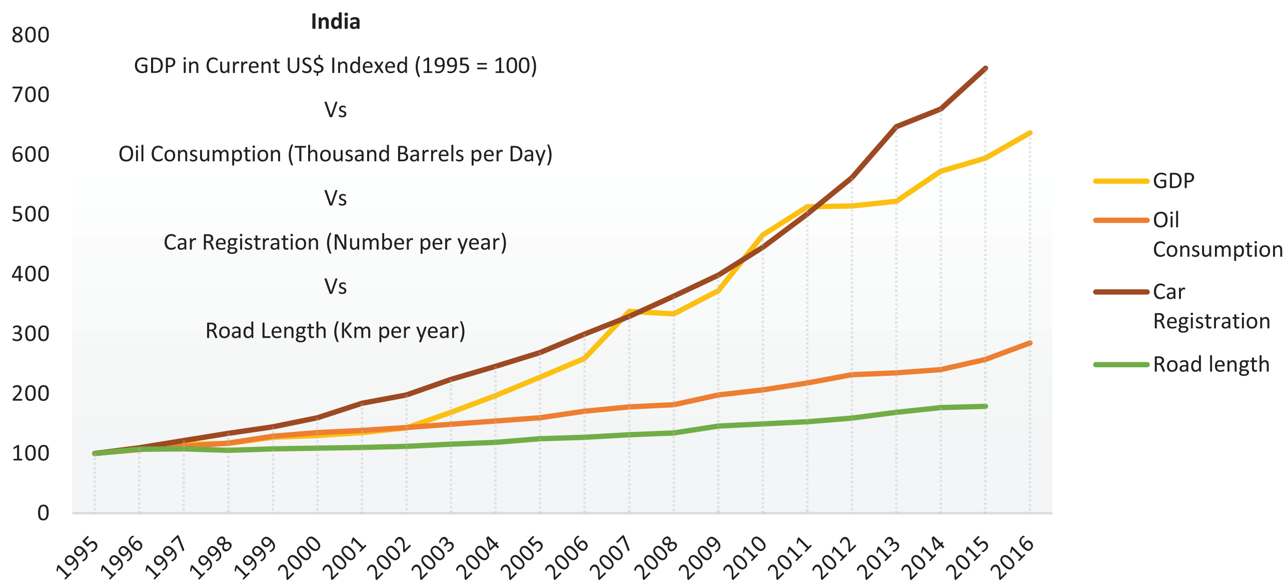

Figure 2. Historic growth rates of GDP, oil consumption, car registration and road length in India. Source: Compiled by author based on data sourced from CEID (2017), EIA (2016), Government of India (2017a), Ministry of Petroleum & Natural Gas (2017), OPEC (2016) and WBG (2016).

[2] India's car ownership is about less than four times of China and less than twenty-five times of OECD countries.
[3] For this article we used the term 'soft power' (inspired from Joseph Nye's work) of cities: characteristics of a city to influence the travel behavior without push or coercion (Nye, 2004).
[4] This could be possibly due to the traditional houses having shop and house on the same land, small business like tailors, tradesman and others are located within the residence.

be funded from the facilitation of transit oriented developments due to the increased value in land around rail stations (Newman & Kenworthy, 2015; Sharma & Newman, 2018).

The 'soft power' characteristics of Indian cities—travel pattern, road length growth, and dense, mixed use urban fabric, seem to be the factors that could have ensured the start of decoupling wealth and car use. Even with a small per capita car ownership the urban fabric of Indian cities has resulted in high traffic congestion and low travel speed thus minimizing growth in the use of cars. It also suggests that without a massive road building program that completely alters the urban fabric (as happened in US cities) there is unlikely to be much more ability of Indian cities to cope with high traffic growth.

The travel speeds of private vehicles in various large Indian cities during peak hour is less than 15 km/hr in most major corridors. This means that even the most basic of urban rail expansions and building would enable Indian residents to travel faster than in the road traffic.[5] Urban rail in Indian cities has an average speed of over 35 km/hr. This would suggest that the big problem is automobile-saturation in Indian cities rather than automobile dependence as is the case in some Chinese cities (Gao & Newman, 2017; Sharma & Newman, 2017a). This is an easier problem to solve as the attraction of urban rail when it is built will be immediate and long lasting.

If the trend to decouple oil from wealth is to continue and accelerate into an absolute decoupling, then Indian cities will need to focus on building a lot more urban rail. As suggested here large Indian cities are looking for fast urban rail solutions to help overcome traffic problems which will increase the urban rejuvenation potential in their dense areas and land development opportunities. The question is whether the political will is there and whether financial mechanisms are available to make it happen.

2.2. Public Transport and Economic Growth in Indian Cities

The strong link between public transport and economic growth has become a major part of national and urban policy in recent decades (Glaeser, 2011; Glaeser, Kahn, & Rappaport, 2008). This is now being widely recognized by Indian cities. Public transport service levels are currently low in Indian cities with a significant public transport supply gap of 240%. This has contributed to the 21% mode share of private transport and 19% mode share of public transport. However, Mumbai's suburban rail is an example of how private vehicle use is restricted without it restricting economic growth (Government of India, 2014; Newman & Kenworthy, 2015; NITI Aayog & Rock Mountain Institute, 2017).

Mumbai's suburban rail-dominated public transport has restricted private vehicle use to 12% as compared to the 40% mode share for private vehicles in Delhi and Bangalore which had no significant urban rail presence in 2011 (Census of India, 2011). A brief analysis of CO_2 emissions in Mumbai, Bangalore and Delhi show that if Bangalore and Delhi achieve similar mode share to Mumbai, which is dominated by rail, Delhi can cut urban transport emissions by 40% and Bangalore by 34%. This analysis is based on Census of India, 2011 data for passenger km and CO_2 intensity has been referred from Dhar, Pathak and Shukla (2018) as presented in Table 1.

Mumbai's low road density, high density of cars per km and high population density among all major Indian cities seems to have resulted in automobile-saturation and hence the dominance of transit mode share at about 79% (Rode et al., 2008; Census of India, 2011). Mumbai has the highest per capita income, quality of life and productivity among all major Indian cities (UN-HABITAT, 2012) coinciding with the analysis of global cities on wealth increase and vehicle km growth by Newman and Kenworthy (2015). Mumbai shows how a rail based urban transport can cut emissions and increase wealth. The Indian government recognizes that densification linked with public transport is essential to sustain urbanization and economic growth (Ministry of Urban Development, 2014). This recognition has resulted in effective policy formulation at the federal government level paving way for over 50 Indian cities to plan for urban rail.

Chauvin, Glaeser, Ma and Tobio (2017) shows that there is a high correlation between density and earnings across Indian cities, that is stronger than in the U.S. cities.

Table 1. Passenger km and CO_2 intensity in Mumbai, Bangalore and Delhi.

	Mumbai & Suburban	Bangalore	NCT of Delhi	
All Modes	**Passenger km (million)**			**CO_2 Intensity (tCO_2/M pkm)**
Moped/Scooter/Motor Cycle	1.9	6.9	7.8	31.9
Car	2.9	4.5	8.5	99.1
Bus	7.4	9.9	14.2	14.6
Train	21.5	0.5	3.0	14

[5] The travel speed and passenger carrying capacity per lane of urban rail is much higher than rubber-based transit. For this article rubber-based transit is not discussed as an option; this is seen as the mode which can help as a feeder to urban rail where the last mile distances are above 1–2km. The potential of urban rail to create high density transit orient development centres would mean walking as a main access mode to rail also and this is better for the 1.5 °C agenda. Cities will always need to invest significantly to improve walking and cycling infrastructure around mass transit.

Cities with higher density also tend to be more productive and have higher quality of life parameters. This density and income would be further facilitated with India's plan to implement urban rail in over 50 cities with aligned policies of land value capture (LVC) and density.

3. India's Plans for Growth in Urban Rail

In rapidly growing Indian cities urban rail has emerged as an efficient and reliable solution to cater to urban travel demand. The growth of India's modern urban rail system has happened in the last decade after the transit-success of Delhi Metro (started in 2002). Urban rail, in August 2017, is operational in 11 cities and under construction in another nine cities. Indian cities have added 370 km operational urban rail and another 556 km is under-construction in the period of 2002–2017. This is far behind China's over 3,000 km of urban rail most of which was built in the past decade.

Indian cities have extensive plans (712 km) for urban rail as shown in Table 2. Delhi's 467 km urban rail network is planned to be constructed by 2021 and around 60% of the city would be within 15-minute walking distance from the network. Mumbai Metropolitan Region plans to add over 192 km of urban rail network in addition to the existing 465 km of suburban rail by 2021 (Delhi Development Authority, 2007; Government of India, 2017b; Kai, Baoming, Fang, & Zijia, 2016; MMRDA, 2017).

This growth is driven by demand for urban rail travel and supported through political leadership. The Indian government has been financially supporting urban rail since 2011 in cities with a population over two million but this norm has been reduced to one million to extend this benefit to medium size cities (Sharma & Newman, 2017b). This is a good outcome for the 1.5 °C agenda though it may not have been a part of the rationale for this decision.

Globally UIC, the International Railway Association

Table 2. Urban rail network in Indian cities.

Sl No.	City	Population (in million)	Urban Rail Project Name	Urban Rail Network in km: Operational	Under Construction	Planned
1	Delhi	16.3	Delhi Metro	218	179*	148*
2	Noida	0.6				
3	Ghaziabad	1.1				
4	Faridabad	1.4				
5	Gurgaon	8.7				
			Rapid Metro	12	0	0
6	Mumbai	12	Mumbai Metro	11	124	57
			Mumbai Monorail	8	0	0
7	Kolkata	4.4	Kolkata Metro	28	113	
8	Chennai	4.6	Chennai Metro	28	19	104
9	Bangalore	8.4	Namma Metro	42	34	57
10	Kochi	0.6	Kochi Metro	13	26	37
11	Jaipur	3	Jaipur Metro	10	2	23
12	Lucknow	2.8	Lucknow Metro	0	33	140
14	Hyderabad	6.8	Hyderabad Metro	0	72	168
15	Nagpur	2.4	Nagpur Metro	0	19	38
16	Gandhinagar	0.2	Metro-Link Express for Gandhinagar and Ahmedabad	0	19	38
17	Ahmedabad	5.5				
18	Kanpur	2.7	Kanpur Metro	0	24	38
19	Navi Mumbai	1.1	Navi Mumbai Metro	0	11	12
20	Pune	3.1	Pune Metro	0	60	0
Total		**84.6**		**370**	**556**	**712**

Note: * includes Noida Metro and Ghaziabad Metro projects. Source: Compiled by author based on data from Census of India (2011) and Ministry of Urban Development (2013, 2014).

(with 240 members worldwide), has proposed to improve the energy efficiency of the rail sector by a 50% reduction of final energy consumption from train operations by 2030 through technical measures, improved management, decarbonization of energy consumption and better use of existing rail assets. There are further energy savings to be achieved by using lighter weight/composite materials (30% potential energy savings), and by optimizing energy recovery devices (up to 45% potential energy savings) and train operation management (Hoen et al., 2017). All these will contribute to the 1.5 °C agenda and will reduce the life cycle emissions of urban rail.

4. The Problem of Urban Rail Funding

At the time when urban rail investment appears to be a priority for cities, governments across the world face budgetary pressure leading to challenges in the funding and financing of urban rail. Funding of urban rail through traditional gross budgetary support from the government seems increasingly difficult in the existing global economic scenario. This traditional way of urban rail investment will lead to a growing debt-subsidy cycle which would undermine economic development and minimize the possibility of India actually phasing out oil the way that the world needs in the 1.5 °C agenda.

Existing Indian urban rail systems are facing a financial deficit as they are highly dependent on fare box revenue and conventional budgetary support from the government, as has been the case globally. Urban rail agencies have significantly struggled to recover even operating costs through fare box revenue as it is inherently limited due to equity demands (Flyvberg, 2007; Jillella, Matan, Sitharam, & Newman, 2016; Sharma, Newman, & Matan, 2015). This has resulted in fare increases in Delhi Metro and proposed fare increases in Mumbai Metro which have created community and political dissension. Mumbai is one city where the fare box may have been possible to cover all costs but even here it does not. It is thus essential for Indian cities to explore alternative funding sources. However, the role of urban rail in facilitating the 1.5 °C agenda and creating better cities in general, is likely to be far more transformative than using other sustainable transport modes as it has an inherent ability to attract private funding through land development opportunities associated with rail systems. Urban rail's impact on land values and the potential of land development, rejuvenation and agglomeration benefits, suggest economic value can be captured by a range of LVC mechanisms (Banister & Thurstain-Goodwin, 2011; Capello, 2011; Newman, Davies-Slate, & Jones, 2017; Newman & Kenworthy, 2015; Sharma & Newman, 2017b).

LVC studies on urban rail projects provide evidence that both government and public private partnership (PPP) urban rail projects are financially viable and can maintain affordable fares through LVC-based funding mechanisms. Indian urban rail systems have shown significant uplift in land value at both a city and corridor level. Sharma and Newman's (2017a) hedonic price model on Bangalore Metro showed a 23% increase in land value in the 1 km catchment area of urban rail and of great significance it appears to have increased land values over the whole city by an average of 4.5%. A study on Mumbai Metro showed a 14% increase in land value for properties between 1 km and 2 km from stations (Sharma & Newman, 2018). Similar results were found on Chinese cities. Zhang, Liu, Hang, Yao and Shi (2016) panel data hedonic price model on housing prices of 35 Chinese cities from 2002 to 2013 showed that a 1% increase in rail transit mileage improves housing prices by 0.023% at the city level. This shows urban rail's crucial role on land values and hence how various 'beneficiary pays' mechanisms could be tapped to rapidly increase urban rail investment.

Not only is there a clear case that urban rail increases land value around stations but the project life cycle of urban rail systems with their associated land uses, are generally longer than any road-based system and hence can attract private investment as there are long-term financial and economic benefits when the transit, land use and finance are integrated. Private sector involvement can address this multidisciplinary integration by bringing innovation, technology, design stage efficiency, market driven land development skills, improved operational efficiency and long-term value for money through risk sharing. These latter skills are not readily available within government. Private participation in urban rail projects has shown efficient exploitation of non-transport revenues such as advertisement, station area development and kiosks/shops at stations along with bringing efficiency in construction and operations when involved from the design stage. Bigger projects which depend on even more land development for private investment opportunities, require even more obvious ways of incorporating private bids on how best to do it. Involvement of the private sector at design stages can also enhance budget predictability for government (Bowman & Ambrosini, 2000; Giuliano, 2004; Medda, 2012; Pojani & Stead, 2015; Sharma et al., 2015).

Governments are therefore seeking private investments and partnerships to implement urban rail projects. This is based on rail's impact on urban land values providing value creation potential thus enabling land development to provide the returns needed by the private sector. Privately financed urban rail is being proposed and debated globally including Australia, India, Canada and the US.

Hyderabad Metro is one such urban rail being built on a Design Build Finance Operate Transfer agreement wherein a private developer was provided about 10% of the capital cost as grant (equity) from the federal government of India and the state/provisional government granted air-rights for commercial development of about 12.5 million sq. ft. over the three depots and 6 million sq. ft. at the 25 selected stations. The private developer has raised capital through loans and equity. The private developer's concession period is for 35 years and the private developer was able to start renting the spaces before the rail was operational. This case shows the private sector's active approach towards enhancing revenue streams. This increase in non-fare box revenue may help maintain low transit fares in the long term based on a similar outcome that has been found in all of Japan's rail system and Hong Kong's Metro where private land development is used to keep fares low and fund the whole system (Newman, Davies-Slate, & Jones, 2017; Sharma & Newman, 2017b).

The Indian government recently approved three highly significant policies of relevance to the topic of this article: the National Transit Oriented Development Policy (Government of India, 2017c); the Value Capture Finance policy framework (Government of India, 2017d); and the Metro (urban rail) Policy (Government of India, 2017b). These policies were also necessary to realize the potential of significant investment in urban rail for future urbanization. Together these policies show the intent of the policy makers to enable density, urban rail, accessibility, urban agglomeration and land-based financing. These will assist in framing a supportive mobility oriented urban planning framework that can increase India's GDP by 1–6% (NITI Aayog & Rock Mountain Institute, 2017) whilst decoupling from automobile dependence and fossil fuels.

The Metro Policy of August 2017 (Government of India, 2017b) mandates Indian cities to involve 'private sector participation' and 'land value capture' in urban rail to access 10% equity funding from the federal government. Such approaches of mandatory private sector involvement will increase the private sector risk appetite. Private sector involvement from the concept stage for urban rail and land development can increase the redevelopment potential commitment from the private sector and lead the public sector to focus on their core role of governance including community engagement and partnership development. Community engagement should be seen as an essential component not an optional extra as this can enable political validation as well as improving local amenity through their detailed knowledge of needs and options and hence provide the basis for partnerships with government and business.

These are a significant set of policy decisions by the Indian government to maximize value creation from urban rail. This may also allow implementation of innovative contracting mechanisms such as the Entrepreneur Rail Model of Newman, Davies-Slate and Jones (2017). There are significant challenges for such processes to be implemented in Indian cities such as digitizing urban infrastructure maps, institutional integration in cities, land use and transit integration, land valuation (at plot level), digitization of land use maps and strategic planning frameworks. However, these are possible to add as the system grows and the key factor in tapping private funds to transform the urban rail market is to have the ability to create integrated partnerships between government at all levels and the private entrepreneurs in urban redevelopment as well as private rail operators. India has begun to do this.

The land development based financing and private sector participation outlined above is likely to help facilitate the expansion of urban rail in Indian cities, as long as urban planning tools are used to help and not hinder this process. This rail growth would enable economic growth while decoupling car use. Indian cities have the advantage that their walking and transit urban fabric are already ideal to be served by urban rail. Thus, these policies are likely to lead to a decline in oil consumption whilst enabling economic growth to accelerate. Urban fabric benefits should mean that the extra wealth will go into using easier ways to enable urban rail as happened in China, and wealth will come to be associated with 'rail not car'. These rail systems would need to be renewable based along with other modes of urban transport to contribute to the 1.5 °C target, we discuss these in the next sections.

5. Solar in Indian Rail

To contribute to the 1.5 °C target urban rail systems should operate on renewable energy, specifically solar in the Indian case. Electric urban rail systems are nonsite emitters. Their emissions depend upon the type of fuel used for the generation of electricity which is currently coal dominated in the case of India. However solar is rapidly competing with coal for Indian urban rail operations.

India plans to generate 175 gigawatts (GW) of renewable energy by 2022—100GW to come from solar. According to Morgan Stanley (2017) solar power is becoming more affordable than electricity generated from coal power generators. This is significant as India is the third-largest source of carbon emissions. The key argument for using coal was that it is affordable and accessible in India but now with solar being 18% cheaper than coal the Indian energy sector is on the edge of a major transformation (Farand, 2017). The Indian government has shown it intends to reduce coal consumption by doubling the 'Clean Environment Cess' on coal in year 2017 budget, and by initiating the International Solar Alliance which is envisaged as an inter-government treaty between solar resource-rich countries aimed at efficient exploitation of solar energy to reduce dependence on fossil fuels and to mobilize USD 1 trillion for it (Ministry of Finance, 2017; UNFCCC, 2017).

India has started relative decoupling in the past decade of Coal and GDP as shown in Figure 1c. The growth of coal has slowed and may change to an absolute decline as India invests strongly in renewables and urban electric rail. Ben Caldecott (2017) from Oxford University suggests that Indian power company's investments in coal are financially unviable whilst solar would be a future investment with many economic benefits. This suggests that Indian economic growth has clear potential to be based around renewable sources rather than fossil fuels leading into the future.

The most recent urban rail system of India—the Kochi Metro—has rooftop solar on all of its rail stations to meet 25% of its electricity requirement. Delhi Metro (urban rail) started in 2002 and thus had negligible solar panels then but now meets 80% of its daytime energy from solar (Energy World, 2017; Sood & Bhaskar, 2017). The recent decline of the cost of energy storage systems may assist the further use of solar energy for urban rail systems. New TODs being built around stations need to be covered in solar with battery storage in the area as is happening in various demonstration sites such as Bordeaux and Boulder, Colorado. The next generation urban rail systems are predicted to be powered by solar and batteries with electric power through high-powered contactless charging at stations (Newman & Kenworthy, 2015).

Indian Railways has also started the process to modernize their existing inter-city railway stations through PPPs. The modernization process will include mixed land use development, maximized solar energy utilization and a focus on non-fare box revenue. The proposed fast-rail along urban growth corridors in India, such as the Rapid Rail Corridor around Delhi, are incorporating solar energy and LVC within the planning and design stage of the project.

The Indian government in their 2017 budget has committed to install rooftop solar in 7,000 inter-city rail stations. This is a significant commitment. The first 300 stations have had solar panels installed (Ministry of New and Renewable Energy, 2017). A recent trial of solar panels on the roof of Indian trains has been made to reduce the energy requirement for wagon's lighting and fans but not for locomotives.

Electric trains with batteries are likely to be another trial especially in smaller trains. Newman (2017a) suggests that this transformation may happen much quicker as the demand for renewables is high and cost of solar and batteries are on a rapid decline curve. Economic growth appears to be substantially changing to being based around renewable energy rather than the fossil fuel-based economic growth of the past 15 years.

6. Electric Mobility

The EV market is growing globally at over 40% per year. In India there is currently a negligible presence of EV at 0.0004% of its total vehicles as compared to Norway's 23%, the Netherland's 6% and China's 1.4% share of EV (International Energy Agency, 2017).

India's National Electric Mobility Mission Plan recognizes that the growth of EV's is critical for the energy transition in India as this will reduce oil imports and help with the air quality problem. As part of the mission the Indian government is providing financial incentives, subsidies and tax rebates to EV users and manufacturers to increase EV presence in India. The Indian government has provided over 30 million USD subsidy for 154,557 EV as of August 2017. India's domestic manufacturing capacity of EV is growing with two-wheelers and cars. However, there is no manufacturing unit for electric buses despite some cities having introduced electric buses on a pilot basis (Dhar, Pathak, & Shukla, 2017; National Automobile Board, 2017).

India has set a goal of 6–7 million EV by 2020 which is higher than China's goal of 5 million. The recent target of India is for all-electric mobility by 2030. This ambitious goal is aimed to provide large economic benefits. NITI Aayog and Rock Mountain Institute (2017) notes that with electric and shared vehicles India can save 100 USD billion annually in fossil fuel foreign exchange and cut 1 GT carbon emission by 2030 (PIB India, 2017; Sharma, Kulkarni, Veerendra, & Karthik, 2016).

Unlike developed countries, EV in India are dominated by two-wheelers and recently by E-Rickshaws that act as an intermediate public transport for short distances (∼2km). Delhi's subsidy of 470 USD for each E-Rickshaw is significant for shared-electric public transport in that it also acts as a feeder system to urban rail such as Delhi Metro (Rokadiya & Bandivadekar, 2016). Such EV vehicles can be efficiently used in smaller Indian cities where travel distances are shorter.

The critical challenge for Indian cities in enabaling EV growth would be providing EV infrastructure in urban planning schemes. In 2016, India only has 328 publicly accessible charging stations which hasn't increased since 2014. Cities would need to play an active role in regard to EV infratructure and can start with pilot city projects as in the case of other countries. India's abundance of solar enegy potential is an opportunity as with only 1% land area of Rajasthan (Indian State) could power the entire EV fleet traffic by 2030 on solar power (International Energy Agency, 2017; PIB India, 2017).

7. Collaborative Consumption

Collaborative consumption is a growing world phenomenon.[6] It is likely to take over much of the growth in the private urban transport sector and create instead shared transportation options. Its most important function is likely to be the 'first mile last mile' service that links people to fast urban rail services. The shared systems can use smart cards to enable a combination of modes that can provide good mobility options including the urban rail services themselves. Thus the future is likely to see city rail and multi-modal local systems integrated around stations and centres. EV shared systems are already operating in many global cities and are on the rise with many cities planning for them. Cities with bike sharing schemes have increased from 4 in 2001 to over 1,000 in 2016 globaly (Tiwari, 2017).

[6] Collaborative consumption is phenomena born of the Internet age driven by information and communication technologies: the peer-to-peer-based activity of obtaining, giving, or sharing the access to goods and services, coordinated through community-based online services.

Technological advancements in recent years have resulted in several cycling start-up companies in India such as Zoom-Pedl, Mobike, Ola-Pedal, Mobycy and Yulu. Mobycy is a recent mobile-app based bicycle sharing platform which allows commuters to unlock a bicycle parked in a dockless way at public places through a mobile-app generated QR code. It has started operations in Gurgaon with a fleet of 5,000 cycles and plans to spread in other major Indian cities. This can contribute to reducing oil based transport along with the other innovations mentioned above.

8. Discussion: Urban Planning Implications

The transitions that are underway in Indian cities towards urban rail expansion, the involvement of private investment based on LVC through TODs, the rapid growth of solar and battery storage in new urban developments, the growth of EVs and shared mobility, are all subjects that need urban planning to facilitate. A series of structural reforms and policy interventions would need to follow from Indian cities to support this transition, all with a strong partnership between citizens, government and industry.

All the major tools of urban planning will be needed to help make Indian cities contribute to the 1.5 °C agenda as well as to develop economically and sustainably. Tools needed include:

1. Tools that ensure equity in housing policies and planning regulations to ensure that not only the wealthy benefit from transit systems and transit-oriented development;
2. Tools to ensure that pedestrian qualities and good building design are features of all the new development around stations;
3. Tools to ensure that transport, land use and finance can be integrated at all stages of the planning process.

A committee (Ahluwalia, 2011) of the Indian government notes that transport, land use and other urban infrastructure are not planned in an integrated way which makes the integration of EV, TODs and urban rail challenging. Shared EV would require parking spaces and integration with transit and publicly accessible charging stations that would need to be addressed in an integrated manner at the city level in urban plans. More importantly, as outlined above, urban planning needs to facilitate partnerships as much of the planning needs to begin with private sector involvement in highlighting the best redevelopment options that urban rail can unlock in a funding partnership.

Recent research on integration between information and communications technology and spatial planning technology is showing the potential to integrate energy, transport and urban planning. Such technologies may help cities create more integrated planning of urban infrastructure. This is on the government agenda in countries such as Australia (Commonwealth of Australia, 2017; Mosannenzadeh et al., 2017; Plume, Simpson, Owen, & Hobson, 2015; Yamamura, Fan, & Suzuki, 2017).

9. Conclusion

India has made a strong start on the transition from 'oil-based automobile dependence' to 'urban rail plus renewable energy'. The Indian government policy to make mandatory private participation and LVC may result in transformative higher density urban redevelopment projects that can fund many of these urban rail and solar projects. This would lead to greater economic gains and agglomeration benefits. Such processes may deepen the correlation of wealth, density and urban rail with reduced oil-based automobile dependency. The key issue will remain in the implementation of such policies and the financial viability of such projects, however Sharma and Newman (2017b, 2018) and the existing Hyderabad case suggest that with existing LVC legislation private-led urban rail can be financially viable.

The critical level of air pollution in Indian cities coupled with energy security issues can lead to rapid adoption of electric based transport modes in automobile saturated Indian cities. Considering the travel patterns in Indian cities the shared-EV, bike sharing and E-Rickshaws could potentially act as a feeder into any expanded urban rail system. This can cater for the majority of motorized travel in major Indian cities in coming decades. Innovative models of shared and connected urban transport systems with a high level of access to smart technology to end-users may enhance seamless integration of multiple modes within each city.

The continuation of these trends will require a combination of different forms of solar-based power and cities would need to integrate and organize such processes into urban planning schemes and different forms of urban fabric (Newman, 2017a, 2017b). As outlined, there are many signs of this beginning in India.

India has started relative decoupling of income and fossil fuel in the past decade which may change to an absolute decline in fossil fuels in coming years. Indian cities are thus likely to contribute to the 1.5 °C agenda based on their urban fabric (inherently low in automobile dependence), electric urban rail growth through financing from land development and public private participation, increased walking and cycling, and the commitment to solar/battery-based mass transit and EV.

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Conflict of Interests

The author declares no conflict of interests.

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Article

Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities

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Abstract
Consumption-based greenhouse gas (GHG) emissions inventories have emerged to describe full life cycle contributions of households to climate change at country, state and increasingly city scales. Using this approach, how much carbon footprint abatement potential is within the control of local governments, and which policies hold the most potential to reduce emissions? This study quantifies the potential of local policies and programs to meet aggressive GHG reduction targets using a consumption-based, high geospatial resolution planning model for the state of California. We find that roughly 35% of all carbon footprint abatement potential statewide is from activities at least partially within the control of local governments. The study shows large variation in the size and composition of carbon footprints and abatement opportunities by ∼23,000 Census block groups (i.e., neighborhood-scale within cities), 717 cities and 58 counties across the state. These data and companion online tools can help cities better understand priorities to reduce GHGs from a comprehensive, consumption-based perspective, with potential application to the full United States and internationally.

Keywords
carbon footprint; climate action plans; climate change; consumption; emissions inventory; greenhouse gas

Issue
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1. Introduction

Stabilizing the climate will require massive changes in systems of production and consumption (Hertwich et al., 2010), with widescale adoption of low-carbon technologies and practices for businesses and households (IPCC, 2014). To-date, local planning and policy have focused largely on production-based emissions (i.e., regulating emissions at the point they enter the atmosphere); however, there is increasing recognition of the value of a consumption-based approach to planning, considering the full life cycle of transportation, energy, food, goods and services consumed by households within communities (Erickson, Chandler, & Lazarus, 2012). Household consumption drives demand for global economic activity and corresponding emission of greenhouse gases globally. As the closest authority to individuals and households, local governments are widely recognized as critical in changing consumer patterns, yet few studies have evaluated the potential of local government policies to reduce consumption-based greenhouse gases.

This article evaluates the potential to deeply reduce household carbon footprints through state and local policies and programs over a long timeframe (from 2010 to

2050) for the state of California. Using a high geospatial resolution, consumption-based greenhouse planning model, we develop carbon footprint profiles and a deep carbon footprint abatement scenario for ~23,000 Census block groups, 717 cities and towns, and all 58 California counties, as well as for the state overall. We investigate the potential of urban infill, conservation, efficiency and renewable energy policies across each area of carbon footprints: transportation, energy, food, goods and services. Our exploration of the model highlights statewide potential of each intervention area and examples from cities with similar populations, but different abatement profiles. While the findings are specific to California communities, the method and perspective provided by carbon footprint planning should be useful to planners and policymakers elsewhere.

2. Previous Efforts to Quantify GHG Abatement Potential of Cities

Local planning to reduce greenhouse gas (GHG) emissions has become increasingly common and is now mandatory in progressive jurisdictions such as California (Bassett & Shandas, 2010; Bedsworth & Hanak, 2013; Boswell, Greve, & Seale, 2012; Bulkeley, Broto, & Edwards, 2014). Community climate action plans typically promote energy efficiency, renewable energy, more compact, transit-oriented urban development, active and public transportation, and waste and water management; however, plans typically do not quantify expected results (Boswell et al., 2012; Bulkeley et al., 2014).

A large number of policies and programs to engage residents successfully in climate action are possible. Behavioral strategies include persuasive appeals, incentives, social marketing, community-based programs and cross-sectoral approaches involving multiple strategies and stakeholders (Abrahamse, Steg, Vlek, & Rothengatter, 2005). Many of these approaches are cost-effective and can be implemented in short timescales (Stern et al., 2016). While attempts to change household behavior often focus on changing lifestyles (e.g., driving less, or changing diets), encouraging adoption of low-carbon technology and urban planning also require important changes in human behavior. Medium and long-terms approaches are ultimately necessary to achieve deeper savings and to engender a culture of sustainability thought to be necessary to achieve and maintain long-term sustainability goals (Wheeler, 2012).

Over the past two decades an extensive literature has documented public and private approaches to engage households in energy efficiency, GHG abatement and sustainability (Abrahamse et al., 2005; Abrahamse & Steg, 2013; Delmas, Fischlein, & Asensio, 2013; Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Stern et al., 2016). Dietz et al. (2009) estimated a 20% reduction in direct household emissions in the U.S. within a decade, and more if a renewable energy is widely adopted. The study considers both the technical potential of taking actions, and the likely number of households that can be engaged based on previously successful initiatives. Jones and Kammen (2011) approximated technical abatement potential for 26 metropolitan regions, finding 20% abatement potential at net negative cost to households for a single year. One study (Erickson, Chandler, & Lazarus, 2012) estimated carbon footprint reduction potential of 47% by 2030 for the city of Seattle, finding that vehicles, energy, extending product life spans and low carbon diets (in that order) have the most savings potential. In contrast, Wei et al. (2013) estimated behavioral savings potential in California as 10% to 15% of statewide emissions, using a combination of technical and achievable potential, while Greenblatt (2015) roughly approximated the potential of local government action in California at 12 $MMTCO_2e$ in 2030 (~5% of emissions), mainly through renewable energy commitments. The present study seeks to quantify local and state carbon footprint abatement potential for all California cities and develop a model that can readily scale to the rest of the U.S., and beyond.

3. A Consumption-Based GHG Inventory Approach

Efforts to reduce GHG emissions depend on understanding the sources and quantities of these pollutants. Since the 1990s, researchers and institutions have developed multiple carbon accounting frameworks (Wiedmann, Chen, & Barrett, 2015). At national and state scales, GHG inventories typically focus on large producers, tabulating the emissions generated by energy utilities, major industries, and other economic sectors using a combination of reported and modeled data. This information then informs large-scale GHG mitigation policies, which often focus on broad forms of regulation such as vehicle and appliance efficiency standards and utility portfolio standards for renewable energy. Increasingly, cities and urban regions create such sector-specific GHG inventories as well; however, these typically exclude emissions associated with the production of goods, food and services consumed within a jurisdiction's geographic borders, but produced elsewhere.

In an effort to provide a more comprehensive accounting framework for the U.S., ICLEI-USA (ICLEI, 2012) developed the U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions (ICLEI Community Protocol). In addition to the five required sources in the global community protocol, the U.S. protocol encourages inclusion of full life cycle accounting of major sources of emissions, while a consumption-based inventory is "strongly encouraged" (ICLEI, 2012, p.16). Consumption-based inventories are not intended to replace the traditional method, which is required under the protocol, but rather to serve as an additional 'story' or lens to view emissions. Sources included in the required approach are thought to be more within the direct control of municipal governments, while the consumption-based approach provides the full carbon footprint of residents. Household carbon footprint data from a previous study (Jones & Kammen, 2014) are freely available for any U.S. zip code, city or county (http://coolclimate.org/data), and a growing list of cities and regions have included the data in their climate action plans, including New York City (Dickinson, Khan, & Amar, 2013) and the San Francisco Bay Area (BAAQMD, 2017).

A consumption-based emissions inventory (CBEI) focuses on the economic activities of residents, allocating all emissions to final demand (mostly consumers, but in some cases government activities and business capital expenditures as well), regardless of where emissions are released into the atmosphere throughout supply chains (Ramaswami & Chavez, 2013; Wiedmann et al., 2015). Household carbon footprints are calculated with the assumption that all global economic activity is at the service of households and, therefore, all life cycle emissions associated with the production, use and disposal of goods and services are included in household carbon footprints. For example, if a factory in China produces a computer that is purchased by a California household, then all emissions related to the mining, refining, manufacturing, shipping and trade of the computer are allocated to the California household, not the Chinese company. Conversely, emissions associated with a product made in California, but consumed in China, would theoretically correspond to the carbon footprint of the Chinese household. Unlike traditional inventories, which include emissions from local businesses, a consumption-based inventory allocates all supply chain emissions to households, regardless of where those emissions originate. Household carbon footprints include emissions associated with all household consumption, including transportation, energy, housing, water, waste, food, goods and service. Any 'carbon footprint assessment' that does not include at least all household economic activities is not technically a household carbon footprint. Summing up, the carbon footprints of all residents in a local jurisdiction is the consumption-based GHG inventory of that location.

Both territorial and consumption-based methods are fully comprehensive—if all countries and regions of the planet accounted for emissions using both approaches, total emissions globally would be the same using either method, but their results can vary greatly for local communities. The consumption-based approach provides a more comprehensive lens by which to view the responsibility of any locality, and suggests a different set of GHG mitigation opportunities (Larsen & Hertwich, 2009). Meanwhile, some researchers (e.g., Lazarus, Chandler, & Erickson, 2013; Ramaswami & Chavez, 2013) take a hybrid approach, seeking to include consumption to some extent but to emphasize those forms of emissions that local governments can control. Such approaches may have practical benefits but risk being less comprehensive.

A growing list of studies from individual locations demonstrates that household carbon footprints and corresponding GHG mitigation opportunities vary dramatically by location. Consumption-based inventories have been conducted for thousands of cities in dozens of countries, including 434 municipalities in the U.K. (Minx et al., 2013), 177 regions in 27 European countries (Ivanova et al., 2017), over a dozen cities in China (Mi et al., 2016), three neighborhoods in Pakistan (Adnan, Safeer, & Rashid, 2018) and multiple studies in Australia (Lenzen & Peters, 2010; Wiedmann et al., 2015). Jones and Kammen (2014) calculated carbon footprints for all (>30,000) populated U.S. zip codes, cities, counties and states, finding considerable differences between locations. For example, electricity accounts for only 5% of household carbon footprints on average in California, but for over 30% in many other parts of the United States. Some studies have noted the distinction between 'consumer cites' and 'producer cities' (Ramaswami & Chavez, 2013; Sudmant, Gouldson, Millward-Hopkins, Scott, & Barrett, 2017), finding residential and higher income cities tend to have higher consumption-based emissions, compared to higher production-based emissions in industrial cities. Such heterogeneity between locations suggests that local climate planning requires a nuanced, place-based application of strategies that consider the unique GHG mitigation opportunities of each location. As is shown in the current study, carbon footprints vary dramatically within city boundaries at neighborhood scales as well. Models that estimate carbon footprints and projections for all cities in a state (or country), ideally at fine geospatial resolution, should be particularly useful for this nuanced approach to climate planning. Policies and programs will have very different outcomes for populations within and between jurisdictions.

Consumption-based inventory methods arose partly due to the realization that a large proportion of emissions that a jurisdiction is responsible for occur outside its borders. For example, Weber and Matthews (2008) estimated that 30% of total U.S. GHG impact in 2004 arose because of imported household purchases. Feng, Hubacek, Sun and Liu (2014) found that between 48 and 70% of emissions associated with four Chinese megacities occurred beyond their borders. Larsen and Hertwich (2009) found that about 90% of the total carbon footprint of Trondheim, Norway, was indirect, resulting from upstream sources that should be considered within municipal decision-making. Minx et al. (2013) found that 90% of the British communities they studied imported emissions on net. In a study of eight U.S. cities, Hillman and Ramaswami (2010) found that trans-boundary activities (import of food, water, energy, and building materials, plus air travel emissions) produced 47% more emissions than shown by the territorial GHG inventories performed by the cities. Such studies imply that local jurisdictions using a territorial method for estimating emissions may be seriously underestimating their own contribution to global warming.

Consumption-based GHG emissions mapping efforts are beginning to develop useful recommendations for local climate action planning. Barrett, Minx, and Paul

(2007) used a regional analysis of ecological footprints in Scotland to develop recommendations on improving land use mix, housing energy efficiency, community garden locations, sustainable eating programs, and waste management strategies. In their consumption-based inventory of Melbourne, Wiedmann, Chen and Barrett (2015) found that local carbon footprint data can help prioritize locations for building retrofit programs and microgrids. In a consumption-based modeling of future emissions for the Seattle region, Erickson, Chandler and Lazarus (2012) found that, unless checked, future increases in consumption would offset decreases in transportation-related emissions, and recommended behavioral measures to reduce meat consumption and purchase of new home furnishings and clothing. However, they admitted that few policy mechanisms exist for such reductions as of yet. Such analyses suggest new priorities for local climate change mitigation planning.

The primary objective of climate action plans is to identify the opportunities with the most potential to reduce greenhouse gases emissions from local activities. Both production-based and consumption-based inventory methods are necessary to fully capture these opportunities and the weaknesses and strengths of each approach complement each other. Production-based accounting is easier to track over time based on local policy outcomes; while the consumption-based approach is more appropriate for engaging households directly in climate action. A simple, free method of identifying consumption-based emissions and abatement potential for all jurisdictions, along with accompanying carbon management tools for households (http://coolclimate.org/calculator), provides a more comprehensive set of GHG mitigation opportunities for communities.

4. Estimating Carbon Footprints and Abatement Potential of California Locations

This article develops a consumption-based GHG inventory of all populated Census block groups, cities, and counties in California, and a deep carbon footprint reduction planning scenario to the year 2050, based on changes in population (urban infill), technology, conservation and adoption of renewable energy. It is the first study to estimate carbon footprints at such fine geospatial resolution—essentially at neighborhood scale in urbanized portions of the state. Our CBEI method has been described extensively in previous publications (Jones & Kammen, 2011, 2014, 2015). It is also described in Appendix R of the ICLEI GHG Protocol (ICLEI, 2012), which planners use to develop community GHG inventories in the U.S. Here we present a brief overview of the methodology for interested readers.

The basic approach is to calculate average household carbon footprints for each U.S. Census block group and then create population-weighted averages for each city, county, and the state as a whole. The average household's consumption of energy, transportation fuels, water, waste, construction, goods and services is estimated—using methods described below—and then multiplied by GHG emission factors and summed for the total household carbon footprint. Multiplying average household carbon footprints by the total number of households in a given location produces a consumption-based GHG inventory of that locale. Emissions from all businesses, whether global or local, are allocated to products consumed by households. We have excluded municipal government emissions, which jurisdictions typically already track and are relatively low (Erickson, Allaway, Lazarus, & Stanton, 2012) .

We obtained local consumption data where possible, including electricity and natural gas consumption by zip code, average fuel economy of vehicles by county, public transit energy consumption by county and local price adjustments for metropolitan areas. Where detailed local information was not available, we developed econometric models of household consumption using local subsamples of the National Household Travel Survey (NHTS) (Oak Ridge National Laboratory, 2013), the Residential Energy Consumption Survey (RECS) (U.S. Energy Information Administration, 2009), and the Consumer Expenditures Survey (Bureau of Labor Statistics, 2013). We estimated motor vehicle miles traveled (VMT) based on vehicle ownership, household size, income, number of workers, and population density for each subsample in the NHTS (San Francisco, San Jose, Los Angeles, Riverside, Sacramento, San Diego areas, plus other California locations). We estimated air travel as a function of income, and public transit use using county-level information from the National Transit Database. Actual electricity and natural gas consumption by zip codes was obtained from the largest electric utilities (PG&E, SDG&E and SCE) and local utilities in the San Francisco Bay Area (Jones & Kammen, 2015). Where utility data were not available, we modeled demand for electricity, natural gas and other heating fuels using demographic information, physical characteristics of homes and weather (heating and cooling degree days) in RECS. We approximated household consumption of goods and services using income and household size, the two variables with the most explanatory power in the Consumer Expenditures Survey. Diets were derived from USDA (2015), the Consumer Expenditures Survey (Bureau of Labor Statistics, 2013) and the Cost of Living Index (C2ER, 2014). Other sources of consumption include water, waste and home construction. See Jones and Kammen (2011, 2014, 2015) for further details on consumption models and emission factors.

The next step after obtaining a consumption-based inventory for all block groups in 2010 was to project these emissions into the future based on a deep carbon footprint abatement policy scenario. There are four types of interventions. Urban infill policies adjust the population of each block group by putting more new development in lower carbon footprint locations and adjusting the size of homes in those locations. Conservation strategies reduce the amount of consumption for each household (e.g., driving less or turning down thermostats in summer). Efficiency strategies involve the purchase of highly efficient technology to use less energy or fuel. Finally, renewable energy strategies replace fossil fuels with renewable sources of energy. Each major source of carbon footprints (vehicles, food, energy, etc.) is associated with each of the four types of mitigation strategies: infill, conservation, efficiency, renewables. We call this combination of carbon footprint source and mitigation strategy a 'policy intervention area'. Intervention areas could conceivably contain multiple specific policies.

Table 1 summarizes the adoption rates of intervention areas in the year 2050. Rates are expressed as a percentage of full adoption by the year 2050. Under this scenario, by 2050, 80% of new homes would be built in urban infill locations; homes would be 25% smaller; vehicle miles and air miles would be reduced by 25%; demand for energy services would be reduced by 20%; 25% of consumption would be shifted from high carbon goods to services; 20% of households would eat a low-carbon, plant-based diet; and waste and water consumption would be cut by 25%. Highly efficient technology would reduce end use energy consumption by between 30% and 60%, depending on the technology. 50% of household vehicles would be electric, while the other 50% would average 50 miles per gallon. Energy would be produced from mainly renewable sources, ranging from 30% for the remaining transportation fuels to 100% for electricity. All home heating would be from efficient electric heat pumps, with mandatory phase in starting in the late 2020s. Total assumed adoption rates for the year 2050 for each intervention area are shown in the final column of Table 1. These rates were chosen based on evaluation of several studies producing scenarios to achieve California's 2030 and 2050 GHG targets (Jones & Kammen, 2018; Greenblatt, 2015; Wei et al., 2013; Williams et al., 2012). Adoption would be accomplished through a combination of existing and new policies.

The policy intervention areas are further separated into 'state only' and 'local' adoption rates; these are estimates of the contribution of each jurisdiction in meeting targets. 'Local' is intended to mean at least partially within local control. For example, the state of California sets targets for land use, but implementation is left to local jurisdictions; we would consider this 'local' in our framework. We make the following assumptions (see Table 1): urban infill and conservation (e.g., programs to reduce energy or meat consumption) are almost entirely in the domain of communities; energy efficiency (e.g., energy efficient equipment and building envelopes) for new construction requires state policy to set targets, and local adoption (1:1 state vs. local split), while retrofits require more community level implementation (1:2 state vs. local split); industrial, agricultural and airline efficiency are not within local control, but the commercial sector (e.g., green business programs) is evenly split (1:1 state vs. lo-

Table 1. Adoption rates of intervention areas in the year 2050.

		BAU	State Only	Local	Total
Urban Infill	New Growth in Low Carbon Zones	10%	0%	70%	80%
	Smaller Home Sizes (new)	0%	0%	25%	25%
Conservation	VMT Reduction	0%	5%	20%	25%
	Air Travel Reduction	0%	5%	20%	25%
	Energy Conservation	0%	0%	20%	20%
	Shift Consumption	0%	0%	25%	25%
	Healthy Diets	0%	0%	20%	20%
	Waste Conservation	0%	0%	30%	30%
	Water Conservation	0%	0%	30%	30%
Efficiency	50+ MPG Vehicles	10%	35%	5%	50%
	Energy Efficiency (new)	10%	20%	20%	50%
	Energy Efficiency (existing)	0%	20%	40%	60%
	Air Travel Efficiency	0%	30%	0%	30%
	Commercial Efficiency	10%	25%	25%	60%
	Waste Efficiency	0%	0%	40%	40%
	Industrial Efficiency	10%	50%	0%	60%
	Agricultural Efficiency	5%	50%	0%	55%
Renewable Energy	Electric Vehicles	5%	30%	15%	50%
	Zero Carbon Fuels	0%	30%	0%	30%
	Low Carbon Electricity	35%	25%	40%	100%
	Heating Electrification	0%	0%	100%	100%

Notes: Adoption rates of policy intervention areas expressed as a percentage of full adoption in the year 2050 (e.g., VMT will be reduced by 25%, and 50% of vehicles will be electric by 2050). Adoption rates under BAU, state only policies, local interventions and total (sum of each jurisdiction) is expressed in columns.

cal split); communities have more control over electric vehicle adoption (e.g., charging infrastructure and social marketing) (2:1 state vs. local split) than promoting high efficiency vehicles (e.g., through social marketing) (7:1 state vs. local split); most communities can switch to community choice energy (local procurement of renewable electricity contracts) with 100% adoption, but not all (5:8 state vs. local split); heating electrification is entirely within local control (assuming a supportive policy environment allowing this). All results are compared to expected business as usual (BAU) in 2050. We are not aware of an accepted definition of local control or estimates in the literature; this distinction between state only and (at least some) local control is our best guess estimate and our results must be considered in the context of the model.

We adjust changes in population (urban infill), consumption, technology and renewable energy based on Table 1 and an assumed adoption curve for each measure (set at 8% by 2020, 60% by 2030, 85% by 2040 and 100% of the maximum rate by 2050).

5. The Spatial Distribution of Household Carbon Footprints

Our study presents a high geospatial resolution, consumption-based GHG inventory of all California Census block groups, cities and counties, and for the state overall. Household sources that are typically included in territorial inventories account for, on average, only 30% of carbon footprints, including gasoline (20%), electricity (5%), natural gas (4%), other fuels (1%), and waste (1%). About 70% are indirect sources, including life cycle emissions from food (19%), goods (17%), services (15%), transportation fuels (5%), vehicle maintenance (3), air travel (4%), home construction (3%), household fuels (3%) and water (2%). Thus, community GHG inventories that do not include consumption exclude the vast majority of emissions related to household behavior and miss important mitigation opportunities.

The total carbon footprint for the average California household is 44 metric tons of CO_2 equivalent gases per year (tCO_2e). When multiplied by all households in the state, the total is 24% higher than the State of California's territorial inventory: 550 $MMTCO_2e$ from a consumption-based approach vs. 445 $MMTCO_2e$ from the state's 2010 GHG inventory. At local scales, the difference can be much larger. For example, our consumption-based inventory is 35% higher than the San Francisco Bay Area GHG inventory, with food contributing the largest differences: only 2% in the territorial approach vs. 20% in the consumption-based approach (Jones & Kammen, 2015). Other research has shown that in primarily residential communities, a consumption-based inventory can be up to three times larger than a production-based inventory (Chavez & Ramaswami, 2013). For most cities, if GHG emissions are only reduced from direct sources, an increasing share of carbon footprints will be embodied in consumption, essentially exporting those emissions to other places.

The size and composition of carbon footprints varies greatly between and within population centers throughout the state, with important implications for planning. When viewed at high spatial resolution (Census block groups), cities show large differences between neighborhoods in all aspects of carbon footprints (transportation, energy, food, goods and services). Figure 2 is a map of total household carbon footprints by block group in the urban core of the San Francisco Bay Area. The lowest average carbon footprint of any Census block group in the Bay Area is 15 tCO_2e per household (about one third of the statewide average) and the highest is 104 tCO_2e (a difference of 7x). While the urban core cities of San Francisco

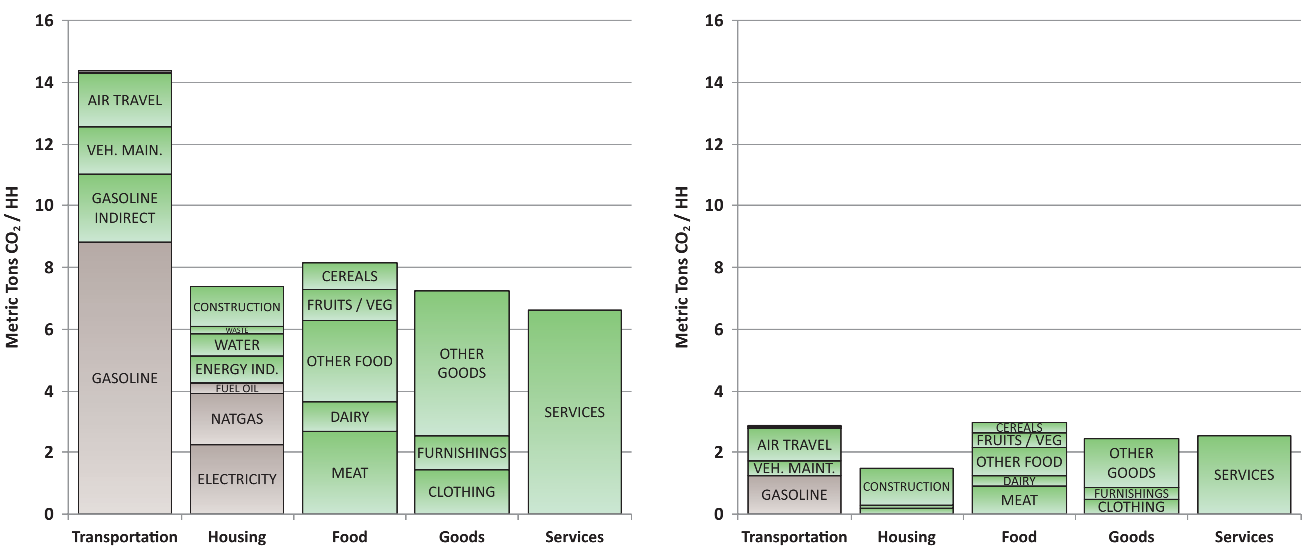

Figure 1. Carbon footprint of average California household in 2010 and 2050 under deep GHG abatement. Green colored bars are indirect emissions from the life cycle of products and services that are not typically covered in production-based inventories (unless produced locally).

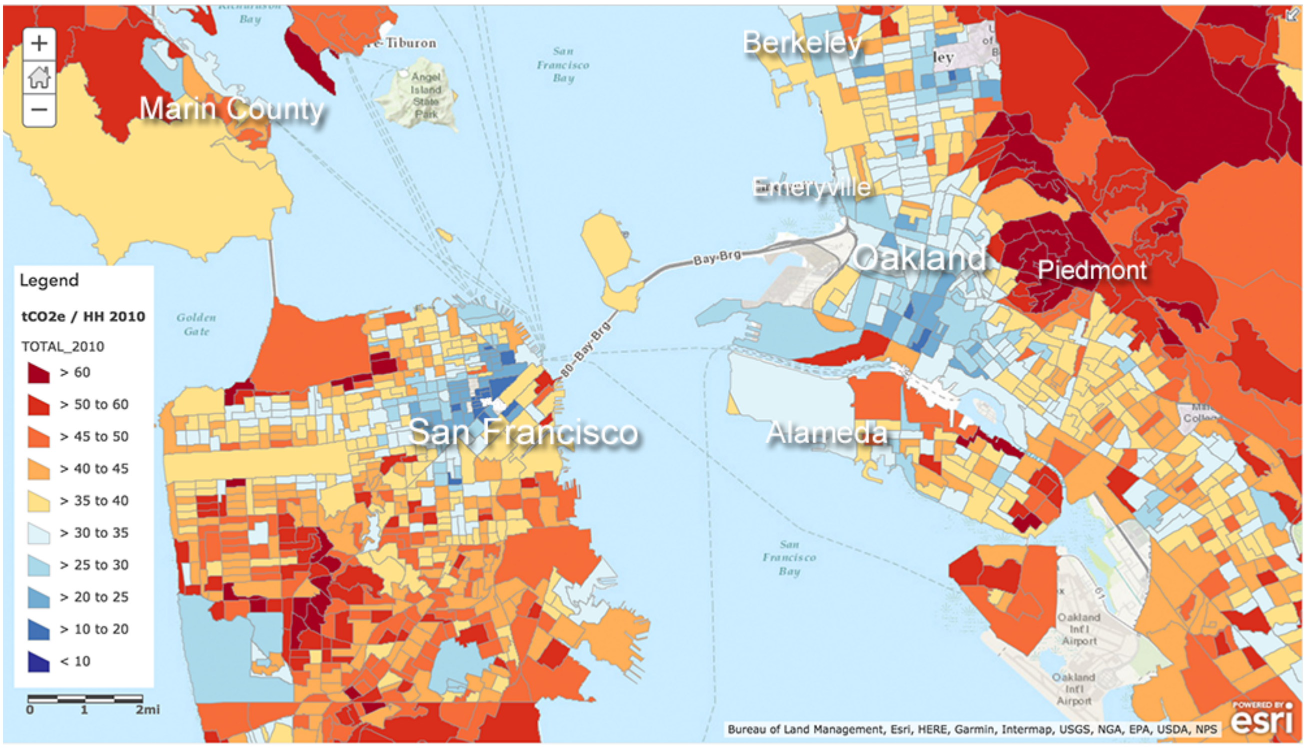

Figure 2. Carbon footprint of S.F. Bay Area households by Census block group.

and Oakland have among the lowest carbon footprint neighborhoods, as well as low emissions overall (40 and 38 tCO_2e, respectively), they also contain some of the highest carbon footprint neighborhoods in the state.

6. Statewide Carbon Footprint Abatement Potential

Ultimately, households have control over their consumption and associated GHG emissions. Local and state governments seeking to influence household consumption may choose from four types of interventions (Raupach et al., 2007): population (urban infill), conservation (consumption), efficiency (energy intensity), and renewable energy (carbon intensity). Each of these intervention types can be applied to different aspects of household carbon footprints: transportation, energy, food, and consumption of goods and service. Different policies and intervention strategies are necessary depending on the intervention type and consumption category. Table 2 provides examples of interventions in each area.

Table 2. Climate policy intervention areas by major category of household carbon footprints.

	Urban Infill	Conservation	Efficiency	Renewable Energy
Transportation	• Shorter travel distances	• Reduce VMT (transit, demand-side management)	• Fuel economy (or efficiency) standards	• Low carbon fuel standards • Electric vehicles
Energy	• Smaller homes • Adjusting thermostats	• Turning off lights • Energy efficiency standards	• Home retrofits • Heating Electrification	• Renewable energy
Food/Diets	• Smaller household sizes • Urban agriculture	• Eating less • Reducing food waste • Reducing meat, dairy & processed foods	• Buy organic, local, efficiently produced food	• Support farmers that have methane capture or renewable energy
Consumption & Waste	• Smaller household sizes • Smaller homes • Higher cost of living	• Improve conservation in commercial sector • Shift consumption to more services • Recycling	• Improve efficiency of local services • Encourage local services	• Electrification and renewable energy in commercial sector

Note: Examples of state and local policies are included in each box.

Baseline GHG emissions, local abatement potential of each intervention area, cumulative state only policies, and remaining carbon footprints under the deep GHG abatement scenario are shown in Figure 3. In 2010, transportation was the largest source of emissions, followed by food, goods, services, and housing. If all policies are successfully applied, transportation and housing emissions are cut dramatically (70% and 90%, respectively), leaving food as the largest source of carbon footprints in 2050. Electric vehicles, commercial efficiency, high efficiency vehicles, urban infill, renewable energy, heating electrification, VMT reduction, and healthy diets are all large sources of abatement (discussed in detail below). The combination of all state and local policies reduces carbon footprints 38% below 2010 levels in 2030, and 65% below by 2050. Further abatement does not appear feasible without similar GHG abatement in imports from other U.S. states and internationally. As direct emissions from vehicles and energy are reduced over time, an increasingly large fraction of carbon footprints will be embedded in goods and services consumed within the state but produced elsewhere. This underscores the importance of tracking consumption-based emissions over time at state and local levels.

The local abatement potential of each type of strategy (urban infill, conservation, efficiency and renewable energy) for each source of carbon footprints (transportation, housing, food, goods and services) in 2030 is presented in Table 3. Technology solutions from adoption of efficiency and renewable energy account for about 70% of total abatement, while conservation and urban infill account for 30%. Nearly half of total GHG reductions are from transportation (50.5 $MMTCO_2e$), followed by housing (24 $MMTCO_2e$), goods and services (16.3 $MMTCO_2e$) and food (9.1 $MMTCO_2e$). Below we discuss potential policies and programs underlying these estimates.

The presence of high carbon footprint neighborhoods in urban cores in Figure 1 may seem to contradict some urban planning principles. Most San Francisco neighborhoods are high density, well connected

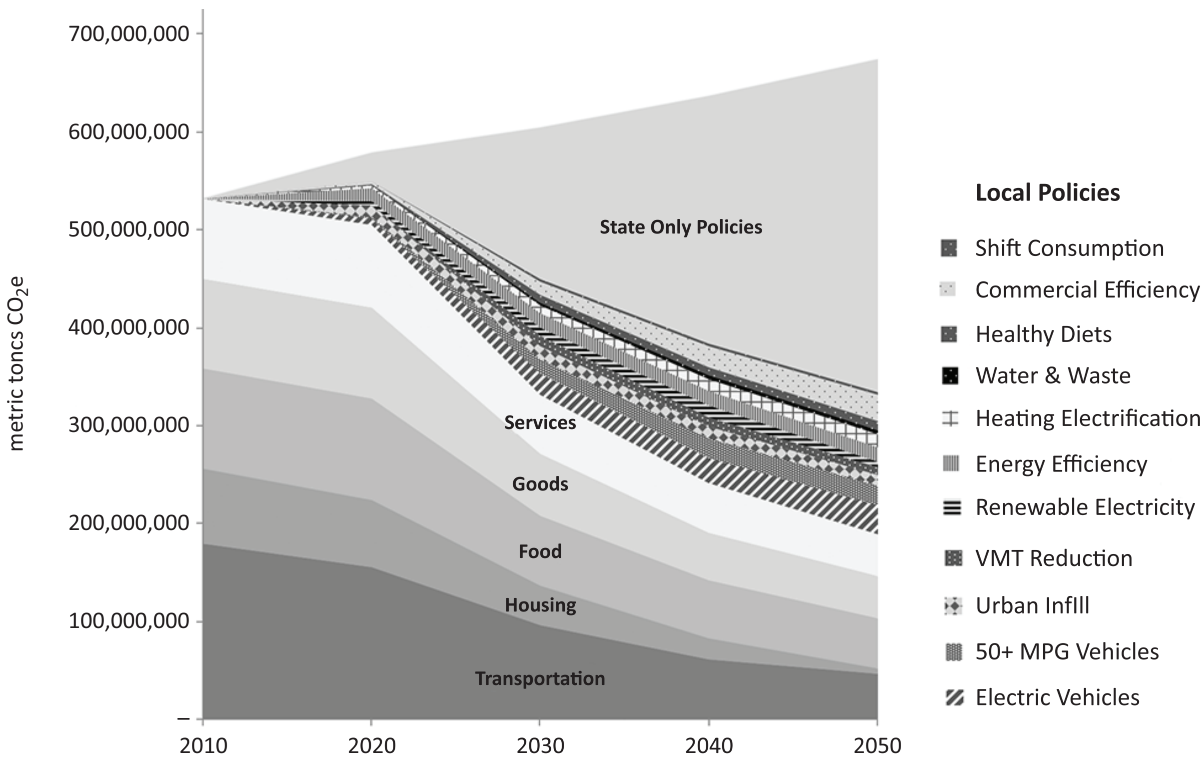

Figure 3. Carbon footprint abatement opportunities from local and state polices for state of California.

Table 3. Local GHG abatement potential in 2030 (million metric tons CO_2e) by carbon footprint category and intervention area.

	Urban Infill	Conservation	Efficiency	Renewable Energy	Total
Transportation	2.5	5.4	15.6	21.1	50.5
Energy & Water	1.3	2.9	5.2	15.1	24.5
Food/Diets	1.8	7.3	—	—	9.1
Goods & Services	1.7	2.0	14.4	—	16.3
TOTAL	7.3	23.3	35.4	36.2	102.2

to transit, jobs, etc., yet many of the city's neighborhoods have higher than average carbon footprints (red colors in Figure 2). Income largely accounts for the discrepancy. Statewide, income explains 62% of the variation between block groups (Figure 4, right), compared to less than 7% for population density (Figure 4, left). This follows since expenditures are highly correlated with income, and each dollar spent produces life cycle greenhouse gas emissions that are captured in the consumption-based approach. However, at each income level there is still a wide range of carbon footprints between block groups. At average household income levels of \$60,000, the range is roughly 30 to 60 tCO_2e (Figure 4, right) for California block groups. These differences may be explained by many factors, including urban planning variables such as proximity to transit, jobs, and services, urban form and home characteristics. In a previous study, Jones and Kammen (2014) found that of 32 variables modeled using a similar approach, six explained 93% of the variation in carbon footprints: vehicle ownership, income, carbon intensity of electricity, home size, household size and population density (in that order).

Following this logic, basing urban infill decisions on the carbon footprints of households at similar income levels may be more effective than basing infill decisions on proxy variables, such as density. To explore this hypothesis, we compared the GHG benefit of adding new housing to all locations over 10,000 persons per square mile vs. locations with below average carbon footprints at all income levels (following the linear fit in Figure 3). Basing urban infill on population density achieves ~3 $MMTCO_2e$ abatement in 2030 in California, which is slightly higher than a recent comprehensive estimate of urban infill (Elkind et al., 2017). If, on the other hand, urban infill occurs where household carbon footprints are low relative to other locations with income levels across the state, GHG savings are 7.5 $MMTCO_2e$, three times larger than previous estimates. Using this approach, more locations become good candidates for urban infill, including many high-income neighborhoods in urban cores, such as most of San Francisco, and the wealthy hillside of the East Bay. While these neighborhoods have higher than average carbon footprints, they have lower than average carbon footprints for their income level. Low carbon footprint cities that make housing available at all income levels help share the burden of meeting housing demand, while lessening the impact on the climate across the population. Using our approach, urban infill reduces all aspects of carbon footprints, including 2.5 $MtCO_2e$ from transportation, 1.3 $MtCO_2e$ from energy, 1.8 $MtCO_2e$ from food, and 1.7 $MtCO_2e$ from goods and services statewide. The abatement potential of infill development for transportation and energy has been extensively covered elsewhere (Cervero & Murakami, 2010; Ewing & Cervero, 2001). Including food, goods and services roughly doubles this potential in our analysis. Additional work would be needed to determine the true land use potential based on political, economic, social, technological, economic and legal factors.

6.1. Conservation Strategies

Conservation requires changing daily activities until those activities become habits. Common strategies include changing environments, for example through choice architecture (Thaler, Sunstein, & Balz, 2014) or infrastructure investments (e.g., public transit), and changing norms of behavior through feedback, social cues, persuasive messaging and other strategies (Cialdini, 2003; McKenzie-Mohr, 2012; Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007; Stern et al., 2016). While generally considered less effective than efficiency (Abrahamse et al., 2005), conservation strategies can be an effective "foot-in-the-door" to energy efficiency and re-

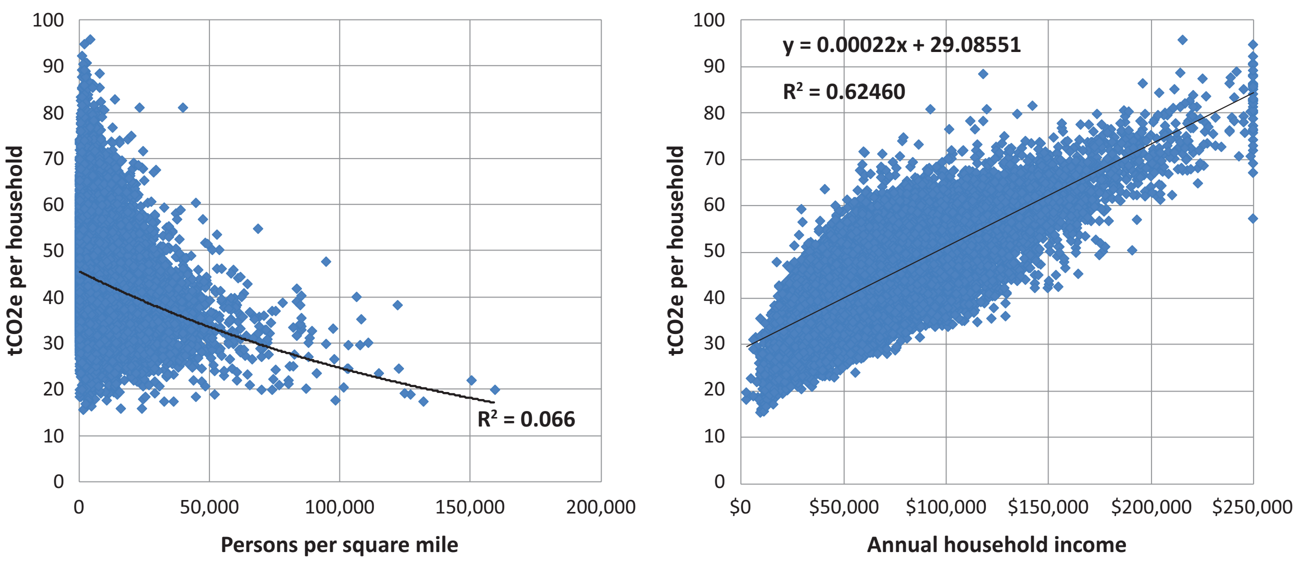

Figure 4. (Left) carbon footprint of Census block groups by population density, and (right) carbon footprints by average annual household income (right-hand figure).

newable energy purchases that require stronger commitments (Cialdini, 2003). Behavior-based programs can also engage, educate, motivate, and empower (Petersen et al., 2015) communities to take climate action, such as competitions between campuses, businesses and communities (Vine & Jones, 2016).

Reducing VMT has been a primary objective of urban planning for decades, yet per capita VMT in the state are once again on the rise. New technologies and strategies offer some potential. California's High Speed Rail system is anticipated to reduce statewide GHG emissions by about 1% when fully implemented (Chester & Horvath, 2012). Combining this system with new investments in transit, and urban infill will offer low to zero carbon short and long-distance travel. The benefits of transit are greater with increased urban infill, modeled separately. Pay-as-you-drive insurance, lane pricing, gasoline taxes, incentives and other market-based strategies will increasingly put price signals in place. Emerging technologies, including automation, electric vehicles and shared vehicles, hold potential to lower traffic and the use of single occupant vehicles. A 10% reduction in VMT would reduce 5.4 $MMTCO_2e$ in 2030, even with aggressive improvements in vehicle fuel economy and electrification.

Conserving energy holds less potential in California than in many other locations due to increasingly low carbon-intensity of electricity and relatively mild climate. Only 10% of household carbon footprints are from electricity and heating fuels combined statewide, and less than 5% in mild coastal areas, such as the San Francisco Bay Area. Full adoption of energy conservation behaviors (curtailment) would reduce 2.4 $MMTCO_2e$ in 2030, with considerably more savings from energy efficiency (below).

Food accounted for nearly 20% of GHG emissions from a consumption perspective in 2010 and we project it will be the largest source of carbon footprints by 2050, even with aggressive efforts to reduce methane from the dairy and cattle industries and other improvements. The average American household spends $7,000 per year on food (over 10% of gross annual income), and each dollar produces about 1kg. CO_2e, on average, throughout supply chains (Suh, 2009). Shifting 12% of Californians to healthy, low-carbon diets (with 50% fewer calories from meat, dairy, and processed foods) would reduce 7.6 $MMTCO_2e$ in 2030. School lunch programs, dietary guidelines, urban agriculture, education, improved food access, reducing food waste, partnerships with restaurants and supermarkets, and product labeling are just a few of the ideas that have been initiated to address food. Commensurate levels of funding and engagement are necessary to address food systems.

Household consumption is the target of polices and campaigns to reduce, reuse and recycle goods and materials. Since life cycle emission factors of manufactured goods already include benefits of recycled materials, we have not included the GHG potential of additional recycling efforts; however, the marginal benefit of recycling for communities is still large. Another possible strategy is to shift consumption by promoting local services. On average, services require ~500 grams CO_2e per U.S. dollar versus ~800 grams for goods produced in the U.S. (Suh, 2009), while California businesses that use local low carbon sources of energy likely produce fewer emissions (Reich-Weiser, 2010). Shifting 15% of expenditures from goods to services would reduce 2 $MMTCO_2e$ statewide. Local governments can also engage local businesses in conservation measures; we include total savings from the commercial sector into efficiency strategies below.

6.2. Efficiency Strategies

Efficiency strategies involve encouraging energy efficient, or efficiently-produced, goods and services, usually at a single point in time. Policies include incentives, labeling, codes, standards and behavior-based programs. While frequently applied to motor vehicles and energy (buildings and appliances), the same strategies are increasingly being applied to encourage low-carbon production and consumption of food, goods and services (Hertwich et al., 2010).

Improving the fuel economy of motor vehicles is the single largest source of emission reductions, savings nearly 15.6 $MMTCO_2e$ by 2030. We have only modeled abatement from fuel economy standards for internal combustion engine (ICE) vehicles, but policymakers can begin encouraging more efficient electric and alternative fuel vehicles as well. The most fuel-efficient ICE vehicles consume 30% less fuel than inefficient ICE's; conversely, the most efficient electric vehicles consume 50% fewer kWh than the least efficient electric vehicles (U.S. Department of Energy, 2010). Efficient motorcycles and electric bicycles should also be considered in a low-carbon motorized vehicle fleet.

California state policy mandates that all new residential buildings be zero net energy (ZNE) by 2025 and the state seeks 40% efficiency gains in existing buildings by 2030. Achieving these targets will require substantial collaboration with local governments. We estimate that total statewide savings potential of 9.2 $MMTCO_2e$ with 57% at least partially within local control. It is important to note that energy efficiency is a short to medium-term strategy. Once 100% heating electrification is achieved and all electricity is produced from renewable sources, energy efficiency will no longer lead to reductions in household GHG emissions.

We have not modeled any GHG benefits for choosing efficiently-produced foods. Despite strong interest in local and organic food, food miles tend to be only 5–10% of emissions from most foods (Weber & Matthews, 2008) and there is wide is variation in the carbon intensity of food production (Cooper, Butler, & Leifert, 2011).

Reducing emissions in the commercial sector by 15% saves 14.4 $MMTCO_2e$ in 2030. Local governments can use their convening power to build coalitions to support local green businesses. California has a robust network of green business certification programs, as well as statewide awards and recognition (http://coolcalifornia.org). While industrial emissions are managed largely by state policy, including cap-and-trade, local governments have considerable influence over commercial emissions.

6.3. Renewable Energy and Decarbonizing Fuels

Decarbonizing fuels has historically been the last option in the loading order of energy policies (Waide & Buchner, 2008); however, this is changing as the cost of renewable energy has decreased. Fully electric homes, combined with electric vehicles and renewable electricity offer a large and quick, albeit still relatively costly, abatement opportunity.

California has set a target of 4.2 million electric vehicles by 2030, a jump from just 200,000 full plug-in electric vehicles in 2010. To-date, incentives have been insufficient to drive widescale adoption of EVs even as purchase prices and leases have come down. Local governments can encourage the use of electric vehicles by adding charging stations, offering free parking or other incentives, equipping new homes with charging infrastructure, fleet purchases, and public engagement campaigns. As these vehicles become more popular there may also be a "Prius effect" (Sexton & Sexton, 2011), with social norms encouraging more adoption. Encouraging 10% adoption of electric vehicles by 2030 (less than 2 million vehicles) would reduce 18 MMTCO_2e statewide.

By 2050, virtually all electricity must come from renewable sources in order to meet California's climate targets (Wei et al., 2013; Williams, et al., 2012). As this transition happens, the GHG abatement potential of energy efficiency and conservation will decrease relative to switching from gas to electricity for most home end uses. California's Draft Scoping Plan does not include heating electrification, but recent analysis demonstrates this policy would not add considerably to the cost of the portfolio of policy measures currently considered in the plan (Raghavan, Wei, & Kammen, 2017). Solar photovoltaic and local renewable energy offer considerable potential for communities to take charge of energy choices. Converting 30% of homes from natural gas to electricity would save 7.7 MMTCO_2e by 2030. Increasing renewable energy by just 10% would also reduce over 7 MMTCO_2e in 2030.

7. The Carbon Footprint Abatement Potential of California Cities

The mitigation potential of jurisdictions depends largely on the size and composition of household carbon footprints. Figure 5 compares local abatement potential of three very different California cities, each with about 100,000 population: El Monte, Berkeley and Tracy. El

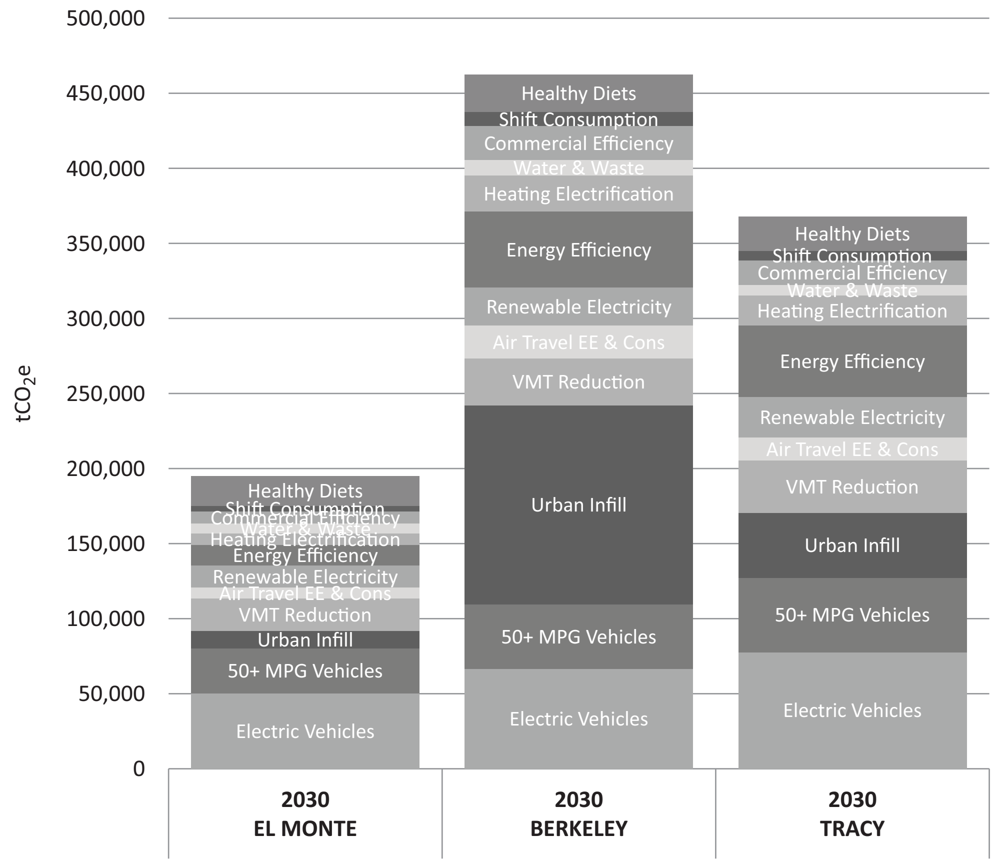

Figure 5. Carbon footprint abatement opportunities for selected cities with ~100,000 population.

Monte (1.25 $MMtCO_2e$) is a relatively low income, low carbon footprint community in Los Angeles County. While population exceeds 101,000, household size is higher than average, translating to relatively higher emissions per household from food, but lower carbon footprint overall. Urban infill potential (using our approach of only moving households with similar income) is low since low income households elsewhere in California also have low carbon footprints. The city of Berkeley (1.6 $MMtCO_2e$), with fewer residents (~92,0000) has more than double the abatement opportunity, with large potential from urban infill (over 120,000 tCO_2e in 2030), energy (mainly reducing, and eventually eliminating, natural gas) and efficiency in the commercial sector. The city of Tracy (1.9 $MMtCO_2e$ with 106,000 people), a distant Bay Area suburb, holds the highest abatement potential from electric and high efficiency vehicles and renewable energy. While these cities are somewhat extreme cases, they demonstrate the range in the size and composition of mitigation opportunities for similarly-sized cities.

Large differences between carbon footprints of neighborhoods present important environmental justice concerns. Those who are least responsible for emissions are frequently the most exposed to harmful effects of pollution. However, under our deep carbon footprint abatement scenario, which is in line with policies to meet California's climate targets for 2030 and 2050, these differences are dramatically reduced over time. Deep GHG abatement reduces air pollution as well as disparities in GHG responsibility (carbon footprints). Figure 6 displays average household carbon footprints in San Diego County under our climate target compliance scenario. By 2050, the average household carbon footprint in San Diego County drops from 44.1 to 12.8 tCO_2e per household, with much smaller differences between neighborhoods: standard deviation = 2.4 in 2050, compared to 9.7 in 2010. If California meets its climate targets, large disparities in carbon footprints will essentially disappear with important co-benefits of reduced pollution in vulnerable communities.

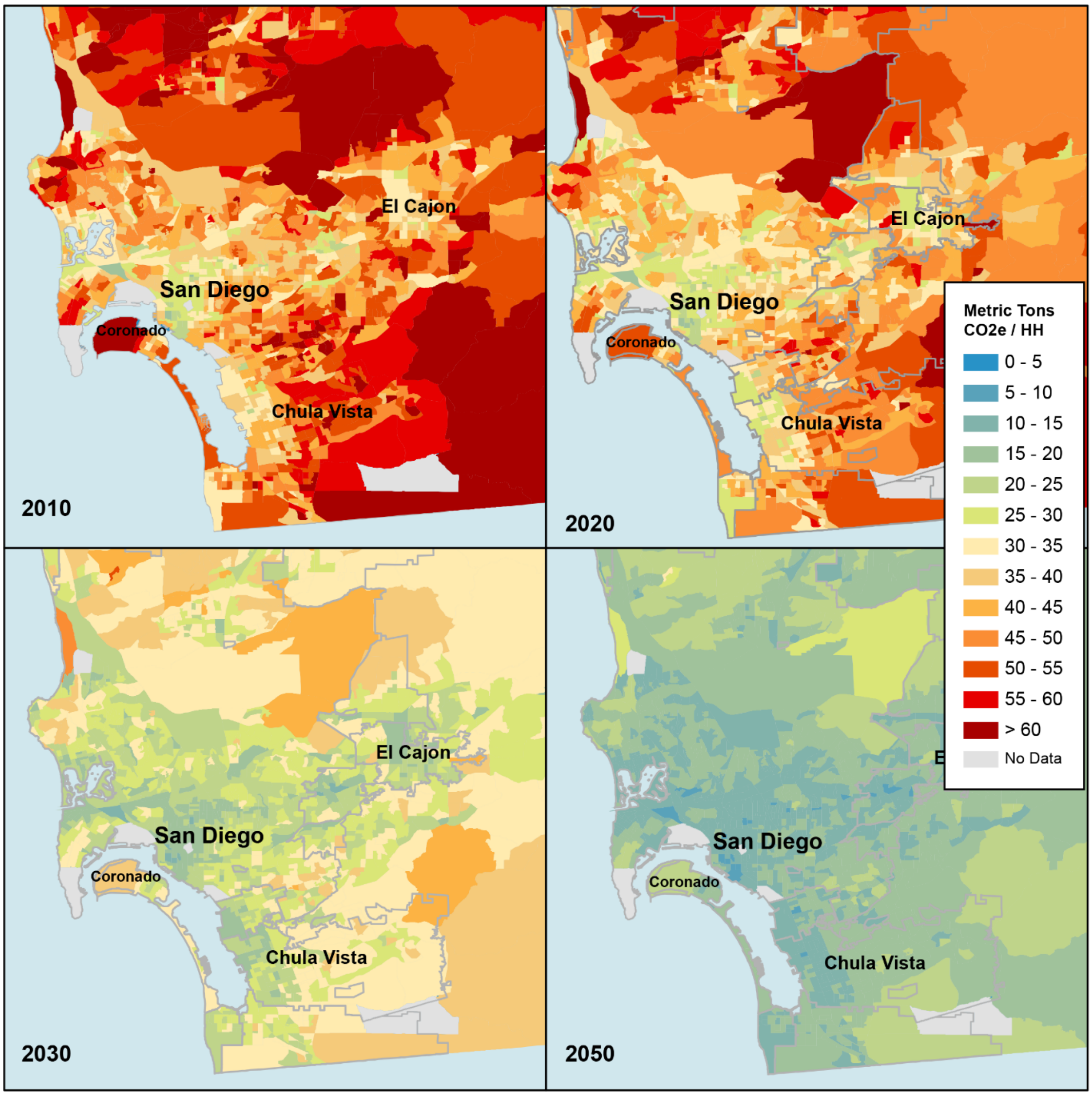

Figure 6. Average household carbon footprints of San Diego County neighborhoods under CA climate targets.

8. Uncertainty and Limitations

Like any model, our results must be observed within the context of the assumptions we have made. Much of our work on carbon footprint modeling has been extensively peer reviewed in previous studies (Jones & Kammen, 2011, 2014, 2015). Potential sources of uncertainty include measurement error (e.g., in surveys used), aggregation error (combining disparate types of products in a single product category), modeling error (e.g., assuming linear models, and goodness of fit), parameter errors (e.g., outdated datasets), and linguistic imprecision, among others. The newest feature of our model is the projection to the year 2050 based on assumptions about potential adoption rates and the split between state only and 'local' policy intervention areas. Adoption rates were chosen to align with previous studies that describe what would be needed to meet California's aggressive GHG targets. This is in no way a prediction of future emissions, but rather a scenario for deep GHG abatement. Free interactive online tools are available for readers interested in developing their own scenarios for any California city or county (http://coolclimate.org/scenarios-california).

The consumption-based inventory approach also has inherent limitations, even if modeled accurately. Actual expenditures on food, goods and services are only known at the scale of large metropolitan areas, and not individual cities or neighborhoods within cities; these are estimated based on household size and income. Thus, there may be important differences between locations, and changes in spending habits over time are only reflected at metropolitan scales. Furthermore, we assume that consumers purchase average quality goods, with similar emissions per dollar of expenditure. This is particularly problematic for high income neighborhoods that are more likely to purchase luxury goods at relatively high cost for similar products. Furthermore, consumption-based inventories, such as ours, may only be updated every five years or more due to data availability and resources. It may therefore be difficult, or even impossible, for cities to track full consumption-based emissions regularly over time without a costly survey approach. While cities may have difficulty tracking emissions over time, households can do this quite effectively using a household carbon footprint calculator, such as ours (http://coolclimate.org/calculator). The real value of a consumption-based inventory is the ability to engage individuals and households in climate action. It should thus serve as a complement, and not a replacement, to a traditional GHG inventory.

9. Conclusion

This study developed a consumption-based GHG emissions inventory of all California neighborhoods, cities and counties, with projections to the year 2050 based on a deep carbon footprint abatement scenario. Statewide, GHG reductions consistent with meeting California's aggressive GHG targets would require local involvement in at least 35% of needed abatement. Urban planning, conservation, energy efficiency and renewable energy all require extensive local participation. A combination of state and local policies consistent with meeting California's production-based target of 80% reduction by 2050 would reduce consumption-based emissions by an estimated 65% by 2050. Increasingly, a larger share of emissions will be exported outside of California. We project food will become the largest source of carbon footprints by 2050; shifting attention to promoting healthy, low-carbon diets is becoming increasingly important from a consumption perspective.

Our analysis of California carbon footprints leads to a number of priorities specific to California locations throughout the state (e.g., vehicle and heating electrification, renewable energy, urban infill, changing diets), some of which would be different for other regions with different climates, amounts of driving, incomes, and physical forms. Regardless of place-based priorities, accounting for consumption and modeling policy outcomes can help local governments concentrate on implementing the most promising policies and programs.

The results also support different GHG reduction priorities for suburban and urban areas. Technology-oriented strategies such as all-electric homes and cars appear desirable for affluent suburban jurisdictions with large houses, large rooftops, and long private-vehicle commute trips (e.g., the city of Tracy). Households in these locations often have the ability to generate photovoltaic electricity which—coupled with conservation and efficiency improvements—could potentially meet their energy demand for both home heating/cooling and transportation. Households in less-affluent, high-density urban neighborhoods (e.g., El Monte) may have lower energy consumption as well as less financial ability or rooftop space to generate photovoltaic energy. Since a larger proportion of their emissions come from household consumption, they appear be better candidates for campaigns to promote healthy diets and sustainable consumption. Mixed income urban core cities (e.g., Berkeley) hold the most potential for urban infill, with statewide GHG benefits.

Reducing consumption-related GHG emissions will almost certainly require changing behavior. Neighborhood-scale GHG emissions data can help target many of these efforts. Comparisons of household carbon footprints may be particularly useful at neighborhood scale where differences are the largest and households can compare their own carbon footprints (http://coolclimate.org/calculator) with neighborhood averages (http://coolclimate.org/maps-2050).

We recognize that in most cases political support, institutions, and economics would need to evolve in order to make such actions possible. To achieve full GHG abatement, local governments will need to think and act in new ways: as conveners, advocates and collaborators in community-wide engagement in climate action. Several cities in California are already moving along this path, serving as models for similar communities beyond California's borders.

Consumption-based, neighborhood-specific GHG footprint mapping and planning has the potential to usher in a new era of climate change planning, one which addresses emissions more comprehensively and more locally, and engages household fully in their climate commitments. The highly scalable method presented here allows cities to get started immediately, without producing expensive inventories of their own. This same method could be applied to all U.S. locations and other countries, helping to identify the most promising policies to drive low carbon economies globally.

Consumption-based, high geospatial resolution GHG inventories and planning tools appear to have some important advantages over other inventory methods. They give local and regional officials the most complete accounting of their residents' carbon footprints and provide potential intervention strategies down to neighborhood scale. Supplemental carbon footprint calculators can engage households directly in tracking and reducing their carbon footprints over time. For California, our inventory, maps, calculator and policy scenario tools can support prioritization of GHG policies for local governments throughout the state.

10. Supporting Online Tools and Materials

Supporting tools and data are available for free access on the project website: http://coolclimate.org.

- A results spreadsheet for all California cities and counties: http://coolclimate.org/data;
- Interactive online map for any neighborhood for years 2010–2050: http://coolclimate.org/maps-2050;
- Carbon footprint scenario tool for all California cities and counties: http://coolclimate.org/scenarios-california;
- CoolClimate Calculator, an online tool allowing users to compare their carbon footprints to similar households and create customized climate action plans: http://coolclimate.org/calculator.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Article

Slum Upgrading: Can the 1.5 °C Carbon Reduction Work with SDGs in these Settlements?

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Abstract
The need to improve slum housing is a major urban planning agenda, especially in Africa and Asia. This article addresses whether it seems feasible to do this whilst helping achieve the 1.5 °C agenda, which requires zero carbon power along with enabling the Sustainable Development Goals. Survey data from Jakarta and Addis Ababa on the metabolism and liveability of slums are used to illustrate these issues. The article shows that this is possible due to advances in community-based distributed infrastructure that enable community structures to be retained whilst improving physical conditions. The urban planning implications are investigated to enable these 'leapfrog' technologies and a more inclusive approach to slums that enables in situ redevelopment instead of slum clearance, and which could be assisted through climate financing.

Keywords
climate financing; informal settlements; metabolism; SDGs; slum redevelopment; urban planning; zero carbon

Issue
This article is part of the issue "Urban Planning to Enable a 1.5 °C Scenario", edited by Peter Newman (Curtin University, Australia), Aromar Revi (Indian Institute for Human Settlements, India) and Amir Bazaz (Indian Institute for Human Settlements, India).

1. Introduction

The Paris Agreement unites all countries in a common cause to respond to and deal with the effects of global climate change. It offers support to developing countries to meet ambitious targets. At the same time as the Paris Agreement, the world has committed to the 17 Sustainable Development Goals (SDGs) which include a range of social and economic goals, especially about ending extreme poverty in an 'inclusive' way. This article seeks to understand how the poorest parts of the developing world, informal settlements, can participate in both of these agendas and how urban planning can assist. It examines these issues through presenting the results of research into slum communities in Jakarta, Indonesia, and Addis Ababa, Ethiopia.

The Paris Agreement sets a long-term temperature goal of holding the global average temperature increase to well below 2 °C and pursuing efforts to limit this to 1.5 °C above pre-industrial levels (Tollin & Hamhaber, 2017). The Intergovernmental Panel on Climate Change is now seeking an agenda where 1.5 °C is seen as the primary focus and this must be achieved whilst enabling the SDGs. This agenda would see an acceleration of renewable energy both replacing old fossil fuel systems and providing new electric power where it has not been before; all the while this needs to happen while significantly improving the social and economic conditions of those consuming this electricity.

For informal settlements or slums, this will need to address the entire urban planning program for such settlements, including what kind of development strategy is preferred. This article compares two strategies with the fundamental question: should the settlements be cleared and replaced with modern high-rise housing linked to centralized renewable power or is it possible to implement distributed renewable power whilst upgrading slums in situ? It will then examine whether the preferred strategy could be assisted using new participatory planning approaches and climate finance from the Paris Agreement.

2. Overview of Slums

Slums present a variety of social and environmental problems. The United Nations Human Settlements Programme (UN-Habitat, 2003) defines a slum household as a group of individuals living under the same roof in an urban area who lack one or more of the following five conditions:

- Durable housing of a permanent nature that protects against extreme climate conditions;
- Adequate living space, which means no more than three people sharing the same room;
- Easy access to safe water in sufficient amounts at an affordable price;
- Access to sufficient level of sanitation in the form of a private or public toilet shared by a reasonable number of people; and
- Security of tenure that prevents forced evictions.

However, all informal settlements do not have the same characteristics, nor do all slum residents suffer the same degree of deprivation, as some may meet only one of the conditions while others may have all five (Givens, 2015; UN-Habitat, 2006). Many rural residents of developing countries migrate to the cities in search of better employment in order to get a better quality of life for themselves and their families. Nevertheless, when they arrive, most are faced with the universal challenges of basic, crowded and poorly built shelter, and a lack of services such as power, water and sanitation facilities (MacPherson, 2013). Most immigrants expect to leave the slum areas shortly after earning enough to afford better housing; however, many do not move as they become structurally part of the informal sector and are unable to achieve more than low incomes (UN-Habitat, 2003). The ending of extreme poverty in the world (SDG1) will need to focus on slums in the developing world, especially Africa and Asia.

Addis Ababa, like many emerging cities, has a high level of informal settlements, perhaps up to 80% (Teferi & Newman, 2014; UNDESA, 2014). Indonesia also has a high (28%) level of informal settlement (Jones, 2017). The questions facing policy makers as explored in this article are how such slums in both areas can be upgraded in a way that achieves the 1.5 °C reductions in greenhouse gases whilst enabling economic and social goals to be achieved as set out in the SDGs (UN, 2016) and how urban planning can help with this agenda.

Two approaches seem to be prevailing with slum regeneration: one approach is urban renewal based on slum clearance and transfer to high-rise dwellings; the other is urban regeneration based on in situ upgrading of infrastructure using solar energy and other community-based distributed infrastructure (Satterthwaite, 2004, 2016; Teferi & Newman, 2017; The World Bank, 2012; UN-Habitat, 2003). Data from three existing slums have been compared to two urban renewal high-rise complexes where residents were transferred from slums (Teferi & Newman, 2017).

This article explores whether it is possible to do zero carbon power cheaply whilst improving housing quality and improving social and economic opportunities rather than destroying important community structures. It examines the potential for new infrastructure to be distributed on a small scale, such as roof-top solar panels and batteries, allowing the strength of informal communities to be maintained. If possible, this could achieve the required carbon reductions for the 1.5 °C agenda as well as substantially achieving the SDGs. The role of urban planning is then outlined.

3. Background to SDGs

During the 2015 United Nations General Assembly, UN-member states approved the 2030 Agenda for Sustainable Development, a global development programme that lays out 17 SDGs to be achieved by 2030. The SDGs, which came into existence in 2016, are a collective set of goals, targets and indicators that set forth objectives with the social, economic, and environmental elements of sustainable development (UN, 2016). Solving acute sustainable development issues such as ending extreme poverty, reducing climate change, narrowing inequality and enabling ecosystem protection are the main focus.

The SDGs come into effect in a world that is continuously growing more and more urban. Urbanisation has some of the world's greatest development challenges, but it also has tremendous opportunities for advancing sustainable development. Now that the SDGs have been agreed upon, the real test of their success lies in their implementation.

The 11th Sustainable Development Goal is to make 'cities and human settlements inclusive, safe, resilient and sustainable'; the first target of the goal aims to ensure 'access for all to adequate, safe and affordable housing and basic services, and upgrade slums by 2030'. In 2000, the total slum population of the developing regions of the world was 760 million, which represented around 39% of the total urban population of those areas. The share of slum population to the total urban population of the developing regions came down to 32% by 2009, yet the total slum population increased to 863 million (UN-Habitat, 2013). Due to the interrelated nature of the SDGs, improving the slum dwellers' living conditions contributes to the achievement of many of the approved goals, such as:

- SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable;

- SDG 6: Ensure availability and sustainable management of water and sanitation for all;
- SDG 1: End poverty in all its forms everywhere; and
- SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all.

Therefore, the objective of this article is to illustrate how the 1.5 °C agenda can be achieved along with these SDGs.

4. The Paris Agreement and the 1.5 °C Agenda

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), aims to reduce the impacts of climate change on socioeconomic and ecological systems and amend current emissions rates to the lowest possible levels by designing an objective setting the rise in the global average temperature from pre-industrial levels to significantly less than 2 °C (IAEA, 2016; Rogelj et al., 2016; Wollenberg et al., 2016). In order to achieve this, countries have submitted Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate action. These INDCs solve a number of problems, which can relate to avoiding, adapting or coping with climate change, among other things. Nevertheless, targets and actions for reducing greenhouse gas (GHG) emissions are core components.

However, the 2 °C agenda of the Paris Agreement is not likely to be enough to reduce climate change to levels that would ease the dramatic increase in global impacts from cyclones, fire and floods as well as the entire loss of coral reefs from ocean warming, despite much scepticism about these issues (Diffenbaugh et al., 2017; Dunlap, 2013). Hence the IPCC has agreed to gather the research for a new agenda that would enable a mechanism to ratchet up the reduction of global greenhouse emissions in a way that ultimately leads to no more than 1.5 °C. It also has agreed to examine how this can be done whilst enabling the SDGs. This article attempts to assist with this agenda.

5. Poverty and World Energy

Nearly 1.6 billion people of the world population had no access to basic electricity in 2014 (Bhatia & Angelou, 2015) and 1.1 billion of them live in developing countries, primarily in Sub-Saharan Africa and South Asia. They rely on inefficient biomass energies, such as wood, animal and crop waste for cooking and heating, which have harmful effects on health and air quality. Around 75% of the world's marketable energy is consumed in urban areas, and many of the poor who need access to improved energy systems are located in rapidly growing slums all over the developing world (GNESD, 2013). Despite such statistics, the energy requirements of poor urban households in the south have not been appropriately addressed as many programs have focussed on rural populations where no power exists (Siddiqui & Newman, 2005). These rural programs have usually been successful as solar PV panels fit easily into village structures and governance (Baldwin, Brass, Carley, & MacLean, 2015; Casillas & Kammen, 2010; Nygaard, 2009; Urpelainen, 2014); this would suggest that similar approaches to slum electrification would work also but these programs are rare (Parikh, Chaturvedi, & George, 2012; Singh, Wang, Mendoza, & Ackom, 2015) suggesting that there may be more of an ideological issue among urban planners.

The greatest population growth is occuring in cities of developing countries; however the world cannot afford a simultaneous increase in the use of fossil fuels accompanied with this anticipated growth. If the world's poorest slum dwellers are to receive power, it must be from zero carbon renewable sources, such as solar power hence it is necessary to resolve this urban planning issue.

Currently, greater than half the world's population live in urban areas (UN-Habitat, 2016). By 2030, it is predicted that six in 10 people will be urban residents (UN-Habitat, 2016). Regardless of numerous planning challenges, urban areas provide more efficient economies of scale on various levels, comprising the provision of goods, services and transportation. With sound, risk-informed planning and management, cities can become incubators for innovation and growth and drivers of sustainable development. This will now need to apply to the provision of slum housing power which is renewable.

A study conducted in five slum settlements using serviced and non-serviced settlements in the state of Gujarat in India showed that energy provision improves productivity and enables slum dwellers to change their ambitions (Parikh et al., 2012). Interventions such as provision of basic services increase productivity and enable slum inhabitants to then emphasise higher level aspirations (Aklin, Bayer, Harish, & Urpelainen, 2015; Parikh et al., 2012). It also tends to be associated with creating formal tenure that unlocks the ability of householders to upgrade their own homes. This will need to apply to the provision of power to slum housing based on renewable energy. It is important for the quality of life of the slum-dwellers, and is a path towards further development (Schaengold, 2006). This article argues that not enough has been done on slum electrification in urban areas and needs to have more direction from urban planners and other decision makers.

6. Global Slum Conditions and Approaches to Their Development

In 2014, 30% of the urban population in developing countries lived in conditions classified as slums (see Figure 1). In sub-Saharan Africa, the proportion was 55%—the highest of any region (UN-Habitat, 2016). Though the percentage of city inhabitants living in such circumstances reduced over the past decade, more than 880 million people all over the world were living in slums in 2014.

The upgrading of existing slums may seem to be at odds with global sustainability goals on resource con-

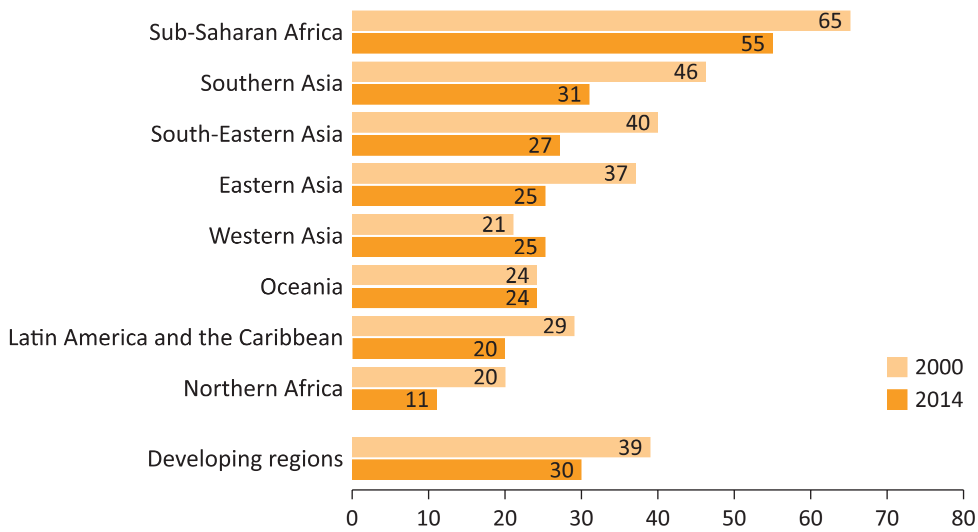

Figure 1. Proportion of urban population living in slums, in 2000 and 2014 (%). Source: UN-Habitat (2016).

sumption. Slum regeneration suggests using more natural construction materials, to build more, for more people, with occupants eventually using more to maintain and operate their houses than they currently do in slums. This would mean an increase in global GHGs for example. The problem, therefore, is to improve the living conditions of the urban poor in a way that does not negatively impact on the global and local environment, while at the same time improving local, regional, and national economies. There is evidence that this is happening as global GHG emissions are now decoupling from economic wealth generation, particularly in developed economies but also in emerging ones (Newman, 2017a, 2017b). Furthermore, in the long term, there is enormous potential for the greening of the housing sector of developing countries precisely because much of the urban housing stock is yet to be built, and this presents an enormous opportunity to build green today and make significant environmental and economic savings in the future (French & Lalande, 2013). Nevertheless, in developing countries, the challenge is not only to address the environmental impacts of the slums but to balance this with the economic, social, and cultural pillars of sustainable urban development (French & Lalande, 2013; UN-Habitat, 2013).

There appears to be two ways of approaching the development of slums in previous decades:

6.1. The Modernist Slum Clearance Method

Slum clearance was and is a policy reaction to the demands of those in need for decent housing, but its aim has rarely been to simply meet those demands. Slum clearance was meant to bring health and hygiene benefits; larger avenues were to accelerate transport and to ease crowd control and surveillance (Frenzel, 2016). In urban planning history, the modernism approach as set out in the Athens Charter by CIEE 'clears the slate' as suggested by Le Corbusier (Ley, 2014). The idea is to start again using modern architecture, mainly high-rise housing (Newman, Beatley, & Boyer, 2017). Since this approach does not take in to consideration the social structure of the neighbourhoods it has been successful at providing good physical infrastructure and economic opportunities as it enables the residents to join the formal economy through achieving tenure, but the social and community benefits were challenged (Jacobs, 1961). Resettlement through relocation of households to distant places in the city can cause economic shocks and social disruptions of the poor (Burra, 1999; Yntiso, 2008). Those against relocation believe that resettlement detaches residents from their livelihoods and expose them to poverty (Takesada, Manatunge, & Herath, 2008; UN-Habitat, 2011;).

6.2. The Organic Slum Development Method

Modernist slum clearance and housing provision were also increasingly lamented by urbanites and a new generation of urban planners following Jane Jacobs (1961) and Turner (1976) who criticized the loss of traditional urban habitats and neighbourhoods in increasingly inhumane urban architecture (Frenzel, 2016). They suggested instead a more organic approach to improving slums. This approach develops slums in situ by providing the residents with formal tenure and enabling redevelopment of buildings and infrastructure by the community. Although this is more uncertain in its progress and outcomes it is designed to build on the social capital of the community rather than remove it. Jacobs (1961) was able to show that the Le Corbusier's modernist approach was socially damaging to the fine-grained community structures of the old, organic urban fabric and hence destroyed the local economy as well as its walkability (Newman et al., 2017; Teferi & Newman, 2017).

Both approaches to slum development will need to manage the potential increase in the metabolism of housing (the consumption of resources including energy and the production of waste including GHGs) if it is to achieve the 1.5 °C agenda. Figure 2 is a schematic illustration of how a more circular metabolism will enable this to happen. However, it will also need to show how it can reduce its metabolism whilst improving liveability as set out in Figure 3.

Urban metabolism modelling provides a tool for understanding and monitoring the performance of urban structures not just in terms of GHG emissions but also as they relate to broader sustainability elements including water, waste, transport, and materials and all the elements of liveability in cities (Newman et al., 2017). As modelling of urban metabolism, along with a general understanding of urban systems improves, there is growing evidence that human settlements have large untapped sustainability potential. Not only may cities potentially have no net impact, but they may even become regenerative, in terms of energy, water, food and biodiversity. Each of these elements needs an understanding of urban stocks and flows, which can be provided through an urban metabolism analysis (Newman et al., 2017). If the Extended Metabolism Model is used it has the potential to assist in understanding both the potential to create settlements that are zero carbon but also whether they are achieving the SDGs at the same time (United Nations, 2016). There does not seem to be a literature on the application of the Extended Metabolism Model to slum improvement apart from Arief (1998). The article sets out to examine whether the Extended Metabolism Model can throw light on the best approach to slum improvement as it lends itself to policy issues in urban planning for sustainability.

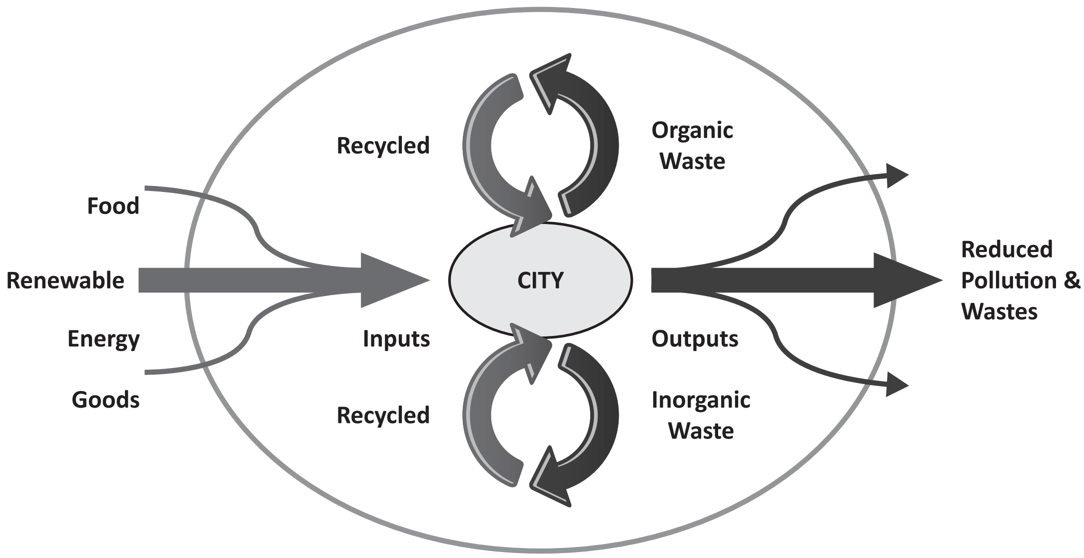

Figure 2. Circular metabolisms (Newman et al., 2017) adapted from Rodgers (1997).

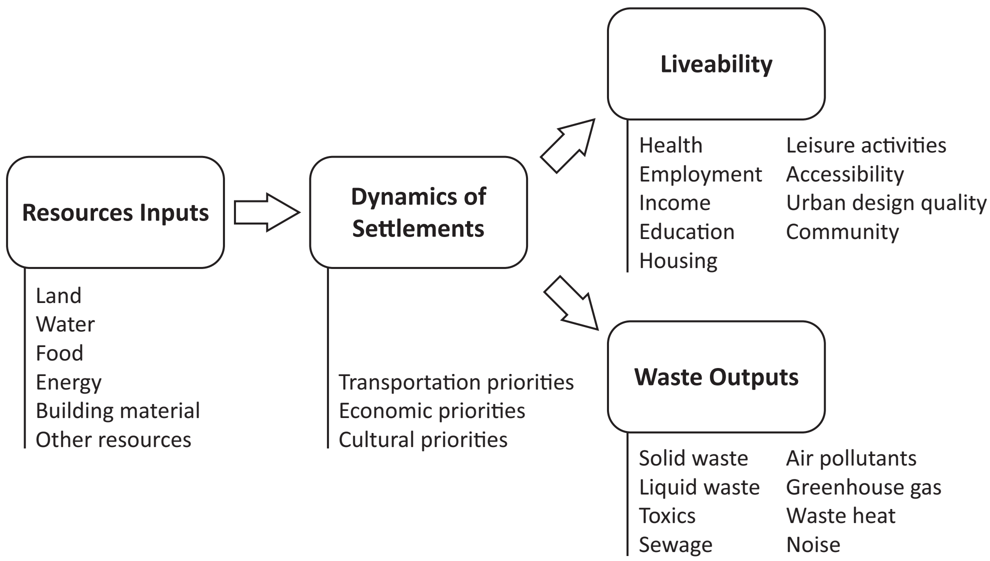

Figure 3. The extended metabolism model (Newman & Kenworthy, 1999).

7. Background of the Study Areas

This article will examine a series of slums in Addis Ababa and Jakarta in order to compare their metabolism and liveability and thus the potential for achieving the 1.5 °C agenda with SDG improvements.

The city of Addis Ababa shares 30% of the country's urban inhabitants with a population of around 4 million. About 120,000 new residents are added to the city every year. Most of this takes place in the slum areas where around 80% of Addis Ababa inhabitants' live (Teferi & Newman, 2017). Arat Kilo is an old, socially mixed slum settlement, where formal and informal structures coincide. Diverse housing typologies, ranging from single detached houses, and cluster housing to poor dwellings can be found. Additionally, the age, construction quality, and infrastructural provisions of the buildings vary but are overall substandard.

Ginfle is a slum clearance high-rise apartment settlement, which is located in the inner city of Addis Ababa, just located a short walking distance from the Arat Kilo slum. Most of the people living here were former residents of Arat Kilo.

Jakarta is a mega city with a population of 10 million and a high proportion of slum dwellings (Aji, 2015). The slum area examined is Ciliwung and the adjacent high-rise was for residents transferred from a slum clearance project. Jakarta has an entirely different culture and climate to Addis Ababa, but they share the kind of rapid growth and economic issues faced by many emerging cities.

8. Results on Extended Metabolism in Slums

The results from a study of two slums in Jakarta are presented first. Tables 1, 2 and 3 show the metabolism (resources and waste) and liveability characteristics of a slum that is yet to be redeveloped on the Ciliwung Riverbank and this is compared to a slum clearance project where high-rise apartments were provided to the residents.

The results show the following:

- There is a small decrease in the metabolism of the residents in the high-rise housing in comparison to the undeveloped slum on the river bank. This is

Table 1. Resource inputs to Ciliwung River slum settlement and high-rise apartments, Jakarta, Indonesia. Source: Arief (1998).

Input	Slum Settlement	High-Rise Apartments
Water (L/household/day)	248	188
Energy (MJ/Household/day)		
Electricity	2.3	1.2
Kerosene	60.8	57.0
Charcoal	0.9	0.15
Gasoline	3.99	7.05
Diesel	3.27	2.35
Total	71.26	67.75
Land (m^2/person)	4.57	0.91
Building materials	Bricks, wood, bamboo frame, tile or tin roofs (very poor quality).	Bricks, ceramic floors, tile roofs (good quality).
Food	Inadequate intake.	More balanced but minimal intake.

Table 2. Waste outputs from Ciliwung River slum settlement and high-rise apartments, Jakarta, Indonesia. Source: Arief (1998).

Output	Slum Settlement	High-Rise Apartments
Solid waste (kg/household/day)	2.16 (82% into river)	1.66 (100% collected)
Liquid waste (L/household/day)	248 (directly into river)	188
Air waste (g CO_2)		
Electricity	626	326
Kerosene	4,487	4,206
Charcoal	85	14
Gasoline	284	502
Diesel	241	173
Total	5,723	5,221

Table 3. Liveability of Ciliwung River slum settlement and high-rise apartments, Jakarta, Indonesia. Source: Arief (1998).

Parameter	Slum Settlement	High-Rise Apartments
Health	Environmental health very poor: 42 ill in 3-month period.	Environmental health relatively good: 34 ill in 3-month period.
Employment	55% street traders; 19% employed in private business; 0% home industries; Most participate in informal economy.	6% street traders; 40% employed in private business; 2% freelance workers; Most participate in formal economy;
Income (average)	Rp151,000	Rp252,000
Housing	Poor; 82% want to move.	Relatively good; Do not want to move.
Education	94% primary school and below.	44% primary school and below.
Community	High level of community; 92% know > 20% by first name; 90% happy to live there; 100% trust neighbours; 100% feel secure; 100% borrow tools from neighbours; 100% borrow money from neighbours.	Not high level of community; 44% know > 20% by first name; 76% happy to live there; 52% trust neighbours; 4% feel secure; 70% borrow tools from neighbours; 22% borrow money from neighbours.

probably due to better technology and living conditions as well as having to pay for their energy and water (most often the informal settlements have informal, unmetered energy and water provision). The wastes are much better managed as would be expected; and

- The liveability in the high-rise development is due to a reduction in poverty, but the striking difference is in the social liveability parameters where it is clear that the informal settlement has much better social capital. It has much higher levels of community trust and neighbourliness. Despite their poverty the residents like living there as they have a strong community that supports each other.

Tables 4, 5 and 6 set out the metabolism and liveability in an informal settlement in Addis Ababa and compare it to a high-rise settlement which received residents from a former informal settlement nearby.

Table 6 shows that resource consumption of energy and water are very similar with only small GHG emissions by comparison with most households in most cities (Newman et al., 2017). The reduction in usage when people move to high-rise is probably because they are generally having to pay more than in the informal settlements for power and water which are often not in formal supply. In terms of liquid and solid waste production, each of the slum groups were almost the same as the production of solid and liquid wastes from the high-rise condominiums. Though, there is a vast difference in how they are disposed (collected). This is because of the limitations of technology in the informal settlements. Despite the fact that the high-rise apartments produce a little fewer wastes, the amount generated is almost similar, which is consistent with the expected result from the metabolism model.

Regarding liveability, even though the high-rise condominium apartment inhabitants are better off in terms of the physical environment and have access to the formal economy, the community cohesion is not as strong as with the slum dwellers. The level of social interaction among the slum settlements is very high; they meet each other almost every day and generate strong levels of

Table 4. Resource inputs to Arat Kilo Slum Settlement and High-Rise Apartments, Addis Ababa. Source: Authors' filed data.

Input	Slum Settlement	High-Rise Apartments
Water (L/household/day)	261	168
Energy (MJ/Household/day)		
Electricity	3.1	2.6
Kerosene	58.0	54.0
Charcoal	2.10	0.12
Gasoline	4.01	7.03
Diesel	3.37	2.45
Total	70.58	66.02

Table 5. Waste outputs to Arat Kilo slum settlement and high-rise apartments, Addis Ababa, Ethiopia. Source: Authors' filed data.

Waste outputs	Slum settlements	High-rise apartments inhabitants
Solid waste (kg/household/day)	3.1	2.6 (90% solid waste collected)
Liquid waste (L/household/day)	341	260
Air waste (CO_2)		
Electricity	726	402
Kerosene	4,321	3,902
Charcoal	123	12
Gasoline	210	490
Diesel	213	180
Total	5,593	4,986

Table 6. Liveability of Arat Kilo slum settlement and high-rise settlement, Addis Ababa, Ethiopia. Source: Authors' filed data.

Parameter	Slum Settlements	High-Rise Settlements
Economic	30% employed in private business, government, and NGOs; 30% self-employed (informal activities); 29% unemployed; 3% pensioners; Average income Br10,560.	45% employed in private business, government, and NGOs; 43% self-employed (informal activities); 7% unemployed; 5% pensioners; Average income Br17,600.
Housing	Constructed from wood and mud; Cooking and sleeping take place in same room; 70% government owned; No bathrooms; pit latrines and communal electric meters; 43% wish to live there with minor improvement; 30% need everything unchanged.	Constructed from concrete blocks; Separate bed and kitchen rooms available; 100% privately owned; Privately owned bathrooms and electric meters; 50% wish to live there.
Education	67% primary school and below.	30% primary school and below.
Community	High level of community; 80% happy to live there; 95% feel secure; 93% enjoy access to at least one informal borrowing or lending network; 97% trust neighbours.	Low level of community; 50% happy to live there; 7% feel secure; 42% enjoy access to at least one informal borrowing or lending network; 34% trust neighbours; 60% have social tie to previous communities.

trust that leads to sharing of assets and money. There is clearly a strong community in the slum settlements. The housing improvements that have been undertaken in the high-rise condominiums compared to the slum settlement have not necessarily brought about parallel increase in social conditions. If the same level of physical infrastructure and access to the formal economy could be provided to the slum dwellers without removing their social structures, then it would obviously be a better way to improve such settlements.

9. Community-Based Distributed Electricity Supply

If slums are to be upgraded in a way that enables their community structure to be preserved, then the urban planning needs to be done differently with the aim of maintaining these social structures that are so strong in the slum communities. Slum clearance with the development of high-rise to replace the buildings is clearly not working in terms of social and community values. High-rise developments that are used to provide housing for people in slums as well as other income levels that help pay for the buildings will help provide more housing options and even with high-rise its possible to develop more community-oriented high-rise design (see Bay & Lehmann, 2017).

The alternative approach as discussed above we have called the organic approach to slum development. In this approach the need will be for small scale, local, community-based energy infrastructure and other services/infrastructure. Fortunately, the world has seen a rapid development of this localized, distributed technology so that it has now become significantly cheaper than much of the centralized, large-scale systems that have characterized urban planning in the 20th century (Green & Newman, 2017b; Lovins, 2003; Marsden, 2011). The technology and the urban planning associated with its management have been recognised as having significant application to the developing world (Brass, Carley, MacLean, & Baldwin, 2012). Mostly this requires solar PV panels and new battery storage systems that enable the electricity to be used in the evenings. Such systems take up very little space (rooftops) and a small area for the battery. They can be provided for a group of houses from just a few to several hundred depending on the management system that it is constructed around.

The management systems associated with community-based distributed power have been described as 'citizen utilities' (Green & Newman, 2017a) and utilize a micro-grid linking just the local householders into a locally managed structure. The micro-grid can be linked into the rest of the city's grid and be used to make money for those who belong to the local system by exporting power at times (Gies, 2012). By having their own batteries, the local Citizen Utility is more resilient if the rest of the system fails which in developing cities can be quite frequent. Details of how such systems work are being trialled (Green & Newman, 2017b) and need to be demonstrated more in slum communities to show how feasible it can be.

10. Urban Planning Implications

10.1. Unlocking Markets for Housing Regeneration

The community-distributed power system offers much to slums and to governments as the cost of redevelopment, especially through high-rise building, is significant. These welfare approaches also may not unlock other approaches to regenerating urban areas. Organic upgrading not only should be a cheaper option overall, but this approach also offers a way for people to improve their own homes once economic development is facilitated by the provision of locally-generated and managed electricity. If the settlement is informal in terms of its land tenure, then this can rapidly be solved as a way of ensuring the Citizen Utility is formalised as well as providing the major step forward of having a formalised address and ability to be recognised for bank finance. The formal process enables households to take out loans and begin fixing their own houses as well as setting up employment opportunities. Thus the Citizen Utility-based approach to providing zero-carbon power can provide a major step towards ending extreme poverty as well as ensuring that no emissions are created. This is the fundamentals of the 1.5 °C agenda.

10.2. Inclusive and Participatory Development

Community-based power systems within slums not only improves the economic situation of the slum dwellers but it is inherently more sensitive to the social infrastructure within the organic structure of the slums. This social capital is likely to be a significant contributor to the ending of extreme poverty through its highly inclusive mechanism. It can also be linked to more participatory governance in general (MacPherson, 2013). Techniques for enabling the process of inclusion have been developed as a major tool in urban planning (Hartz-Karp & Marinova, 2017).

10.3. Local Environmental Improvement

The same community-based approach can be used to assist with water and waste management using new technology such as MBR sewage treatment that not only can fit seamlessly into small communities but can provide a water source for growing local food and greening (D'Amato, 2010; Zodrow et al., 2017). Both can be upgraded as a local, distributed, community-based approach rather than a highly centralized mechanism as has been the way in the past. This can use a range of small-scale local water and waste systems that can be largely self-sufficient but also link to the city-wide grids for resilience and reliability (Cowden, 2008; MacPherson, 2013). Both of these systems can be part of the same Citizen Utility and enable local environmental improvement.

A more community-based approach to infrastructure appears to mean improving the living conditions of the urban poor in a way that does not negatively impact on the global and local environment using more natural resources than the existing experience. This would suggest a policy implication for the 1.5 °C agenda.

11. Financing

The Paris Agreement has established a broad mechanism for funding and financing infrastructure that is both low carbon and helps achieve the SDGs. By enabling a Citizen Utility structure within slums it is possible to create an on-going structure that can directly utilize the funds from the global Green Fund but can raise local finance to support such development (Pahl, 2012).

12. Conclusion

The 1.5 °C agenda is largely an issue for the developed world and emerging places like China and India who need to adopt zero carbon economic development mechanisms. However, Africa and places like Indonesia will need to show they can be part of this new agenda. Slums are a dominant part of the agenda for urban development in the emerging world and like all new city development will require a different approach if it is to be part of the 1.5 °C agenda. This article shows that there is an urban planning approach using more organic upgrading and community-based infrastructure with Citizen Utilities that can enable slums to leapfrog into a future which is both zero carbon and can achieve the SDGs. Urban planners need to establish demonstrations of such Citizen Utility-based slum regeneration projects.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

WGV: An Australian Urban Precinct Case Study to Demonstrate the 1.5 °C Agenda Including Multiple SDGs

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Abstract

The WGV project is an infill residential development in a middle suburb of Perth, Western Australia. Its urban planning innovation is in its attempt to demonstrate net zero carbon as well as other sustainability goals set by urban planning processes such as community engagement and the One Planet Living accreditation process. It is a contribution to the IPCC 1.5 °C agenda which seeks to achieve deep decarbonization while also delivering the UN Sustainable Development Goals (SDGs). Solar photovoltaics and battery storage are incorporated into the development and create net zero carbon power through an innovative 'citizen utility' with peer-to-peer trading. The multiple sustainable development features such as water sensitive design, energy efficiency, social housing, heritage retention, landscape and community involvement, are aiming to provide inclusive, safe, resilient and sustainable living and have been assessed under the SDG framework.

Keywords

decarbonizing; sustainable development; Sustainable Development Goals; sustainable precinct; zero carbon

Issue

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1. Introduction

WGV is the name of a new infill development focusing on meeting the 'missing middle' of medium density housing in Australia (Thomson, Newton, & Newman, 2017). WGV is in White Gum Valley, a low density suburb of Fremantle which is undergoing redevelopment as the first generation of housing from the 1950s is being replaced or restored with a denser and more sustainable housing product. It has been created by LandCorp, the Western Australian government's land development agency, with a charter to demonstrate innovation in urban planning and development. This article aims to show how WGV demonstrates how it achieves the two key components of the UN's 1.5 °C agenda:

1. Net zero carbon, a goal now being required by global commitments if climate change is to be kept below the 1.5 °C warming limit as suggested by IPCC;
2. A series of other sustainability outcomes that can be related to the UN Sustainable Development Goals (SDGs) which all nations are committed to achieve, especially SDG 11 which aims to make settlements 'inclusive, safe, resilient and sustainable'.

As a LandCorp development WGV must also be a commercially viable urban development product that can be sold into the market. It must, therefore, be able to create innovation within housing market constraints.

This article sets out to examine the extent to which WGV aspires to, and is achieving the 1.5 °C and SDG goals as well as being a marketable product. It will do this by examining the urban planning context, the urban planning process to deliver this, the results that can now be seen and what these suggest are the conclusions for urban planning.

2. Urban Planning Context

2.1. The 1.5 °C Agenda and Urban Planning

Climate change impacts on development and growth globally with the main contribution resulting from urban carbon emissions (Wang, Zhao, He, Wang, & Peng, 2016, p. 1066). The Paris Agreement in 2015 was an important step in creating a global climate change response that was shared and equitable for the parties involved. This was a key development as it has the potential to limit global temperature increase to 1.5 °C above pre-industrial levels (Roberts, 2016, p. 71). The IPCC are now assessing the options for achieving the 1.5 °C agenda (Boucher et al., 2016, p. 7287). The Paris Agreement has introduced a 5-year submission cycle for Nationally Determined Contributions (NDC), through the creation of voluntary short-term domestic climate policies together with the measurement, verification and monitoring of the NDCs for all parties. However, cities have a chance to commit to both short and long term processes that can help drive the 1.5 °C agenda.

Cities make a large contribution to greenhouse gas (GHG) emissions (Kennedy et al., 2009) as they are epicenters for economic activity and therefore represent a challenge but also an opportunity for climate change policy (Corfee-Morlot, Cochran, Hallegatte, & Teasdale, 2011, p. 169; Solecki, 2012, p. 557). Cities are where most economic growth now happens and so in their choices over infrastructure, technology and urban planning outcomes they can play an important role in developing mitigation strategies to reduce carbon emissions (Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). For the first time the UN have set an urban goal, as part of the SDGs, which sets out seven indicators for urban development (as set out below). Therefore urban planning needs to try and achieve these seven indicators in every part of the urban development process and thus these goals must play a pivotal role in shaping future trends for infrastructure, land use and urban activity (Corfee-Morlot et al., 2011, p. 169; Kennedy et al., 2009; Yam et al., 2016) as was concluded by the UN Habitat Conference (UN Habitat, 2015).

Cities offer a platform for local level adoption of multi-scale approaches to climate change (Ostrom, 2010, p.27) with over 10,000 climate actions recorded (C40, 2015). Cities within Australia have been leaders in the push for sustainable cities, for example the City of Fremantle (where WGV is situated) has been at the forefront of climate action mitigation and adaptation with policies such as Carbon Neutrality which was the first in Western Australia in local government (City of Fremantle, 2011). Cities can “bend the climate curve” at a global scale with a 2-pronged approach of ambitious mitigation and transformative adaptation actions (Roberts, 2016, p. 71). Cities can act as the “starting point for the use of low-carbon ideas and technologies” (Wang et al., 2016, p.1066) to help achieve 1.5 °C and promote the benefits of low-carbon cities. The 1.5 °C agenda is an important opportunity for local governments as they play a key role in urban planning and are vital in creating the vision of low-carbon, sustainable, climate resilient and vibrant cities (Roberts, 2016, p. 71).

Without adaptive and innovative urban planning, it has been shown that urban expansion alone can raise temperatures by 1–2 °C (Georgescu, Morefield, Bierwagen, & Weaver, 2014, p. 2909). Cities that are “green, inclusive and sustainable” (The World Bank, 2010) are becoming increasingly important and therefore are a key focus for urban planning. This article outlines how urban planning in WGV can demonstrate how to achieve the 1.5 °C agenda.

2.2. The SDGs Agenda and Urban Planning

The SDGs are succeeding the Millennium Development Goals (MDG) and are a universal international consensus on sustainable development where a range of collective goals have been agreed upon including ending poverty and reaching gender equality (Sachs, 2012, p 2206). The SDGs are a transition from the MDGs and are furthering and expanding the pursuit of these goals into the future (Sachs, 2012). In 2000, the member states of the UN agreed upon the vision for the MDGs and recognized the need for global cooperation in the spheres of “development, peace and security, and human rights” (Singh, 2016). The MDGs were an expression of international public concern over significant issues such as “poverty, hunger, unmet schooling, environmental degradation and gender inequality” (Singh, 2016). To combat these global challenges a set of eight goals were established to enable the establishment of a set of quantifiable and time-bound objectives to ensure awareness is raised on these issues (Griggs et al., 2013, p 305; Sachs, 2012, p. 2206).

The transition from MDGs into SDGs was enabled through a significant consultation process within and by the UN which began in 2012. The SDGs were adopted in September 2015 and provide the current international framework for addressing global sustainability, with a framework of 17 goals, 169 targets and numerous indicators (Wellard, 2017, p 16) (see Figure 1). Having a cities goal (number 11) was a major step forward for urban planning in a global context.

The SDGs are interconnected and somewhat lacking in a structure to enable their delivery with so many different areas that are meant to be achieved simultaneously. The key features for delivery of the SDGs are partner-

1 NO POVERTY	End poverty in all its forms everywhere
2 ZERO HUNGER	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages
4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5 GENDER EQUALITY	Achieve gender equality and empower all women and girls
6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all
7 AFFORDABLE AND CLEAN ENERGY	Ensure access to affordable, reliable, sustainable and modern energy for all
8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation
10 REDUCED INEQUALITIES	Reduce inequality within and among countries
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and production patterns
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts
14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15 LIFE ON LAND	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16 PEACE AND JUSTICE	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalise the global partnership for sustainable development

Figure 1. The UN SDGs. Source: Global Goals (n.d.).

ships and demonstrations and hence an obvious place to do this is where economic growth is being focused, in the cities of the world. The SDG that focusses on cities is SDG 11 which states "making cities inclusive, safe, resilient and sustainable"; this incorporates seven indicators that have been selected to measure and monitor SDG 11's delivery (Table 1).

This article is seeking to show that the WGV example is tackling both the challenge of 1.5 °C in terms of energy and GHG innovations and that it can simultaneously achieve multiple SDGs using the urban planning framework. The SDG Framework and the Urban SDG Indicators will both be used to assess WGV as well as the demand and hence saleability of the development.

Urban planning should be an effective tool for achieving the SDGs as it often uses established frameworks and guidelines that can be selectively applied or adapted to meet the targets for achieving the SDGs. The world now needs many demonstrations of how to achieve these multiple goals through integrated urban developments. Shared-learning from such demonstrations can contribute to the international cooperation required to address the risks posed by climate change and its impacts through the SDGs (Griggs et al., 2013, p 305).

2.3. The WGV Context and Urban Planning

WGV is an infill residential development that evolved into a demonstration housing project, located in the capital of Western Australia, Perth. Perth has a Mediterranean climate with an average of 8.8 hours of sunshine per day, 300 cloud-free days a year ideal for solar energy (BOM, 2016). The development aims to offer an example of innovation in sustainable housing featuring a range of innovations but having a special focus on whether the solar energy can be enough to create a net zero emissions development. It is also an important demonstration of how to turn a middle suburban redevelopment site into a workable, saleable product at medium density, an agenda of interest across Australia and other car dependent cities in North America (Newman, 2015; Newman, Beatley, & Boyer, 2017; Thomson et al., 2017). The residential development is situated on the site of a former school which ceased to operate in 2008 and provided a site of 2.3 ha with approximately 100 housing units now being built in a medium density format and with a highly mixed tenure. Figure 2 is an artist impression of the site, which in early 2018 is about 70% completed.

WGV aims to demonstrate that precinct-scale design can contribute to sustainable development by incorporating various building typologies, climate sensitive designs, urban greening, water and energy management strategies, as well as including affordable housing options and a sense of place and community.

This article outlines how the aspirations of the WGV development and actions implemented to date demonstrate inclusive urban planning and design that can lead to the achievement of various SDGs as well as being zero carbon. By using the SDGs as a template against which to assess WGV, we can identify to what extent the WGV development has contributed to achievement of the SDGs. This article illustrates the demonstrated attempts to realize the ambitions of achieving both the 1.5 °C agenda and the SDGs at the WGV residential development.

3. The Urban Planning Process

The urban planning process is outlined to show how it incorporated both the 1.5 °C agenda and the SDGs.

This article has been developed based on data from various research projects that are utilizing WGV as a

Table 1. Indicators used in analysis of Goal 11: "Make cities and human settlements inclusive, safe, resilient and sustainable". Source: compiled based on UN SDGs indicators.

Target
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.
11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage.
11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.

Figure 2. Artist impression of the WGV residential development, in the suburb of White Gum Valley. Source: LandCorp (2015).

case study. The data is drawn from a combination of semi-structured interviews with diverse stakeholders involved in the urban planning process, archival records, correspondence with WGV planning stakeholders, resident interviews of their expectations for moving into the precinct and current resource use, modelling as well as building monitoring.

While the WGV development was not specifically designed with the seventeen SDGs in mind, archival records show that it was developed with the general principles of sustainable development as a driver. Therefore, rather than assessing WGV against specific SDG indicators, this article takes a qualitative approach and assesses the WGV development process and outcomes against the principles of the SDGs and the 1.5 °C agenda. This assessment takes a localized approach, examining how an infill residential precinct in a developed country might contribute to achieving the SDGs at a local level.

As the construction of the WGV development is not fully complete, this article will focus on the as-designed phase of WGV with some early results that can help answer the question about its zero carbon goal. Future research and publications will follow the completed project, including a longitudinal study of resident resource use in the various dwellings in WGV and comparison of the as-designed and as-used electricity and water technology features.

The urban planning process methodology was typical of any LandCorp development where a strong emphasis is put on innovative design and parallel community engagement to see the extent to which it can deliver on the innovations in that community, but also how it can complete their obligation to be a commercial success.

3.1. The Urban Planning Process and 1.5 °C

Sustainable development through urban planning is necessary for cities to successfully adapt to climate change as it is aimed at achieving urban livability while avoiding adverse impacts, such as resource depletion and GHG emissions, within and outside the urban perimeter (AlQahtany, Rezgui, & Li, 2013, pp. 177–78). The core principles that have been accepted for sustainable urban planning according to AlQahtany, Rezgui and Li (2013, pp. 177–78), include: being responsive to market needs; integrating with multiple systems including transport, energy, housing and utilities; using partnerships; considering social, economic and spatial inequalities caused by climate change; and considering local culture and context. By utilizing the opportunity presented by this conflux of issues, the SDGs and the 1.5 °C agenda can be furthered through the use of sustainable urban planning and this is what set the context for LandCorp's process.

The reduction of non-renewable energy use and carbon emissions was a key focus for WGV and is central to its vision, as is necessary for achieving the 1.5 °C agenda. Through various initiatives and innovations such as energy efficient design, use of renewable energy and tech-

[1] Figures based on average Perth consumption for single residential dwellings, when adopting WGV's Design Guidelines and Sustainability Upgrade Package.

nologies, the reduction of grid energy consumption was set at 60% for WGV and 100%[1] in dwellings taking advantage of a WGV sustainability rebate package. Energy reduction measures such as the use of solar power, embedding of energy efficiency requirements in the design guidelines, and a precinct layout ensuring that homes are north facing, therefore benefiting from solar passive orientation, were major urban planning initiatives to reduce carbon and improve occupant thermal comfort.

In order to meet the 1.5 °C agenda it is necessary for rapid transformation so that any new development can make a significant contribution to the necessary changes in global emissions. Rapid transformations cannot be done using large scale centralized power systems; however, in cities where new developments are happening all the time an organic and exponentially increasing process can occur if the new technologies for energy efficiency are implemented as part of the new development. This is termed disruptive innovation as it is demand led and can cause dramatic change in short periods of time (Green & Newman, 2017a). Roof-top solar and lithium-ion battery storage were seen as having the potential to create such disruptive innovation. These were brought in through the involvement of academic advice (from Curtin University in partnership with industry) and were made possible to implement with assistance from a Federal Government grant to demonstrate how they can be used to contribute to savings, both monetary and carbon.[2]

During its design phase, WGV was established as a 'living laboratory' for a four-year research project supported by the Cooperative Research Centre (CRC) for Low Carbon Living and Curtin University (Burbridge et al., 2017). This research project was set up to provide collaborative innovation guidance, monitoring of energy and water usage and technology performance, as well as sharing the learnings with industry, government and the wider community.

Energy efficiency and other low carbon measures that were required in the design of WGV include:

- Climate responsive design and landscaping to harness the sun's energy to provide natural heating and cooling solutions, including intelligent use of trees for seasonal shading;
- WGV Design Guidelines set a minimum seven-star[3] energy efficiency rating;
- Mandated rooftop solar of 1.5kW for all attached and detached single dwellings with extra panels (upto 3.5kW) provided for single lot dwellings (through the WGV Sustainability Package Rebate);
- Battery storage and solar panels for the apartment developments;
- A shared Electric Vehicle for use by the community;
- Solar hot water systems or heat pump technology;
- Energy efficient electrical appliances;
- Energy efficient lighting solutions;
- Low energy space heating and cooling systems;
- Education material and support provided to residents.

Innovative research programs conducted as part of the project include:

- CRC for Low Carbon Living research program and partnerships to monitor energy use and water use, technology performance and facilitate knowledge sharing;
- Australian Renewable Energy Agency (ARENA) research program and partnerships to test viability of solar battery storage on strata buildings;
- A unique solar power and battery storage technology research trial in a shared strata-building setting at the Gen Y Demonstration Housing Project;
- A governance model to allow shared solar photovoltaics (PV), battery and monitoring systems to be used in medium density apartments; the governance models involving peer-to-peer (P2P) trading and using blockchain technology to be tested at 50 units of WGV;
- A study of household resource practices with comparison to individual baseline practices from before the residents move into WGV.

As well as the technology to enable rapid transformation of the energy provided, there was a necessary consideration for the management system in the WGV precinct and in this we have focused on how to create a Citizen Utility as set out by Green and Newman (2017a, 2017b). The context for this is set out below.

There is a growing trend in Australian energy markets where energy consumers have started to produce their own renewable energy—over 30% of households in Perth now have roof top solar panels representing some 700MW of power. Households are doing this to complement the grid sourced electricity they have traditionally relied completely upon. High retail energy prices coupled with low energy sale prices are incentivizing households to generate energy behind the meter and to store any surpluses. For the first time in history, network operators are now having to consider a future where householders are treated as both producers and consumers. However, whilst owner occupied low-density suburban households have benefited most from the renewable shift, several barriers still exist for those in strata (common property) arrangements as in WGV. Shared roofs have in the past been difficult to make available for the use of solar panels due to strata title governance requiring all residents to agree. This project aimed to get around that barrier by building solar and storage into the shared contracts

[2] It is worth noting that since the purchase of the PV and batteries the cost of these have continued their dramatic decline and are now being mainstreamed in a number of urban developments in Perth.
[3] Nationwide House Energy Rating Scheme—7 Star is above the mandidatory 6 star performance benchmark.

of all residents and providing a clear set of benefits by enabling them to have much better options for power into the future. This approach has been called a 'citizen utilities' approach, where a distributed, decentralized, decarbonized and democratized energy market is created (Green & Newman, 2017a). The Citizen Utility at WGV was therefore set up as a model for how a multi-residential medium density strata title company, that manages the shared spaces in a building complex, can also manage the power using a blockchain software system involving P2P trading (Green & Newman, 2017a, 2017b). One of the complexes was also fitted out with a shared electric vehicle linked into the solar energy and the Citizen Utility.

The importance to urban planning of these innovative energy models is that to phase out large scale fossil fuel power systems will require local urban developments that can become completely zero carbon with full electrification of buildings and transport (Kennedy, Stewart, Westphal, Facchini, & Mele, 2018). The technology for individual buildings and individual vehicles is well established but how to join them together into an urban system is the big question. WGV seeks to help answer this. The project is just one precinct but it is establishing a model for how it can be fitted into an urban system consisting of multiple precincts joined together through P2P trading. WGV was the first example of P2P to be established in Australia and possibly the world.[4] Thus citizen utilities across multiple precincts can create whole cities with their buildings and transport powered through these distributed, linked systems exchanging their energy services (Glazebrook & Newman, 2018). Considered in aggregate, Citizen Utilities will give rise to Precinct Utilities and Urban Utilities: decentralised and distributed utility services operating throughout the world's cities and suburbs. As WGV is one of the first of these in the world to be established and tested the project has considerable global significance with other precincts already copying the technology and the governance/management system created[5] (Kennedy et al., 2018).

The governance models developed at WGV to manage energy and GHGs were set up to research the shared benefits, risks and costs between developers, owners, tenants, strata bodies and utilities. The models also include the energy system design, billing, legal addendums for dwelling purchasers and dwelling leases. The financial aspects of the governance models are being further studied, tested and demonstrated in three different strata lot developments over time. The models developed were set up to be adaptable and scalable to suit different development types. The project thus provides scalable and generalizable models for shared ownership of solar and storage in medium density developments. The WGV site serves as a demonstration of the effectiveness of the governance model in enabling greater solar PV and storage to be adopted across apartment housing in Western Australia and across other parts of Australia and the world (Green & Newman, 2017b). Once established any housing, whether high density or low density, will be able to make the most of being in a local Citizen Utility. The urban planning implications of these Citizen Utilities are not known so the project has many years of examining such matters.

3.2. The Urban Planning Process and the SDGs

The first step in innovative and perhaps controversial urban regeneration projects was to develop an effective community engagement process to support the inclusion and participation of diverse voices. The second step was to develop the innovations in sustainability using an accreditation process and innovative approaches to urban design, affordable housing, landscapes and water. And the final process was to create a Master Plan with associated scenario planning.

3.2.1. Community Engagement and Community Culture

The community in the City of Fremantle where WGV is located is well known as a center for sustainability (Beatley & Newman, 2009) and strong commitments to carbon neutrality as one of its core principles. The development at WGV needed to take advantage of this commitment to sustainability and to further encourage and develop this culture, while providing a practical demonstration for sustainable living in Australia. Through energy saving initiatives, affordable living options and a wide range of shared amenities, WGV aimed to become a community where it was easier and more affordable for people to live in a sustainable manner. To achieve this goal, the developers of WGV created a partnership with the City of Fremantle and other stakeholders to develop a series of strategies and incentives, such as building attractive community spaces, community housing and introducing new residents at the development to community activities, to help achieve this sustainable standard of living. A further incentive for residents to commit to WGV's vision is a funding package worth up to $10,000 for eligible single-lot buyers where the price and installation of technologies such as solar power, water tanks, advanced tree provision and smart meters, is offset.

WGV aimed to be 'inclusive' in the following ways. It set out to provide a range of affordable housing typologies and rental/ownership options, with a mix of 23 single residential developments, two apartment sites, a Gen Y demonstration housing project and one affordable housing apartment site. It aimed to address the rising cost of living through the reduction in use of mains water and retail electricity; thereby offering lower operating costs for residents. A sense of community is supported through the provision of community-based re-

[4] https://onestepoffthegrid.com.au/peer-peer-solar-trading-kicks-off-wa-housing-development
[5] https://onestepoffthegrid.com.au/tag/peer-to-peer-trading

sources such as barbeque and picnic facilities, nature play areas, and informal seating to foster community contact and promote livability at WGV. Transport in WGV is an issue as it is not centered around a major public transport system; however, a regular bus service is within a short walking distance from the WGV precinct. Several alternative transport modes were developed in WGV such as walking and cycling paths, provision for electric car recharging, an electric car-share program on site, and bike parking spaces. Help with the building and construction process was provided to future owners through workshops on sustainable house and landscaping design. Lessons learnt throughout the development of the precinct are being shared between the government and industry stakeholders, research partners, and the residents through online publications and research-related events.

Archival records together with interviews with stakeholders demonstrate that the development process was characterized by the following features:

- Visioning for sustainable development and a site/context analysis early in the business case development stage;
- Incorporating community participation through workshops at an early stage (before detailed planning was completed) that enhanced local context, sense of place and community aspirations, particularly relating to affordable and sustainable housing;
- Bringing together various planning-related professionals such as urban planners/designers, engineers, landscape architects and estate architects to ensure collaboration between stakeholders. This collaborative and participatory approach enabled multi-disciplinary planning professionals to simultaneously consider the positive and negative impacts of each other's proposed planning actions upon each other's plans, in the context of the developer's overarching vision for a sustainable development. This ensured fundamental design requirements for solar access (including to adjoining sites), communal open space and active building facades were included.

These three elements in the planning processes were necessary to ensure that WGV could simultaneously reduce urban GHG emissions and achieve the SDGs as outlined in the results section below.

Germinating from the abovementioned community workshops arose an understanding of the community's desire for a residential development that was in keeping with the strong environmental and community-oriented values of the existing local community. One key aspiration was the desire to secure a site for a housing cooperative for a group of local artists known as SHAC (Sustainable Housing for Artists and Creatives). At the time, SHAC was unincorporated and non-financial which presented logistical challenges in terms of securing land and financing a building.

Consistent with SDGs 16 and 17, a local partnership between SHAC and a local community housing organisation (a not for profit social/public housing provider called Access Housing) was facilitated via the developer. The partnership process guided the artists' cooperative toward incorporation as a legal entity, which enabled its recognition within a legal and financial context. In an innovative partnership, the community housing provider entered into a novel agreement with SHAC to purchase a parcel of land at the WGV development and build housing for SHAC. The community housing provider then enabled an inclusive design process giving SHAC early input into the building's design, incorporating many of their unique needs as residents, including artistic spaces for them to work onsite (Ward, 2016).

This partnership approach between tenant and landlord represented a new way to develop an affordable housing project for this community housing organisation and demonstrates the importance of grassroots empowerment and inclusion in the implementation of SDG 16 (Lawson-Remer, 2015). The outcome is access to sustainable housing for people who experience financial challenge due to the atypical labor market patterns of the arts industry (Throsby & Zednik, 2011). Further, the early introduction of artists and creatives into this residential development supported the function that culture and art play in facilitating civic development and inclusion (Plant, 2016).

3.2.2. Sustainability Accreditation

In recent decades, various certification systems have been developed to support sustainability in the urban planning process that could be used by developers to further the SDG and 1.5 °C agenda (Newman et al., 2017). Initially limited to the building scale, some systems have since recognized the need to encapsulate a more holistic and wider community scale approach to sustainability (Haapio, 2012). Some of these certification systems have been criticised as they often do not include clear and specific targets aimed at performance and that evaluation of final outcomes can be deficient (Wangel, Wallhagen, Malmqvist, & Finnveden, 2016, pp. 200, 204, 210). However, most innovative developments use accreditation to help provide a systematic approach to precinct scale sustainability (Rauland & Newman, 2015; Webb et al., 2017).

One Planet Living (OPL) is an accreditation scheme developed by Bioregional, a UK firm that created BedZED in London. The OPL scheme is an international sustainability initiative based upon the idea that people need to live within the limits of one planet's natural resources. OPL provides a framework, built around 10 principles (see Figure 3), which guide sustainable development. The use of OPL at WGV innovatively addresses the concerns of certification systems raised by Wangel

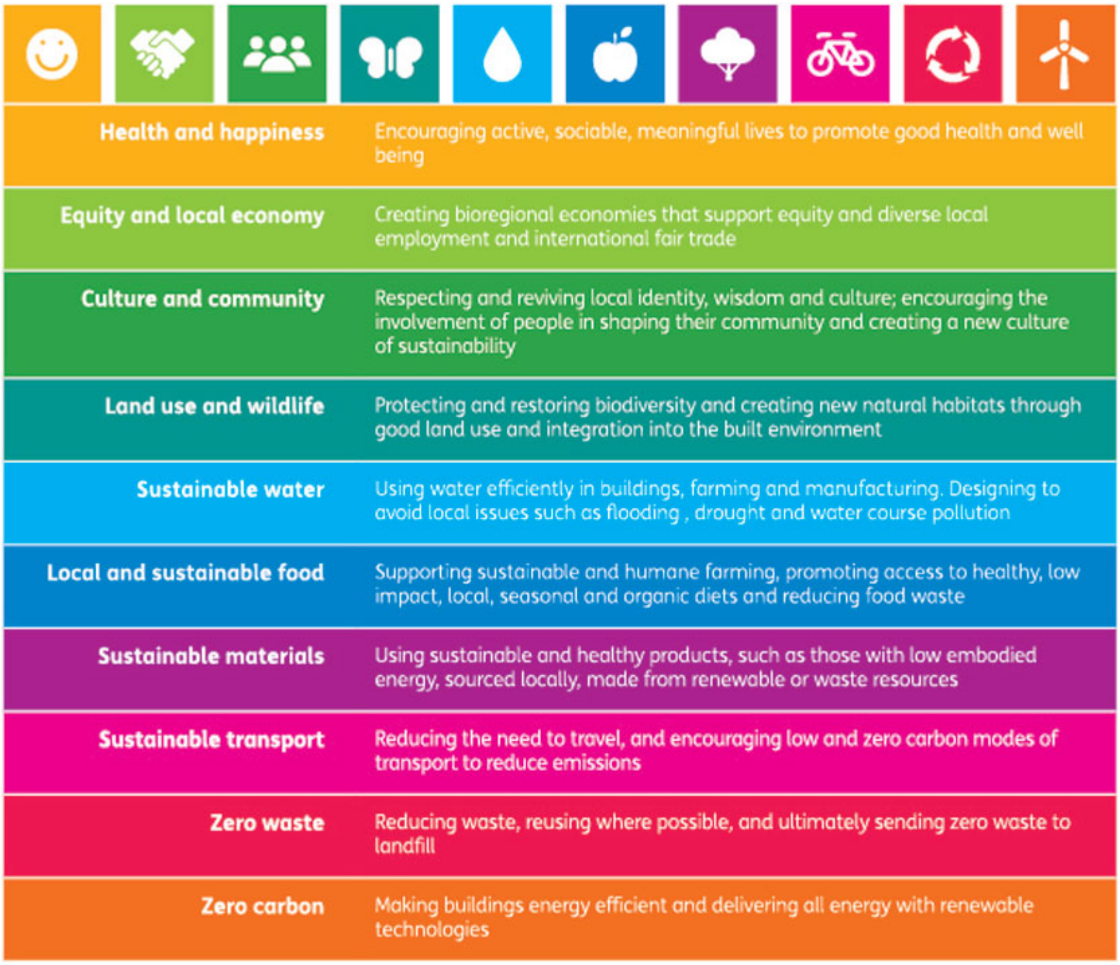

Figure 3. The OPL Goals. Source: Bioregional (n.d.).

et al. (2016) through specific performance targets, post-planning evaluation while taking a holistic approach to sustainable urban planning.

WGV is Western Australia's first residential project to achieve national recognition for its adoption of the OPL scheme to guide each stage of the urban planning and development. It is only the second project in Australia and only the eleventh worldwide to achieve an international endorsement as a One Planet Community through OPL. The City of Fremantle is one of the first One Planet Council's in Australia, therefore the required One Planet Assessment Report for WGV links in well with the City's One Planet Strategy and provides a solid framework for community members to implement sustainable living practices within their own homes. The main goal of OPL is to create neighborhoods where it is easy, attractive and affordable for people to live enjoyable and healthy lives using an equitable share of the earth's resources. As it requires zero carbon and has a range of 'inclusive' requirements, it is an ideal accreditation system for guiding the 1.5 °C agenda with the SDGs.

At WGV, the OPL's 10 principles were used to help guide the development and to demonstrate to the community, and potential buyers, that the project is a pioneering, real world, highly innovative, urban development.

3.2.3. Urban Design

The WGV project applied a multi-faceted design approach to sustainability with affordable housing and numerous environmental initiatives integrated into the design. The partnership between various stakeholders was seen as the basis for the development to be set up as a 'living laboratory' where energy use, resident behavior, energy initiatives and the implementation of the WGV Design Guidelines (LandCorp, 2015) can be monitored and assessed. WGV features innovative and pioneering energy, water and climate responsive design, innovative housing design for each of the development sites, e.g., the Gen Y project and a free open source website for the exchange and sharing of information on the design process.

The Gen Y Demonstration Housing Project is a prime example of quality urban design with its efficient use of the residential block through density and shared infrastructure and services. The increase in density has not come at the expense of livability for its residents and neighbors with each apartment having private and communal areas, generous ceiling heights and high thermal efficiencies. The Gen Y Demonstration Housing Project has been accredited with a gold medal level life cycle analysis by eTool (Beattie, Bunning, Stewart, Newman, & Anda, 2012), meets the principles of the OPL sustainability framework and has been designed to meet the essential requirements of Liveable Homes accessibility standards. The development was awarded the Australian Urban Design Award for Urban Design, Policies, Programs and Concepts: Small Scale in 2017.

A key aspect of the development project is the climate responsive layout which integrates solar passive design principles which ensure natural light, cross ventilation to each apartment and use of sustainable materials such as green concrete using low carbon furnace slag that increases thermal mass. Initial conversations with residents indicated that although they have moved from housing that has had air conditioning and heating systems that were regularly used, they are comfortable in the new dwellings that do not have these, verifying the climate responsive design. The three apartment developments on site have been designed to use renewable energy, water sensitive practices and battery storage technologies which include the installation of a 9kW Photo Voltaic system with battery storage, a 10,000L underground rainwater harvesting tank, and performance monitoring for all key services. The performance monitoring undertaken through the living laboratory research will provide valuable input for future developments on how the urban design principles perform with residents living at WGV, ensuring the results can be utilised by other developments targeting the SDGs and 1.5 °C agenda.

3.2.4. Affordable Housing

Affordable housing is critical for any development striving to be a model for multiple SDG goals. In Australia, it is estimated that 13% of the population is living under the poverty line, many of these children and old aged pensioners (Australian Council of Social Services, 2016). WGV addresses the lack of affordable and diverse housing in Perth through a range of dwellings and the inclusion of 15% affordable housing stock in the development (Housing Authority, 2016). The partnership between LandCorp, Access Housing and SHAC came together to deliver a community housing development specifically for local artists and their families at WGV. This initiative aims to support the local creative industry and encourage greater diversity and culture within the community. The partnership provides affordable housing for artists who work in the cultural and artistic center of Fremantle but have been priced out of the residential housing market and were travelling long distances (upwards of 50kms) to work and cultural events, often not using public transport. The SHAC development is part of a diverse range of housing and living options within WGV and includes apartments, townhouses and single homes that has attracted a broad cross section of society to WGV, resulting in a strong diversity of residents.

Along with the SHAC development, WGV is home to the Gen Y Demonstration Housing project, which is a practical demonstration of sustainable and cost-effective housing to suit living in the 21st century as well as two other demonstrations of social housing: a Baugruppen Model housing co-op and a privately funded housing co-op. WGV thus provides a practical demonstration of several new housing models that can be replicated to provide affordable housing for a range of people.

The various apartments of the WGV project also explored how to address the problem of the 'missing middle' of medium density housing, where cities like Perth have a plethora of either low-density single family homes in outer suburbs or higher-density apartments in inner areas, but not medium density dwellings in middle suburbs (Thomson et al., 2017). This project demonstrates a solution where the gap between single homes and apartment blocks can be bridged through some increase in density while also integrating well within the landscape of low-density housing surrounding the area.

The diversity of housing options was a key way that WGV was inclusive of the local community and could facilitate SDGs.

3.2.5. Landscape and Water

The creation of an attractive and highly liveable environment was seen as central to the design for WGV where local biodiversity, shade and shelter and opportunities for community interactions are supported. Through careful planning, 25% of the existing trees were retained in the subdivision design. Beyond this, there was a prioritization on the reuse and repurposing of materials to minimize waste. Before site work commenced on the project, a tree assessment was undertaken to determine suitable timber for harvesting and reuse with the development. Limestone recovered during project civil works was also incorporated into the landscape to celebrate local materials.

There was a fauna relocation program undertaken prior to site works commencing and the strategic provision of habitat structures has been considered within the new landscape. The planting of new trees was a priority with the project aiming to match the predevelopment canopy density while increasing dwelling density. This is an important strategy to improve livability but also contribute to the urban forest of the greater area. The re-engineering and revegetation with native plants of a large stormwater sump adjacent to the precinct was undertaken in partnership with the City of Fremantle to create a public space that was both attractive and engaging with the public while maintaining biodiversity and fulfilling its original drainage function (see Figure 4).

Overall the landscape design aimed to reflect White Gum Valley's character, support local biodiversity and promote community use of public spaces. 30% of the street trees are edible fruit species to support local food production and foster community sharing of resources. Public spaces include BBQ facilities and shaded picnic areas, nature play areas, informal seating and a network

Figure 4. Left: installation of drainage cells as part of the retrofitting of the stormwater sump; right: the completed stormwater sump with a newly landscaped parklet for community use. Source: LandCorp (2015).

of walkways and cycle paths to encourage active, outdoor lifestyles.

A range of positive benefits is set to be achieved as a result, including:

- Improving community health and wellbeing through the creation of an attractive and engaging outdoor environment;
- Providing habitat and native food sources to support local wildlife;
- Activating public open spaces to foster community cohesion and improved safety;
- Encouraging shared local food production to build community;
- Utilizing locally sourced materials, including repurposing of demolition materials to minimise waste.

Integrated Urban Water Management (IUWM) is a key feature of the precinct. The project is targeting a reduction of mains water consumption by 60–70% compared to the Perth average per capita consumption across the various housing typologies. To meet this goal, there is leading in-house and ex-house water efficiency measures, rainwater harvesting on the single residential lots and the Gen Y Demonstration House (for toilet flushing and washing machines), and a community bore water supply for irrigation. Each of these initiatives is supported by a combination of Design Guidelines (controls) and developer incentives (sustainability package) to increase successful implementation.

In addition to mains water reduction through efficiency and source substitution, water sensitive design has been applied to ensure stormwater is carefully managed across the landscape to promote local infiltration and groundwater recharge.

3.2.6. Master Plan and Associated Scenario Planning

Once the outline of a potential product was determined meeting all the above design objectives and providing a saleable product, it was possible to draw up a Master Plan and assess various scenarios that provided the planners and developers with necessary densities and expected outcomes for WGV. Such modelling was done using the Kinesis Modelling tool (Beattie et al., 2012) to assess the cost of the housing products, the carbon emissions, water consumption, transport and proportion of affordable housing. The project was then put to the market.

4. Results and Discussion

The results are set out to show how well WGV has turned out in terms of the 1.5 °C agenda, the SDGs and the saleability of the product.

4.1. WGV and Net Zero Carbon for the 1.5 °C Agenda

The results from the Kinesis modelling are summarized in Figure 5. They show that WGV was overall likely to be around 59% lower in carbon emissions, 75% lower in water and 21% lower in operating costs. Transport is almost identical as the site it is not well placed for public transport. This is further discussed later in the article.

The Kinesis modelling was undertaken at the completion point of Structure Planning, prior to detailed design and the incorporation of innovative programs like the strata solar energy storage trial on the multi-residential buildings, and the sizing of solar energy systems for the single residential lots to meet a net zero energy status. At the time of publishing this article, detailed modeling of the 'As Designed' scenario that incorporates the full suite of initiatives in partnership with industry and researchers was still being finalized. However it was clear that the potential for a zero carbon power system was now possible—at least in terms of design. As an example, the first multi-residential building to be completed, occupied and monitored (the Gen Y Demonstration House) is close to meeting 100% operational power requirements. Ongoing assessment through the seasons will be required to determine the extent to which the building can meet its operational energy needs. Likewise, the modelling indicates that the residential dwellings will

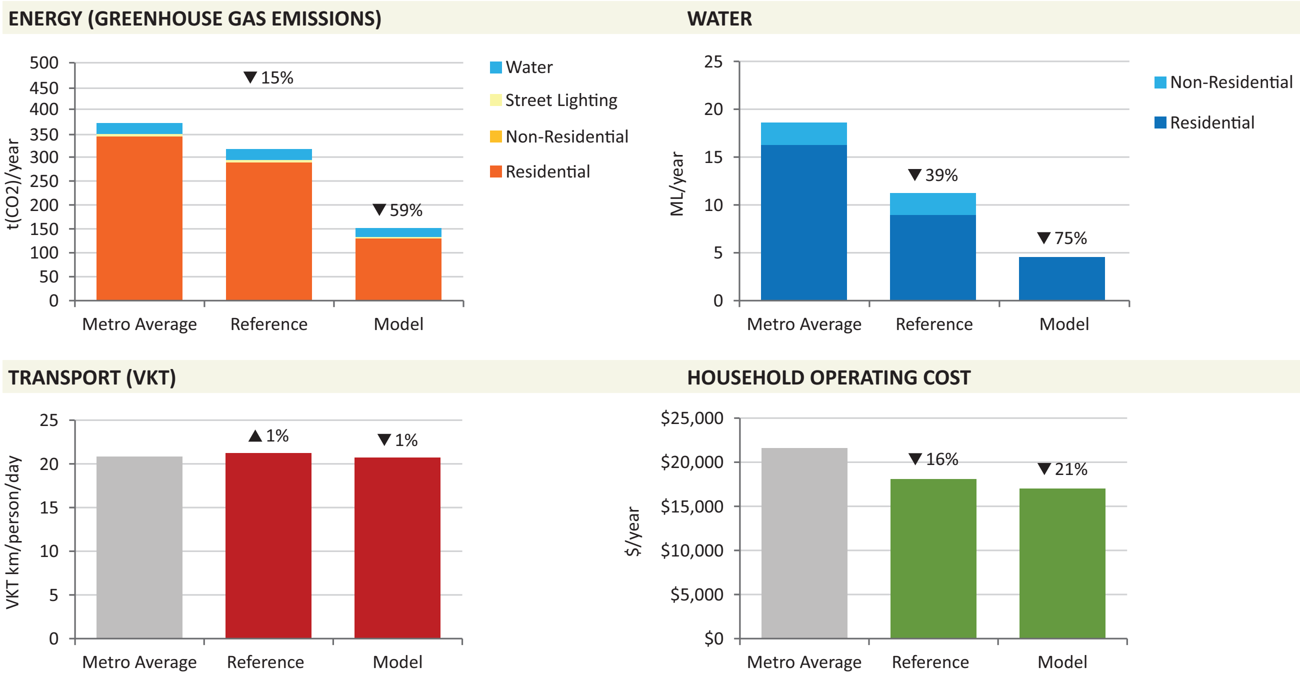

Figure 5. Results of early scenario modelling on WGV.

meet net zero energy, assuming the homes are operated as intended as early data shows between 72% and 98% of the power needs will be met from the solar and batteries. Thus, with the solar energy being exported to the grid (once batteries are filled) this means more renewables are being produced than energy consumed.

The establishment of a monitoring program across the whole site with detailed monitoring of particular developments like Gen Y and SHAC will provide the extent to which the design for zero carbon has been translated into real living situations.

4.2. WGV and the SDGs Agenda

Table 2 summarizes the work at WGV to create an urban development that can be close to zero carbon and at the same time help achieve the SDGs. The Table shows for each SDG how well the SDG has been met in WGV—major, medium or minimal—and what in particular was done.

Table 2 shows that the major focus of the 1.5 °C agenda, achieving a zero to low carbon development, is likely and that at the same time the development has contributed significantly to the SDGs. It demonstrates that, of the 17 SDGs, 12 SDGs were achieved in a major way, and five in a minimal way. This would suggest that a significant urban development demonstration has been achieved in the design of the WGV project. Initial modelling of the infrastructure performance and interviews of the residents indicate that WGV is on track to achieve these goals as planned from the design stage.

Another way to use the SDG framework is to examine the indicators that were set up by the UN for the SDG 11 urban goal. These are set out in Table 3.

Out of the seven indicators only one shows up relatively poorly, the transport indicator, as WGV is not a transit oriented development. However residents are already finding innovative solutions to transit problems, with some returning to their habit of bicycle riding that was not used in their previous households. Others are staying closer to home for recreation with their small children and utilizing the shared spaces instead. For SHAC in particular, the residents have been able to work onsite in the artist studios, or close by in the center of Fremantle, reducing the need to travel the long distances they were in previous housing. The first steps towards making this area more transit oriented through urban planning are happening along the corridor into the Fremantle CBD where a new development around ten times the size of WGV is being planned with opportunities to scale up many of the innovations in WGV; this should include a transit system with innovative smart systems and an autonomous electric bus service that could also be brought to WGV. This would help considerably in completing the agendas for both 1.5 °C and the SDGs.

4.3. WGV and Market Results

As the West Australian Government land development agency, LandCorp is obliged to deliver its projects on commercial terms. As such, the broad range of innovations described in this article were scrutinized to ensure they were technically and financially viable. Except for the research grants identified, WGV has met the necessary business case considerations of a successful land development based on market return. In addition, the offerings were very well received by the market, with all lots sold in good time at a period where the market was

Table 2. SDGs and how the WGV residential development contributes to their achievement.

UN SDGs	UN SDGs Defined	WGV Details and Extent	Overlaps with other SDGs
1 NO POVERTY	End poverty.	Major: affordable and social housing.	10, 16
2 ZERO HUNGER	End hunger, achieve food security and improve nutrition.	Minimal: planting of edible fruit tree varieties; promoting home food growing in the Design Guidelines; connecting residents with local community gardens through the Resident Information Pack.	3, 12
3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being.	Minimal: attractive and engaging outdoor environments; connecting residents with activities and networks through the Resident Information Pack.	
4 QUALITY EDUCATION	Ensure quality education for all.	Minimal: educational demonstration project of sustainable living.	
5 GENDER EQUALITY	Achieve gender equality.	Major: strong women's leadership in social housing.	
6 CLEAN WATER AND SANITATION	Provide safe and affordable water and sanitation for all.	Major: reduction of water usage, water efficiency, water sensitive design.	3, 17
7 AFFORDABLE AND CLEAN ENERGY	Ensure access to affordable, reliable, clean energy for all.	Major: solar and battery storage, energy efficiency, renewables.	9, 12, 13, 17
8 DECENT WORK AND ECONOMIC GROWTH	Promote decent work for all and sustainable economic growth.	Major: citizen utility, sharing of energy through peer to peer network, 'pro-sumer'; affordable housing.	
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure; promote inclusive and sustainable industrialization and foster innovation.	Major: innovative design and demonstration project fully monitored.	7, 11
10 REDUCED INEQUALITIES	Reduce inequality within and among countries.	Major: Gen Y housing project, SHAC "sustainable housing for artists and creatives" housing project.	

Table 2. SDGs and how the WGV residential development contributes to their achievement. (Cont.)

UN SDGs	UN SDGs Defined	WGV Details and Extent	Overlaps with other SDGs
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable.	Major: shared amenities, community gardens and activities, consultation and innovative technologies.	
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and production patterns.	Major: renewable energy, production of resources, resource efficiency.	2, 7, 9
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts.	Major: zero carbon, renewable energy, accreditation.	7, 9, 11, 12
14 LIFE BELOW WATER	Protection and sustainable use of marine resources.	Minimal: advising residents on ethical purchasing programs through the Resident Information Pack, storm water cleaning in innovative sump.	
15 LIFE ON LAND	Protection and sustainable use of land resources.	Medium: habitat and food sources for local wildlife.	
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies, provide access to justice, and provide strong institutions.	Major: SHAC, Gen Y housing demonstration project; community engagement.	1, 3, 11
17 PARTNERSHIPS FOR THE GOALS	Work together for sustainable development.	Major: community consultation, partnerships with local, state and federal government; research bodies; private enterprise; and not-for-profit sector.	9, 10, 11, 16

down. Market interest has also been strong on the multi-residential units. This is important context as it demonstrates both the financial viability and market appetite for quality projects that provide leadership in a low carbon future. The challenge is how these concepts can be upscaled and delivered into other regions around the country and the world.

5. Conclusion

Rapidly growing cities need to tackle the agenda of 1.5 °C to keep the extremes of climate change from impacting on global environments, societies and economies. Cities also need to implement urban planning and development that achieves the SDGs in an integrated and systematic way. WGV is an example of how this can happen using established accreditation processes such as the OPL framework.

WGV is a development where precinct-scale planning has been focused upon improving the livability of the development through various building typologies, climate sensitive designs, urban greening, water and energy management strategies, as well as a sense of place and community engagement strategies. Partnerships and early planning of innovations enabled solutions to be found to many problems faced in everyday urban precincts and thus were able to move the development towards achieving its three goals of zero carbon for 1.5 °C, inclusive design for the SDGs and a marketable product to enable mainstreaming.

By using the SDGs as a template for assessing WGV we can see how targets can be reached and the ways in

Table 3. Urban SDG indicators and how they apply to WGV.

Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable Targets:	**WGV Achievements**
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.	Housing affordability mainstreamed through different housing and tenure types and through reduced operational costs. Basic services all available through community utility.
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.	Public transport is not much more available as WGV is not close to economic activity or on a transit route of any significance, however it is close to schools, local shops and local green spaces. Walkable and cyclable internal street designs and the availability of a shared EV all assist. Universal access has been built into homes and internal roads.
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.	Inclusive community already exists in the area and WGV builds on that with a landscaped BBQ area, internal streets encouraging walkability and community events organised by residents. The Citizen Utility can use infrastructure management and planning for greater community engagement in urban living processes.
11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage.	Many features of cultural heritage were incorporated into the new development including naming some streets with Nyoongar words, restoration of the old Community Hall restored for public use, local artists engaged in designing elements of public space, reuse of trees removed during the building process on the site.
11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.	New solar/battery systems and water sensitive urban design (especially storm water sump) are much more resilient for future climate change or disaster management. Citizen Utility will mean very strong social capital that is also critical to resilience.
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	Waste management and air quality improved by community infrastructure.
11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.	Green spaces created, existing trees retained and canopy cover planned into the development; Citizen Utility will ensure area regenerates organically.

which they can be made possible. This article illustrates the demonstrated attempts to realize the ambitions of achieving both the 1.5 °C agenda and the SDGs at the WGV residential development through thoughtful and inclusive urban planning. The lessons from it can now be mainstreamed and translated to other environments and cultures.

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Conflict of Interests

The authors declare no conflict of interests.

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Article

Beijing's Peak Car Transition: Hope for Emerging Cities in the 1.5 °C Agenda

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Abstract

Peak car has happened in most developed cities, but for the 1.5 °C agenda the world also needs emerging cities to go through this transition. Data on Beijing shows that it has reached peak car over the past decade. Evidence is provided for peak car in Beijing from traffic supply (freeway length per capita and parking bays per private car) and traffic demand (private car ownership, automobile modal split, and Vehicle Kilometres Travelled per capita). Most importantly the data show Beijing has reduced car use absolutely whilst its GDP has continued to grow. Significant growth in electric vehicles and bikes is also happening. Beijing's transition is explained in terms of changing government policies and emerging cultural trends, with a focus on urban fabrics theory. The implications for other emerging cities are developed out of this case study. Beijing's on-going issues with the car and oil will remain a challenge but the first important transition is well underway.

Keywords

Beijing; emerging cities; peak car; traffic demand; traffic supply; urban fabrics

Issue

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1. Introduction

Some developed cities witnessed a plateau in per capita car use in the early part of this century, which became known as 'peak car' (Headicar, 2013; Newman & Kenworthy, 2011; Puentes & Tomer, 2008; Stanley & Barrett, 2010). The phenomenon of peak car provides hope for reductions in oil consumption and greenhouse gas (GHG) emissions (Goodwin, 2012; Millard-Ball & Schipper, 2011; Newman, Beatley, & Boyer, 2017). However, it will not help agendas like the UNFCCC agenda to reach 1.5 °C, unless the vast mega cities of the emerging world also undergo peak car. This article will examine the extent to which Beijing is demonstrating peak car as an example of how close the emerging world could be to contributing positively to the 1.5 °C agenda. The question underlying this article therefore is whether peak car is happening in one of the world's largest and fastest growing emerging cities.

China was well known as the 'kingdom of the bicycle' in the 1980s. The modal split of daily trips by bicycles was as high as 63% in Beijing in 1986 (BJTRC, 2015). Beijing was then recognized as a Non-Motorized Mode City (NMM) in 1995 in a global cluster analysis (Priester, Kenworthy, & Wulfhorst, 2013). However, the Chinese bicycle culture had started to decline by the end of 20th century as a direct result of Chinese economic growth, urban development and the prosperity of the Chinese automotive industry (Gao & Kenworthy, 2016). China replaced the US as the largest automobile producer and consumer from 2009 (Gao, Kenworthy, & Newman, 2014). The resulting affordability and availability of automobiles facilitated rapid growth in car use across Chinese cities. Beijing is an example of how the bicycle was rapidly replaced with automobiles: automobile modal split went from a meager 5% in 1986 to 34% by 2010. The resulting traffic did not suggest that Beijing had much hope of contributing to any agenda on reducing automobile-based emissions.

The popularity of automobiles in China undoubtedly facilitated economic growth and urban mobility. However, it also generated negative impacts upon the Chinese economy, society and environment, especially in relation to oil consumption, GHG emissions and smog emissions, some of the most pressing problems for urban sustainability. The potential to reduce such environmental impact was not seen to be very high as the economic conditions leading to reduced environmental impacts in the developed world happened at much higher levels of per capita economic development (Asian Development Bank, 2012). However, the theory of what brings such change suggested that rapid urbanization could also bring about a new set of priorities that enable higher environmental concern and priority. As China's built-up area increased six-fold in 28 years from 1987 (Ministry of Housing's China Urban Construction, 2015), it was quite clear that rapid urbanization was a Chinese characteristic.

Part of the response that leads to change of priorities in cities is how quickly governments respond to the new needs of such rapidly growing cities. Part of the necessary government change happened in recent times due to the global climate debate. China has been a strong part of the global climate change agenda for over a decade. The Paris Agreement came into force in 2016 and aims to 'keep a global temperature rise this century well below 2 °C above pre-industrial level and to pursue efforts to limit the temperature increase even further to 1.5 degree Celsius' (United Nations, 2015). China signed the agreement and took a strong stand that it will meet their commitments of 60–65% reduction in carbon dioxide emissions per unit of GDP (Gross Domestic Products) by 2030 from the 2005 level (NPC, 2016). Beijing, as the national center of politics, culture and foreign relations, was necessarily a major part of the new climate agenda and, its transition will be a live demonstration of how cities can take a bold step towards creating a more sustainable urban environment.

The transition to peak car should not therefore have been a great surprise but indeed the changes are still quite remarkably fast and thus the data will be set out showing trends in car ownership and car use, transit trends and traffic infrastructure, as well as GDP data and electric vehicle trends. An attempt will then be made to explain the phenomenon through government policies and urban planning theories.

2. Traffic Demand, Private Car Ownership and Use

Chinese cities, along with their respective provinces, have increased their car ownership over recent years and now provincially range in car ownership from a meager 51 per 1,000 persons in Tibet, up to 198 per 1,000 in Beijing, with a national average of 93 per 1,000 persons (see Figure 1). This national level of car ownership is less than countries such as Swaziland, El Salvador, Honduras, Guyana and Azerbaijan (NationMaster Online Database, 2016). These levels are nowhere near the car ownership levels found in cities in more developed countries. For example, in 2005–2006, cities in the US averaged 640 cars per 1,000 persons, Australian cities 647, Canadian cities 522, and European cities 463 per 1,000 persons (Newman & Kenworthy, 2015). Thus, Chinese provinces and cities, even during what could be called a rampant period of motorization, had by 2015 not even come close to car ownership rates in more automobile dependent regions, and were even less nationally than in some significantly less developed countries.

Private ownership of motor vehicles especially small- and mini-sized passenger cars stimulated the growth of the total number of motor vehicles to some degree as shown in Figure 2. A fear of the consequences of China's growing vehicle ownership on traffic and air quality led to dramatic restrictions on car ownership and use. Beijing has rationed road space in 2008 to limit car travel and deployed an unpaid lottery system in 2010 to distribute license plates to public applicants to cap the number of new car registrations (BMCT, 2010). Besides these, the other Transportation Demand Management (TDM) policies like the termination of national pro-car policies designed to assist the economy during the global financial crisis (GFC) (Ministry of Finance, 2011a, 2011b, 2011c) have also accelerated the sharp drop in the growth rate of private car ownership (see Figure 2). There was just a 3% growth rate in 2011 compared to 2010 level of 23%.

The actual car use, different from car ownership, is reflected by per capita Vehicle Kilometres Travelled (VKT) and modal split of daily trips by automobiles. Per capita, VKT has increased steadily through the beginning of the 2000s and then peaked in 2010 before sharply declining despite the continuing economic growth (see Figure 3). It is set out showing how the decline is not caused by a decline in economic growth; on the contrary car use has declined during a period of substantial economic growth in Beijing. This is 'peak car' as seen in most developed cities and now clearly evident in Beijing, though a little delayed from the peak around 2004 in US and Australian cities (Newman & Kenworthy, 2015).

The GDP increasing is an important parallel result for the global agenda which is seeking to eliminate extreme poverty and other important social objectives through the SDGs. The 1.5 °C agenda is unlikely to be met unless emerging cities are going to begin a peak car transition whilst also achieving economic and social development goals. Figure 3 suggests that this may be possible. It is important therefore to see how Beijing seems to have achieved this.

The data on Beijing's modal split show a similar critical turning point to peak car around 2010 when the pro-

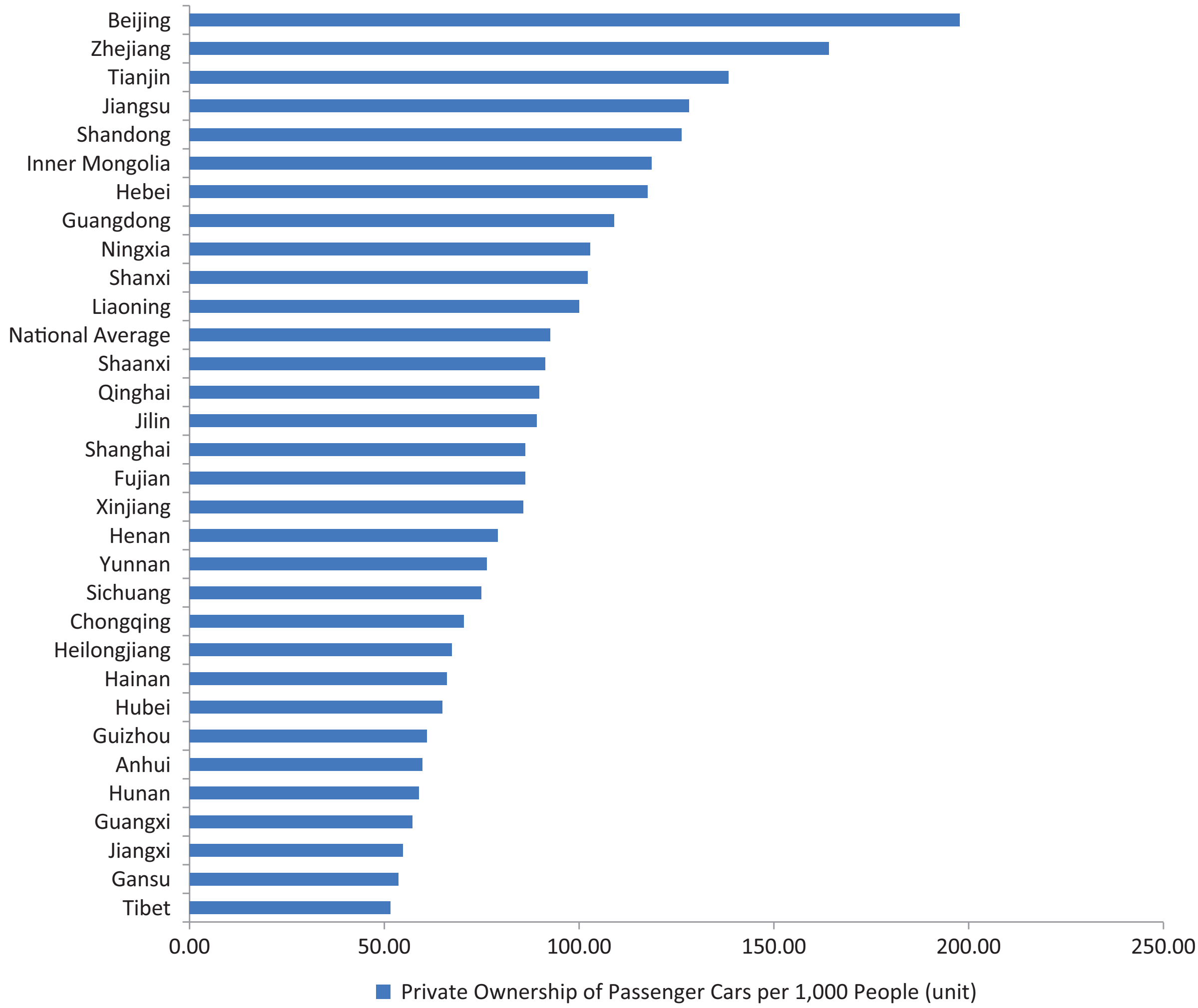

Figure 1. Private ownership of passenger cars per 1,000 people across China in 2015 (unit). Source: Compiled based on data provided by the National Bureau of Statistics of the People's Republic of China (NBSC, 2016).

portion of transit use began to increase sharply and the proportion of car use began to go down after initially replacing bicycle use (see Figure 4).

The switch to transit is due to a rapid growth in the provision of urban rail through municipal and national support especially the Five-Year Plan, a package of incentives to assist the national economy and social development. The Tenth Five-Year Plan in China 2001–2005 was the first to embrace 'developing urban rail transport' and then the Twelfth Five-Year Plan (2011–2015) started strong encouragement of the public transport system, including the dramatic growth of Metro systems across the nation's cities. Quality transit appears to be the first clear policy to assist in achieving peak car goals. Further data on how this was done is therefore examined in terms of investment trends in road and rail.

3. Changing Development Trends in Infrastructure

Beijing operated its first metro line in 1969 and it took 33 years to complete two more lines (BJMBS, 2016). The Metro system in Beijing since then has undergone rapid development, starting with the 2008 Olympics with 3 new lines constructed from 2007 to 2008 and then continuous expansion until the present. The expansion of the Metro is clearly shown in Figure 5 below from 2 lines, 54 km of track and 469 million passengers a year in 2001 to 18 lines, 554 km of track and around 3,324 million passengers a year in 2015 (around 9 million passengers a day). Bus patronage share has declined as the rail system grew (see Figure 5).

At the same time as investment in rail grew, there has been a reduction in the priority given to freeways and parking infrastructure for cars in Beijing despite continuous increase in economic capacity (see Figure 3) and traffic demand, both of which decline in per capita terms in the period leading up to the decline in per capita car use (see Figure 6). This is significant for any emerging city wanting to reduce its car use.

4. Spatial Distribution of Population

In Beijing there are 16 different sub-divisions governed directly by the Beijing Municipality (BJMBS, 2016). These

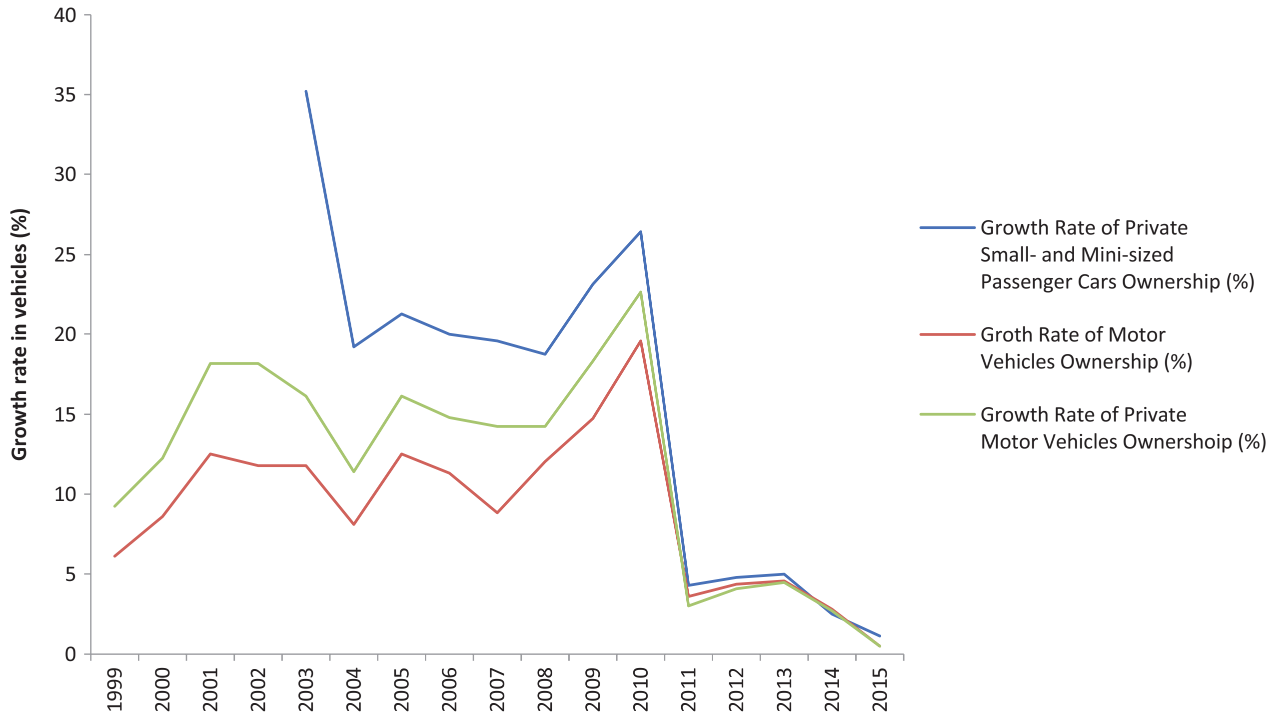

Figure 2. Comparisons of growth rate of ownership between motor vehicles, private vehicles and cars in Beijing from 1999 to 2015. Source: Compiled from data provided by the Beijing Transportation Research Centre (BJTRC, 2002–2015, 2016).

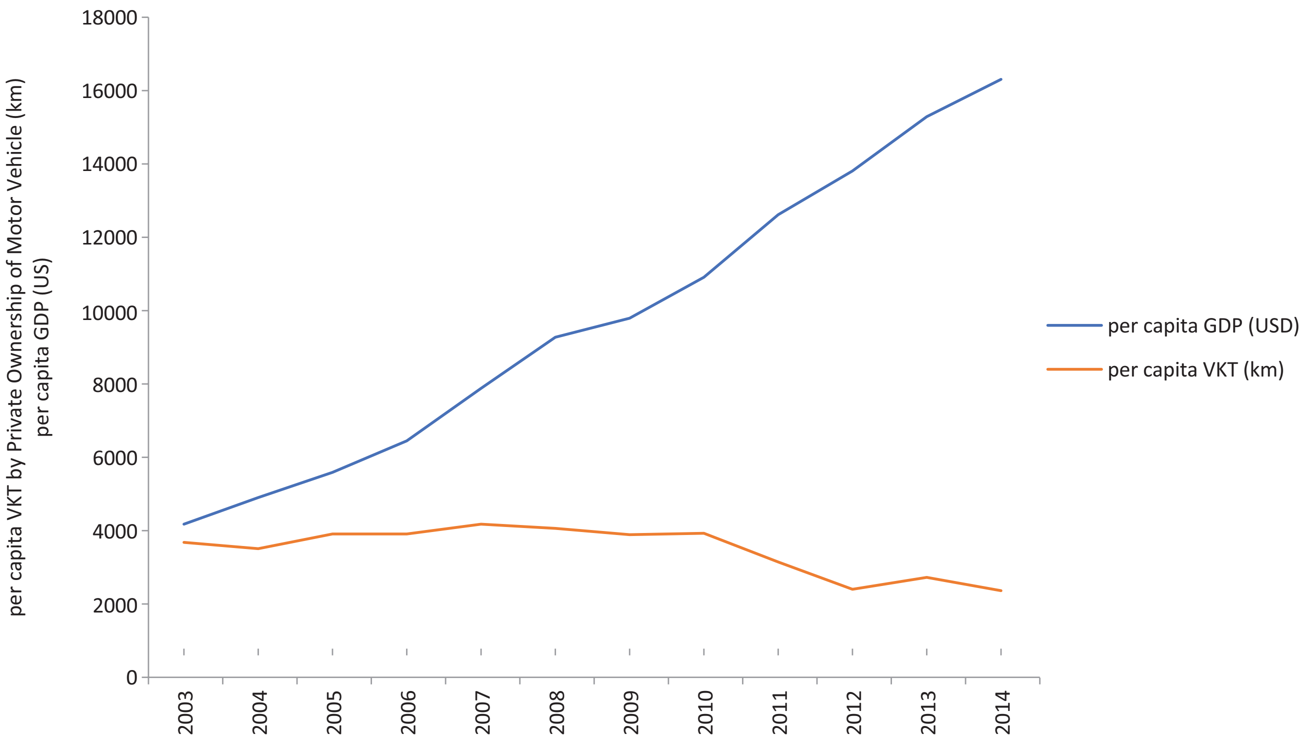

Figure 3. Peak car in Beijing: relationships between economic performance and private automobile use in Beijing from 1986 to 2014. Source: Compiled based on data provided by the Beijing Municipal Bureau of Statistics (BJMBS, 1982–2015, 2016) and the Beijing Transportation Research Centre (BJTRC, 2002–2014, 2015).

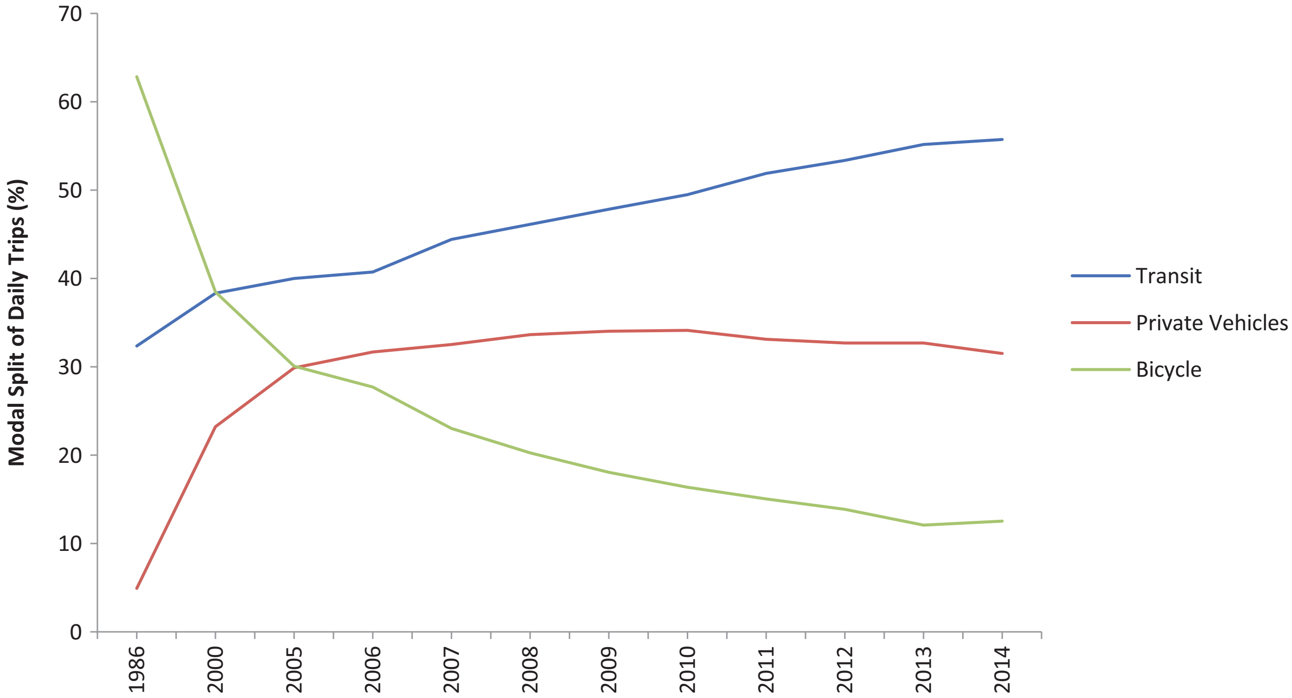

Figure 4. Modal split of daily trips in Beijing (excluding walking). Source: Compiled based on data provided by the Beijing Transportation Research Centre (BJTRC, 2002–2014, 2015).

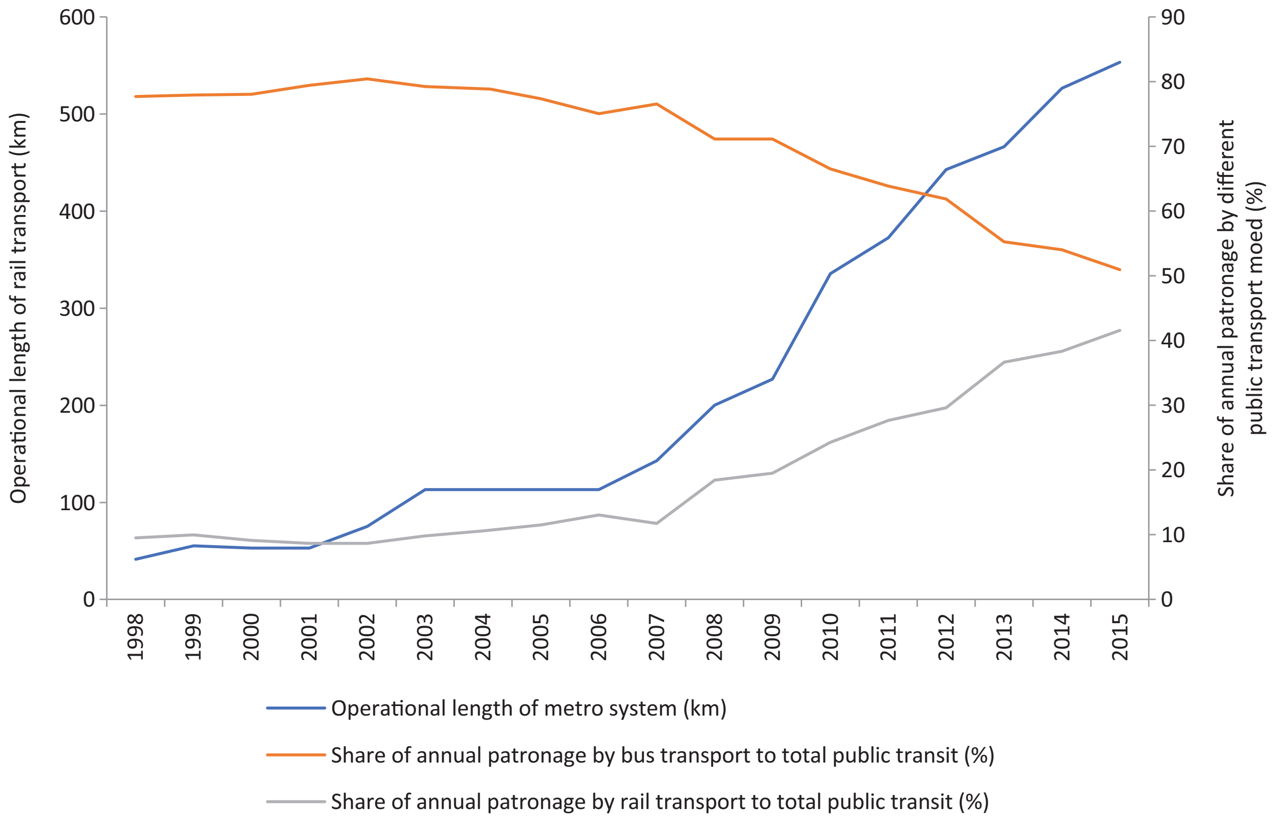

Figure 5. Operational length of rail transport and the share of annual patronage by rail transport to total public transport modes in Beijing (including rail transport, taxi, bus and trolley bus). Source: Compiled based on data provided by the Beijing Transportation Research Centre (BJTRC, 2002–2014, 2015).

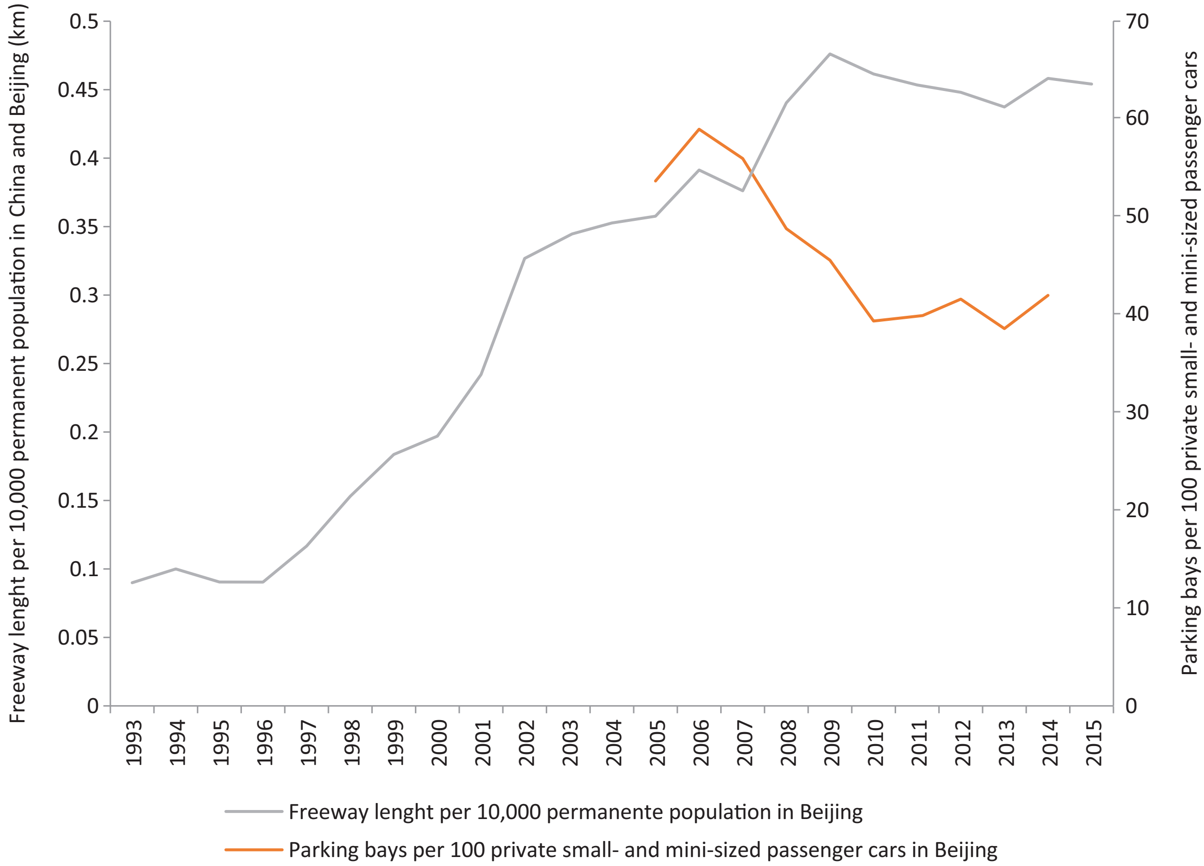

Figure 6. Trend of freeway length per 10,000 permanent population (km) and parking bays per 100 private small- and mini-sized passenger cars in Beijing. Source: Compiled based on data provided by the Beijing Transportation Research Centre (BJTRC, 2015) and (BJMBS, 1994–2015, 2016).

16 districts are also categorized into four different types for economic development and environmental protection perspectives. Table 1 defines the three different types of districts according to their distinct urban fabric (see Table 1).

The spatial distribution of the population plays an important role in per capita car use (Headicar, 2013). Usually the outer suburbs have much higher car use than the inner and central areas (Newman & Kenworthy, 2015). In Figure 7 the central city has remained static in population over the past decades but the inner and outer areas have both grown substantially. The data would suggest that the inner area growth has enabled low car use destinations to be able to grow more swiftly than the higher car using areas and together with Metro lines going to all parts of the city, the overall result is reduced car use.

5. Urban Density and Urban Fabric

The data on transport and infrastructure are clearly suggesting a major discontinuity between the growth in car use that would have been expected in an emerging city like Beijing and the actually observed peak car use. The difference is likely to be a combination of these transport and infrastructure priority changes and the fundamental land use in the city.

The ‘Theory of Urban Fabrics’ explains the interactive relationship between urban transport and urban form (Newman, Kosonen, & Kenworthy, 2016). It identifies three distinct urban fabrics by the priority of transport infrastructure systems: Walking city (pre-history to the 1850s), Transit city (1850s to the 1950s) and Automobile city (from the 1950s). Car use declines exponentially with urban density increases (Newman & Kenworthy, 2015) and thus as the densities declined in each of these three phases the amount of car use has tended to go up. However, in recent years in all developed cities people began to move back into walking and transit urban fabric and hence densities began to go up again leading to a decrease in car use.

The spatial data would suggest that the transit fabric of inner areas, where most growth has happened, has been a factor in these reduced car use levels. However, there is another factor as even the outer areas have substantial density levels that make transit and walking options much easier. In China, the cities were very dense during the historic walking city period and the transit city period as well with high-rise buildings stretching along corridors. The recent rapid urbanization period has continued to build at high densities as extra layers around the old cities were built. The density was thus significantly higher than in developed world cities.

Table 1. Different categories of districts in Beijing. Source: Compiled based on data provided by the Beijing Municipal Bureau of Statistics (BJMBS, 2016).

Administrative Division	Four Different Types of Functional Zones	Three Different Types of Districts with Different Urban Fabrics
DongCheng Xicheng	Capital Economy Code Zone	Central City
Haidian Chaoyang Fengtai Shijingshan	Municipal Development Zone	Inner Area
Tongzhou Shunyi Fangshan Daxing Changping	Municipal Development New Zone	Outer Area
Huairou Pinggu Mentougou Miyun Yanqing	Ecosystem Development Zone	

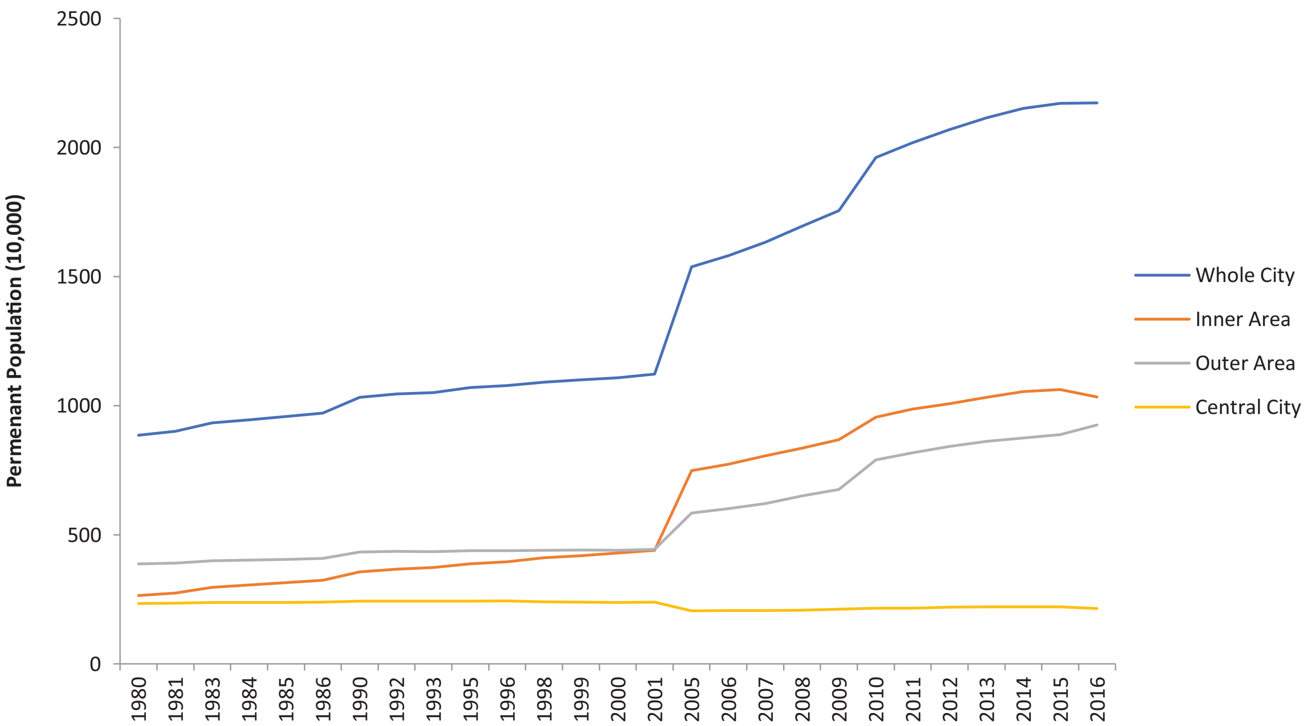

Figure 7. Changing spatial distribution of population in Beijing (10,000) from 1980 to 2016. Source: Compiled based on data provided by the Beijing Municipal Bureau of Statistics (BJMBS, 1982–2015, 2016).

The central city in Beijing features typical walking city fabric, with urban density of close to 250 persons per ha (see Table 2). The inner area is less dense but it is still in favour for walking and cycling. The whole city becomes denser despite the urban expansion, typical of European transit-oriented regions (see Figure 8). The outer area features the lowest urban density in Beijing, but still the high end of automobile city fabric found in Australian and US cities.

From an international comparison perceptive, Beijing is not an automobile city even in the rapid course of urban development and automotive industry prosperity. It features walking and transit urban fabrics, with increasing urban density.

Table 2. Urban density (persons/ha) by different districts in Beijing from 1980 to 2013. Source: Compiled based on data provided by the Beijing Municipal Bureau of Statistics (BJMBS, 1982–2015, 2016).

	Central City	Inner Area	Outer Area	Whole City
2009	229.08	94.93	21.86	42.86
2010	234.61	103.11	25.15	47.16
2011	233.31	105.70	25.75	48.07
2012	238.19	107.46	26.29	48.90
2013	240.04	109.51	26.69	49.62
2014	240.15	111.17	27.00	50.23
2015	239.06	111.51	27.29	50.50

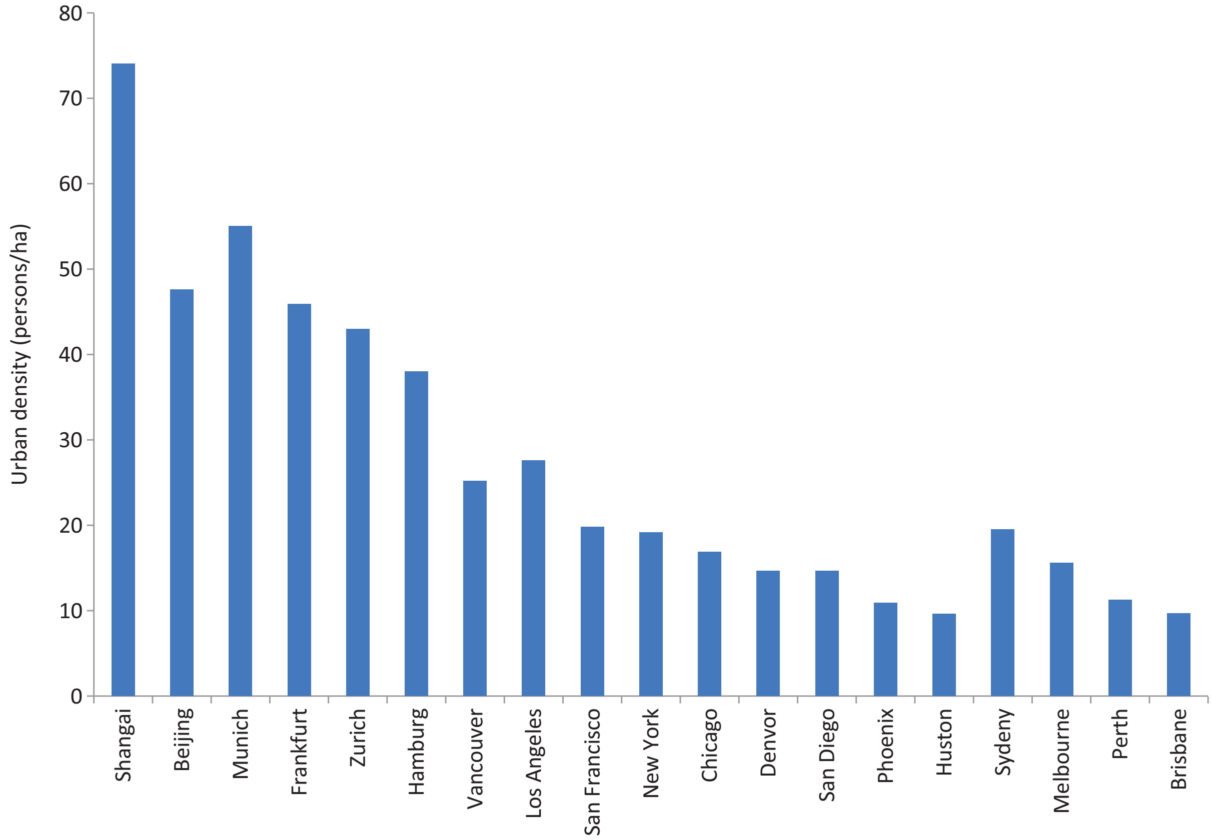

Figure 8. Comparisons of urban densities between Beijing and other cities in the developed world in 2005. Source: Compiled based on data provided by the Beijing Municipal Bureau of Statistics (BJMBS, 1982–2015, 2016) and Newman and Kenworthy (2015).

This difference in density can be explained in terms of different cultural traditions about urban space with the anti-density tradition of Anglo-Saxon countries (including the UK, the US, Australia, Canada and New Zealand) (Newman & Kenworthy, 1999), whilst in Chinese cities the cultural tradition is much more pro-density (Gaubatz, 1999; Lin, 2007) leading to traditional compact urban form. This traditional urban form has paved the foundation for a lower level of car use and peak car in Beijing.

The low rise, high density blocks which characterize China's traditional way of building local neighborhoods rather than the western-style low-density and single-family detached houses, facilitate the walking-scale environments typical of Chinese cities. In particular, the mixture of residential, commercial and recreational land use within these traditional Chinese communities provides local shops, small public spaces (squares or playgrounds) and other community services. It enables these local areas to cater for their daily necessities within walking distance. The close proximity generated by the short blocks also shortens the pedestrian walking distance (Ewing & Cervero, 2010). Finally, this type of urban form helps to facilitate and operate more efficient public transport for these communities.

As well as the organic density of traditional Chinese cities there has been a long commitment to planning the city into a central square with dense linear corridors leading to the centre. This is known as the imperial-centred and axisymmetric urban form, which is affected by the Doctrine of the Mean (Sit, 2010). The Kao Gong Ji document presents a city centre based on a square or rectangular shape, a pattern that was developed during the Dynasty of Western Zhou (1046BC–771BC) and led to the traditional road grid. This chessboard-like urban form based on small block sizes with multiple route choices is ideally suited to walking which has dominated Chinese urban transport for thousands of years. It also laid the foundation for the later construction and development of efficient public transport corridors across many Chinese cities and because it was dense and had relatively clear roadways it was also suitable for the bicycle that grew rapidly in China from the end of the 19th century (Gao, Newman, & Webster, 2015). Then when trams came they followed these roads and took them further out into longer corridors.

When this road structure is combined with high density and mixed land uses, as it is in China, it means that the major parts of Chinese cities were fundamentally Walking and Transit City fabrics and became an entrenched part of how cities were built in the Chinese cultural and political landscape. Automobile fabric only develops where a new kind of urban form is sought further out from the fabric already there and at considerably lowers densities. This did not happen very much in China, instead the city fabric from the walking and transit eras were rebuilt at much higher density and followed the same corridor-based form into new areas.

Beijing has served as the capital for six dynasties, and also for New China since it was established in 1949. The Forbidden City has been at the heart of the whole city, with other important buildings symmetrically distributed around the central axis. Until today, its traffic corridors such as the Metro system and highway loop roads are still following the urban pattern (the red building in the centre of the Beijing subway system shown in Figure 9 is The Palace Museum).

6. Future of Beijing, Other Chinese Cities and Emerging Global Cities

Sustainable development is listed as one of seven main strategies for Chinese national development in the latest 19th National Congress of the Communist Party of China (NPC, 2017). The Five-Year Plan has evolved from encouraging private vehicles to propel economic growth towards 'Prioritising Public Transport' since the Twelfth FYP, 2011–2015 (NPC, 2011). China has adopted limitations to control private car ownership and use and to continue to prioritize urban public transport at the national and municipal levels. Thus, it is not expected that peak car in Beijing is likely to reverse and begin growing again.

In addition to legislation aiming to make automobile travel less needed or encouraged, changing social trends are in favour of alternative modes over automobiles. In China, the docked public bicycle program is supported by local government and a dockless shared bicycle system is being operated by a market for over 200 million shared bikes across urban China. They provide a gateway for casual users and tourists and increase the access and uptake for bicycle users (Mason, Fulton, & McDonald, 2015). The lightly motorized mode, e-bikes, has replaced the normal bicycle as the dominant cycling mode with over 250 million e-bikes now operating across the country. In Shanghai, the e-bike modal split soared from 3% in 1995 to just over 20% in 2014, while bicycle use dropped from 39% to 7% (SCCTPI, 2016).

The peak car phenomenon in Beijing is a powerful signal that 1.5 °C agenda can be approached in such emerging cities. The other part of the 1.5 °C agenda is electric transport. This is being done for air quality reasons as well as climate emissions. China is the largest electric car market around the world in 2016, with 336,000 new-registered cars—doubling the sale in the US. It has

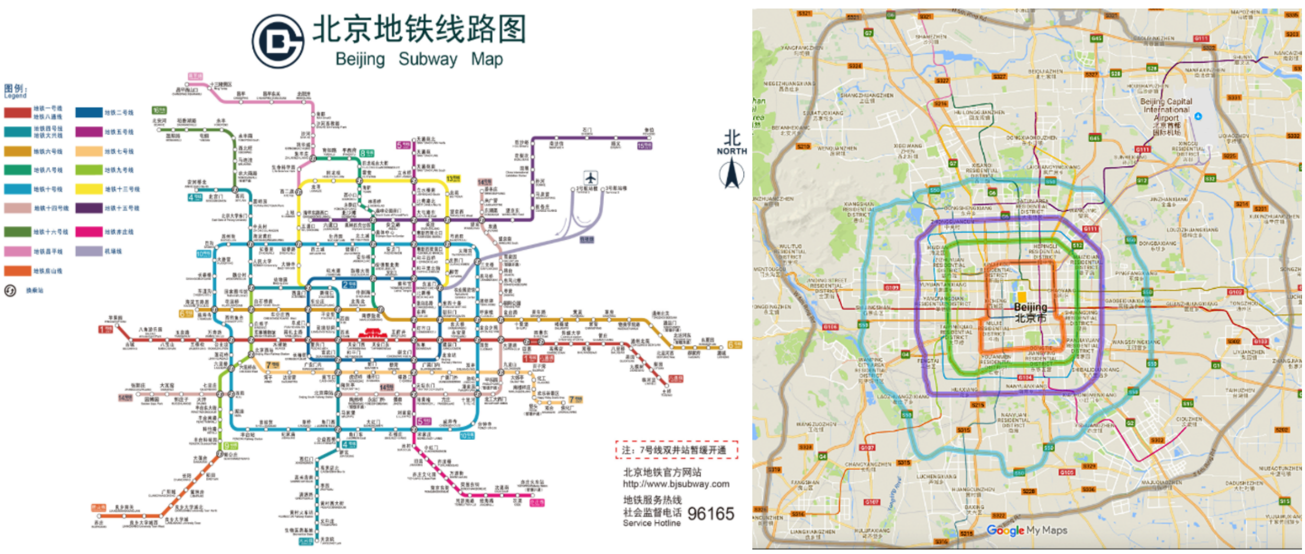

Figure 9. Beijing subway map, updated to 2017 (left), and map of ring roads in Beijing (right). Source: Compiled based on data provided by the Beijing Subway Official Website (2017) and Google Maps.

also exceeded the US with the largest electric car stock since 2016 (International Energy Agency, 2017). In China, an app-based car-sharing program has also emerged since 2012 with total passengers dramatically increasing up to 300 million in 2015. Such trends would suggest Chinese cities would continue to decline in transport-related GHG.

Beijing has also provided a model for the emerging cities around the world with similar conditions. But there are some other emerging cities, which struggle financially to invest in urban rail development and/or face the challenge of urban sprawl. Newman and Kenworthy (2015) have examined several other emerging cities in Latin America and Eastern Europe where the first signs of peak car can be seen. Similar results will no doubt depend on the extent of transit building compared to roads as well as the extent to which walking city and transit city fabric is where the focus of development is provided.

7. Conclusion

Beijing, as the capital of the largest emerging economy, represents and leads China's development and evolution. Hence, its peak car transition is of great importance for China and the entire world. The decline in VKT per capita was not expected based just on GDP levels associated with peak car in other parts of the world. But Beijing has made the transition without reducing its economic agenda and perhaps even suggesting, because of it. The changes can be seen to be related to a combination of investment priorities changing and inner urban fabric priority being a focus for development. Direct policies that favour rail over road with reduced per capita freeway growth and reduced parking provision as well as some travel demand management policies, have been implemented. Beijing features Chinese traditional urban fabrics of walking centres with transit linear corridors all with dense, mixed land use patterns that favour public transport and walking and cycling. These areas are where the major job growth and urban activity is focused, and thus private vehicle use has decoupled from wealth and has now peaked. The positive signs for achieving the 1.5 °C agenda in terms of oil are being supplemented by vehicles powered by renewable energy and lightly motorized modes (e-bikes and e-cars). Beijing is now providing a model of how an emerging city can begin to reduce its car-based greenhouse emissions. The future is likely to see this trend continue.

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Conflict of Interest

The authors declare no conflict of interests.

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Article

Bhutan: Can the 1.5 °C Agenda Be Integrated with Growth in Wealth and Happiness?

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Abstract

Bhutan is a tiny kingdom nested in the fragile ecosystem of the eastern Himalayan range, with urbanisation striding at a rapid rate. To the global community, Bhutan is known for its Gross National Happiness (GNH), which in many ways is an expression of the Sustainable Development concept. Bhutan is less known for its policy of being carbon neutral, which has been in place since the 15th session of the Conference of Parties meeting in 2009 and was reiterated in their Nationally Determined Contribution with the Paris Agreement. Bhutan achieves its carbon neutral status through its hydro power and forest cover. Like most emerging countries, Bhutan wants to increase its wealth and become a middle income country by 2020, as well as increase its GNH. This article looks at the planning options to integrate the three core national goals of GNH, economic growth (GDP) and greenhouse gas (GHG). We investigate whether Bhutan can contribute to the 1.5 °C agenda through its 'zero carbon commitment' as well as growing in GDP and improving GNH. Using the Long-range Energy Alternatives Planning model, this article shows that carbon neutral status would be broken by 2037 or 2044 under a high GDP economic outlook, as well as a business as usual scenario. National and urban policy interventions are thus required to maintain carbon neutral status. Key areas of transport and industry are examined under two alternative scenarios and these are feasible to integrate the three goals of GHG, GDP and GNH. Power can be kept carbon neutral relatively easily through modest increases in hydro. The biggest issue is to electrify the transport system and plans are being developed to electrify both freight and passenger transport.

Keywords

Bhutan; carbon neutral; economic growth; electrified transport; emission; energy policy; greenhouse gas; Gross National Happiness; LEAP model; urbanisation; wellbeing

Issue

This article is part of the issue "Urban Planning to Enable a 1.5 °C Scenario", edited by Peter Newman (Curtin University, Australia), Aromar Revi (Indian Institute for Human Settlements, India) and Amir Bazaz (Indian Institute for Human Settlements, India).

1. Introduction

Human society is gradually becoming an urbanised habitat (UN-DESA, 2014) and rapid urbanisation is expected to concentrate energy demand in cities (Newton & Newman, 2013). Urban centres are being recognised as a place for population and economic growth (GDP) (Jiang & O'Neill, 2017). As nations around the world urbanise, reducing greenhouse gas (GHG) emissions will become more critical, which is at the heart of climate policy ever since the establishment of the United Nations Framework Conventions on Climate Change (United Nations, 1992). However, GHG emissions are fully integrated with the economy, hence reducing them is a critical threat to socio-economic development (IPCC, 2014). Recent research argues for net zero emissions between 2045 and

2060 to hold the global temperature rise below 1.5 ºC (Rogelj, Luderer, et al., 2015; Rogelj, Schaeffer, et al., 2015), and the world's nations have committed to begin that journey in the Paris Agreement by making various pledges. Bhutan has pledged for carbon neutrality, which is a heavy commitment for an emerging nation. The question examined in this article is whether such a plan can be achieved along with Bhutan's other major commitments to growth in wealth and the social goals expressed in the unique Bhutan parameter of happiness, measured as Gross National Happiness (GNH).

A carbon budget for a 1.5 °C consistent world is estimated at 365 Gigatonnes (Rogelj, Schaeffer, et al., 2015). For Bhutan that can be considered as a tiny proportion of just 6.3 million tonnes, but the power of Bhutan's ability to integrate GNH, GDP and GHG emissions can send a strong message to the world. The issue examined in this article is whether such integrated goals are possible for an emerging nation like Bhutan.

GDP is well-known globally, but it is also often criticised for undermining socio-environmental issues. GHG is the primary cause of human induced climate change and is seen in most planning to be inconsistent with GDP, though possibilities of decoupling the two are now appearing (Newman, Beatley, & Boyer, 2017). GNH is a development philosophy for which Bhutan is known to the outside world (Brooks, 2013; RGoB, 2012; Schroeder & Schroeder, 2014; Ura, 2015). The term was first pronounced by the 4th king of Bhutan in the 1970s and it seeks to balance material and non-material development through the integration of its four pillars: socio-cultural, economic, environment and good governance (Thinley, 2005; Ura, 2015). Detailed narratives on GNH are provided elsewhere (Alkire, 2015; Centre for Bhutan Studies, 2012, 2016; Thinley, 2005; Ura, 2015) and the importance of GNH to sustainable development and the Sustainable Development Goals (SDG's) is being recognized as well as suggesting potential conflicts with other national goals (Allison, 2012; Brooks, 2013; RGoB, 2012; Schroeder & Schroeder, 2014). How these three goals can be integrated is an important element of Bhutan's planning.

The strong commitment to carbon neutrality is based in the culture of Bhutan. Bhutan is vulnerable to climate change due to low adaptation capacity (Bisht, 2013; NEC, 2011) and being located in the fragile mountainous ecosystem it is highly vulnerable to changes in climate. Thus the bold declaration made by Bhutan during COP15 was to remain carbon neutral for all time to come (NEC, 2011). This was indeed visionary and was reiterated in their Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) (RGoB, 2015). The need to reduce GHG emissions is being acknowledged by Bhutan (GNHC, 2011; RGoB, 2015) and pursuing a low carbon economy is seen as an inevitable choice to achieve economic development in the face of climate change (Mulugetta & Urban, 2010).

The planning scenarios examined in this article to enable the integration of these three goals inevitably must involve urban planning. Most new development in Bhutan, like all emerging countries, is in cities, especially the capital city of Thimphu. Urbanisation in Bhutan is projected to reach 77% by 2040 with many urban growth centres with implications for more travel demand (Asian Development Bank, 2011). Urban planning will need to play a big part in how Bhutan achieves its goal of remaining carbon neutral while improving its GDP and GNH. Increases in the travel demand will lead to a rise in emissions from the transport sector unless travel demand can be carefully managed and there is a shift to carbon neutral fuels. This anticipated issue is of prime concern given that the petroleum products consumed in Bhutan are 100% imported and the transport sector is thus the major consumer of oil. The rising import of automobiles and fuels and their associated congestion and emissions remain a national concern (GNHC, 2011; NEC, 2011; RGoB, 2012) and will need to be addressed. This concern is not just in Bhutan, it is being felt globally. For instance, the need to cut emissions from the transport sector, which contributed to 23% of global GHG emissions is well acknowledged (IEA, 2016a). How to deal with such critical issues are discussed in many forums including IPCC (2014) and Newman, Beatley and Boyer (2017).

The United Nations Environment Programme 2011 recognises that environmental issues arise as a side effect of socio-economic activity in pursuing a desired goal. To this end, the UNEP (2014) acknowledges that there are more options to achieve significant decoupling if the aim is to increase wellbeing rather than just increasing GDP but of course these are all linked. To this end, the focus of the article is about how climate policy commitments may need to be adapted based on scenarios integrating the three key strategies around GHG, GDP and GNH. The article thus examines how Bhutan could leverage technological options and environmentally benign behaviour to achieve carbon neutral development through scenario-based LEAP modelling (see section 4 of this article).

The following sections provide background on the environmental stance and energy situation in Bhutan, the Bhutan-LEAP modelling, model results and discussions, concluding remarks and policy implications.

2. Environment and Human Wellbeing in Bhutan

A range of environmental issues are examined to show how interconnected they are with human wellbeing.

Bhutan's forest policy mandates minimum forest cover of 60%, which is now enshrined in its Constitution (RGoB, 2008) and encouragingly forest cover is being maintained at 71% (Ministry of Agriculture and Forestry, 2017). Research has suggested this regulation as the key to successful conservation in Bhutan (Jadin, Meyfroidt, & Lambin, 2015), while Buch-Hansen (1997) attributes environmental protection in Bhutan to their enlightened leadership and low population. Brooks (2010) applauds Bhutan as a living lab for integrated conservation and development. To this end environmental protection and wild life issues form some of the ecological indicators of the GNH index, which informs policy making in Bhutan. However forest conservation is encroaching on farm land and rising human-wildlife conflict is being faced by the Bhutanese farmers through loss of farm produce to wildlife where there is no formal compensation mechanism in place (Rinzin, 2006; Ura, 2015). The issue of conservation and rural livelihood remains unresolved (Ura, 2015) and the topical discussion warrants separate research.

Taking GNH seriously, Bhutan conducted a national GNH survey over the two periods[1]—2010 and 2015—the GNH index has increased by 1.8% (Centre for Bhutan Studies, 2016) and its Human Development Index (HDI) also increased from 0.572 in 2010 to 0.607 in 2015 (UNDP, 2016). Over the past decades, Bhutan has witnessed an average GDP growth rate of 7.8% (National Statistics Bureau, 2015). Extreme poverty in Bhutan is said to have been eliminated within the living memory of one generation (World Bank, 2014). While Bhutan is a 36% urban population at present, it is expected to reach 77% by 2040 through urban expansion and also due to rural to urban migration (Asian Development Bank, 2011). For instance, the population of Thimphu—the largest urban centre in Bhutan—is expected to increase from 147,000 in 2015 to 300,000 in 2040 (Asian Development Bank, 2011). The Asian Development Bank attributes the rural to urban migration as a consequence of aspirations for a better lifestyle ensuing from better amenities in urban areas, which are called an 'urbanisation bonus' (Lin & Zhu, 2017). However rapid urbanisation along with industrialization were seen as the drivers of GHG emissions in South Asian countries including Bhutan (Shrestha, Ahmed, Suphachalasai, & Lasco, 2013). Furthermore, being in the fragile ecosystem of the Himalayan range, Bhutan is very much vulnerable to the impacts of global climate change (GNHC, 2011; Hoy, Katel, Thapa, Dendup, & Matschullat, 2015; NEC, 2011). Bisht (2013) even suggests that climate change is the key determinant of Bhutan's future development and security. Climate change policy entails reducing GHG emissions. Plans for reducing GHG emissions centres around the energy mix and energy use, lifestyle, economic activities and land use forming the main drivers of anthropogenic GHG emissions (IPCC, 2014). Considering the energy system as one of the key drivers of GHG emissions, a brief background of the current energy system of Bhutan is provided.

The energy mix in Bhutan comprises: hydropower (28%), biomass (36%) and fossil fuels (37%). At 42.86 kW/capita, Bhutan has the highest theoretical hydropower potential in South Asia (Shrestha et al., 2013). However, the per capita energy consumption at 36 GJ (Department of Renewable Energy, 2015b) is 55% lower than that of the world average at 79 GJ (IEA, 2016b) suggesting there is potential to increase the hydropower side of the economy. The sectoral energy shares are shown in Figure 1 (Department of Renewable Energy, 2015b). Fossil fuels are predominantly used in transport and industry and their associated emissions could undermine any potential future carbon neutral pathway especially in the near future as the economy of Bhutan expands. The need to reduce GHG emissions is being acknowledged by Bhutan (GNHC, 2011; RGoB, 2015) and to this end a National Low Carbon Strategy has been developed (NEC, 2012). However, the strategy document assumes demand saturation in the industry and transport sectors after 2020, thereby underestimating the challenges of the rising energy and emissions from these two sectors, the main contributors of GHG emissions in Bhutan. To this end the following section intends to highlight the challenges and opportunities to reduce GHG emissions in the two sectors- policy directions will be concluded after the scenario analysis.

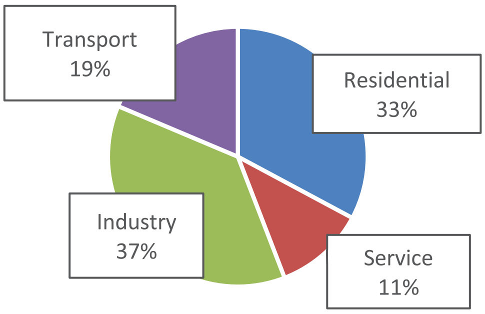

Figure 1. Sectoral energy share (%). Calculated based on Department of Renewable Energy (2015b).

3. Challenges in the Transport and Industry Sectors

Between 2005 and 2014, energy demand in the transport and industry sectors grew at a compound annual growth rate of 9% and 11% respectively, whereas that of service and residential sectors grew at 4% and 1% respectively (Department of Renewable Energy, 2015b; DoE, 2007).[2] At this growth rate, the transport and the industry sectors being major consumers of oil and coal have the potential to derail the carbon neutral pathway of Bhutan. This is the kind of issue faced by many emerging nations.

Furthermore, the transport and the industry sectors are considered to be hard to decarbonize (Rogelj, Luderer, et al., 2015) nonetheless it is not impossible. Industry can be electrified but transport will require a more complex set of urban planning policies.

[1] There was a GNH index for 2008, however the survey conducted in 2007 for that index has been noted as a preliminary survey with fewer questions and covering fewer districts to collect feedback and further expand the questionnaires that were then used for the next two nationwide GNH survey (Centre for Bhutan Studies, 2012).

[2] Authors' calculation based on the referenced sources.

Urban planning has developed an approach to promote pedestrianisation and bus based public transport in the urban areas of Bhutan (Asian Development Bank, 2011) and plans have been developed to electrify both freight and passenger transport in Bhutan (Hargroves, Gaudremeau, & and Tardif, 2017). A study on transport electrification in Nepal (Shakya & Shrestha, 2011), a neighbouring country to Bhutan with similar topography, found there were economic benefits, employment generation, enhanced energy security as well as beneficial environmental outcomes in such a policy. For carbon neutral transport, recent research (Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017) has highlighted the need for radical changes both at the supply side and the demand side. Empirical studies at the global level have advocated rail based transport to reduce automobile dependence and associated emissions (Newman & Kenworthy, 2015; Newman, Kenworthy, & Glazebrook, 2013). Kołoś and Taczanowski (2016) found light rail to be feasible in medium sized towns in central Europe with a population between 100,000 to 300,000 and there are many cities with population just over 100,000 having such rail systems as a successful mode of transportation (Newman et al., 2013). The above approaches to urban planning will be included in the modelling outlined below.

With this as background the article will now show how the complex integration of GHG, GDP and GNH has been attempted as the basis of generating policy scenarios.

4. Methodology

This study expands on the Bhutan-LEAP model developed by Yangka, Newman and Rauland (2017) but with distinct scenario characterisation not covered in the previous work. LEAP stands for the Long-range Energy Alternative Planning system model, which is a flexible and user-friendly energy-environmental planning tool developed and licensed by the Stockholm Environment Institute (Heaps, 2016). However, LEAP is not a climate simulation model having earth system dynamics, though it is being used to assess climate policy through scenario-based energy system analyses and associated GHG emissions. For instance it is widely used for climate policy assessment and low emission development notably in developing countries (Kumar & Madlener, 2016; Ouedraogo, 2017; Sadri, Ardehali, & Amirnekooei, 2014; Shakya, 2016). The scope of an energy model is inherently vast (Nakata, Silva, & Rodionov, 2011), it is limited by the research questions that are being evaluated and the scenarios that are being formulated to address those queries. Once a database is developed, any pertinent issue can be studied within the scope and limitations of the model. This study used a scenario-based long term energy-economy modelling, which is acknowledged as an important method to explore uncertainties in the future (O'Neill et al., 2017). The alternative scenarios were formulated to address the present research objective.

4.1. Structure of Bhutan-LEAP Model

Bhutan-LEAP model was structured into key assumptions, demand branch, resource branch and non-energy branch. The planning horizon extends from 2014 to 2050. The demand branch is comprised of transport, industry, residential and service sectors to account for energy consumption and associated GHG emissions, and to study plausible policy interventions to contain the rising emission levels. Further disaggregation to sub-sector levels were limited by data availability. For instance, the tourism sector[3] wasn't shown as a separate sector in the model due to lack of data on energy consumption specific to the tourism sector. However, the service sector shown in the model includes the commercial sector (such as hotels and restaurants) which are impacted by the number of tourists (NSB, 2017), suggesting that the energy consumption under the service sector can be assumed to include energy consumption by the tourists visiting Bhutan. Furthermore, energy consumption in air transport can also be assumed to be impacted by the tourists coming to Bhutan given that 2/3rd of the flight passengers are tourists (Asian Development Bank, 2011).

4.2. General Assumptions

In this study a discount rate of 10% was used, consistent with that used in earlier studies and furthermore, a discount rate of 10% is mentioned as a global average opportunity cost of capital in a study on low carbon development for India conducted by World Bank (Gaba, Cormier, & Rogers, 2011). Considering forest cover of Bhutan as a carbon sink, for accounting purposes the emissions from wood-based energy consumption were accounted as positive rather than as a carbon neutral energy source. The emission factors for the demand technologies and the fuels were referred from the Technology and Emission Database of the LEAP model provided by SEI (Heaps, 2016). The emissions from waste disposal and agricultural activities—farming and livestock rearing—were accounted for under 'non-energy'. The amount of waste generation and disposal were assumed to increase along with urbanisation, whereas emissions from agriculture were assumed to remain constant as per the past trend (NEC, 2011). This assumption is plausible due to the ongoing rural to urban migration that is causing decline in the farming activities and livestock rearing. Furthermore, the amount of agricultural land in Bhutan is limited due to topography and forest conservation.

Paucity of data on long term macroeconomic parameters, cost and technological datasets for various demand technologies poses a daunting task, hence surrogate data from the literature were imputed and adapted, with consequent implications for the model results. In this regard,

[3] The brief note on tourism sector was provided to address the comment of a reviewer on the tourist sector being neglected in this article.

higher confidence levels could be placed on the data that were sourced from Bhutan specific studies.

4.3. Distinct Features of Bhutan's Energy System

From a modelling perspective, the energy system in Bhutan is relatively simple in that the energy supply side does not have the complex fossil fuel extraction and conversion processes except for limited coal mining and the hydropower system. Similarly, there is no rail system or transport using water ways and limited domestic air ways. Furthermore, accounting for primary energy supply and final energy consumption are similar except for the transformational losses occurring in the electricity system (Yangka & Diesendorf, 2016). Bhutan neither has oil reserves nor oil refineries, thus petroleum products consumed in the demand sectors are 100% imported.

4.4. Projection of Energy Demand and Energy Prices

Future prices for petroleum products, which are 100% imported from India were assumed to follow the international oil price and thus indexed to the price changes calculated from future oil price projection done by the US-Department of Energy (US Energy Information Administration, 2016). Oil import dependency of India itself is expected to increase from 74% in 2013 to 91% by 2040 (IEA, 2015). Bamboo chips and wood charcoal which are mostly imported from India for use in the Industry sector were assumed to rise at 4.1% per annum (Feuerbacher, Siebold, Chhetri, Lippert, & Sander, 2016). The projected energy prices and end-use energy services in the four sectors are provided in the Annex.

The end-use energy services such as the heating, cooking, passenger travel, freight travel, which drives the corresponding energy demand are projected through the expression builder[4] under the activity variable of the demand module of the LEAP model.

5. Scenario Storyline

This article formulated two base scenarios and two corresponding alternative scenarios. The two base scenarios are: the Business as Usual (BAU) trajectory and a trajectory based on high GDP (HGDP). Their characterisation and key features are provided in Table 1. The two alternative scenarios intend to investigate the future that Bhutan aspires to—societal happiness within net zero greenhouse emissions reflecting carbon neutral development in a GNH state. These alternative scenarios attempt to contain the rising emissions from the BAU and the HGDP scenarios within the carbon sink capacity available for Bhutan. The storyline acknowledges that human settlements are sooner or later expected to be largely urbanised (Jiang & O'Neill, 2017; Newton & Newman, 2015).

The alternative scenarios are designated as Knowledge-Based Society (KBS) and GNH society, which are outlined in sub-sections 5.1 and 5.2 of this article. The GNH scenario is inherited[5] from the BAU scenario, while the KBS scenario is inherited from the HGDP scenario. Under these two alternative scenarios, a case study, with and without light rail transport, was also conducted to examine how light rail can support the carbon neutral pathway of Bhutan.

5.1. Wealthier and Knowledge Based Society (KBS)

This scenario imagines human settlements in Bhutan moving towards a greater proportion knowledge based economic activity in urban society during the later part of the planning horizon and enjoying a high economic outlook as a result of this. The Bhutanese society is likely to embrace such knowledge economy goals which include walking and public transport based on light rail and aggressive expansion of electric vehicles (Newman & Kenworthy, 2015). Such economic activity is less intensive in both energy and emissions. Being a KBS, the contribution of the service sector to the national GDP increases while that from the Industry sector decreases. The specificities of this scenario were outlined under Table 1.

5.2. GNH Based Society

This scenario contemplates a happy society derived from community vibrancy and symbiotic relationships between the human and the natural world, manifesting the essence of GNH—balancing material and spiritual development and co-existing with nature. The economic pathway under this scenario is assumed to follow the GDP growth rate of the BAU scenario (7.8% growth rate in the medium term and sustaining at 5.6% growth rate by 2050). Community vibrancy is defined as the people adopting the walking and public transport system. Harmony with nature is defined as less polluting and with more efficient socioeconomic activities including more knowledge-based activity. These definitions are for modelling purpose only. Similar to the KBS scenario, the specificities of this scenario were outlined under Table 1. While this is an initial attempt to construct scenarios around some key features of the GNH, there is no way to incorporate the entirety of GNH into the modelling work. We expect future work to expand on this.

6. Results and Discussion

The model results for the BAU scenario and the alternative scenarios are presented and synthesised with relevance to the 1.5 °C climate consistent world. The results discussed in the following section do pose a certain level of uncertainty attributable to the assumptions of the key variables, use of data which were adopted from various

[4] A flexible feature in LEAP, which allows user to write mathematical expressions to link various branches (the component of the LEAP structure).
[5] 'Inherited' in LEAP model can be simply understood as 'derived from' or 'built on'.

Table 1. Key features of the four scenarios.

Scenario	Residential sector	Service sector	Transport sector	Industry sector
BAU (GDP growth rate of 5.6% and increasing to 7.8% and sustaining at 5.6% until 2050)	Energy demand increases with the increase in the number of household; Fuelwood usage in all end-uses expected to decline to 23% by 2050 following the declining rural population; Saturation level of households with heating facility increases from 50% in 2014 (NSB & ADB, 2013) to 70% by 2050.	Energy demand increases with value added of the service sector; Fuelwood usage expected to decline.	Energy demand in passenger transport increases with per capita GDP and that for freight increases with the value added of the transport sector; Share of passenger travel demand met by bus increases from 15% to 25% by 2050; Share of passenger travel demand met by air transport increases from 20 to 25% by 2050; Share of freight travel demand met by light diesel truck increases from 17% to 30% by 2050.	Energy demand increases with value added of the industry sector.
GNH state (GDP growth rate assumed to be sufficed with the BAU growth rate)	Firewood and kerosene used in the building sectors reaches zero by 2030 and substituted by electricity and biogas.	The GDP share of the Service sector increases from 33% to 45%.	Walking meets 10% and light rail meets 30% of the passenger travel demand by 2050. Electric vehicles were assumed to penetrate at half the rate specified in IEA (2016a).	The GDP share of the Industry sector decreases from 11.70% in 2014 to 10.70% by 2050; A move towards industrial symbiosis.
HGDP	High economic outlook of 10% in the medium term and declining to 5.6% by 2050.			
KBS—Knowledge based society with high economic outlook	Dirty fuels used in the building sectors reaches zero and substituted by electricity and biogas.	The GDP share of service sector increases from 33% to 45%.	Walking and light rail meets 10% and 30% of the passenger travel demand respectively by 2050; Electric vehicles assumed to reach following share by 2050: 100% for 2-wheelers; 60% for passenger light duty vehicles; 30% for buses and trucks; (this assumptions exceed the rate provided in the IEA (2016a).	The GDP share of industry sector declines from 11.70% in 2014 to 10.70% by 2050; A move towards industrial symbiosis (Liu et al., 2011; Morrow, Hasanbeigi, Sathaye, & Xu, 2014).

sources, the projection methods for energy demand and energy prices. The study also does not analyse possible uncertainties associated with the carbon sink capacity of the forest cover over the planning period.

6.1. Energy Demand and Decarbonisation Rate

Since there are no major differences between the total primary energy supply (TPES) and the total final energy consumption (TFEC) in Bhutan (see sub-section 4.3 of this article), the results and discussion are focussed on TFEC. The final energy consumption exhibits a compound annual growth rate of 5%, 4.3%, 6.4% and 5.3% under the BAU, GNH, HGDP and KBS scenarios respectively. Over the planning period, the energy mix varies among the three major energy groups as shown in Figure 2. The three major energy groups being: 1) fossil energy, 2) biomass, and 3) electricity (which is essentially hydropower). Substantial variations in the energy mix are observed. For instance, in the base year, biomass dominates the fuel mix at 41%, while fossil energy dominates the fuel mix under both the BAU and the HGDP scenarios by 2050. Not surprisingly, hydropower dominates the fuel mix under the GNH and KBS scenarios by 2050 contributing to 48% and 61% of the final energy demand respectively.

The carbon intensity of the final energy demand at 86.41kgCO_2eq/GJ in 2014, which is lower than that of the present world average at 90kgCO_2/GJ (Rogelj, Luderer, et al., 2015) steadily decreases over the planning period under all the four scenarios. For instance, by 2050 the carbon intensity decreases to 52.55kgCO_2eq/GJ under the BAU scenario, further decreasing to 33.71kgCO_2eq/GJ under the KBS scenario. Interestingly under the KBS scenario, the energy system of Bhutan exhibits a decarbonisation rate of 2.6% per year, which is well within the range of 2% to 2.8% per year proposed for a 1.5 °C consistent world (Rogelj, Luderer, et al., 2015).

6.2. Emissions Trajectory

Variations in the energy mix discussed in sub-section 6.1 lead to variations in the emissions levels over the planning period under the four different scenarios; these are shown in Figure 3.

Figure 3 shows that the non-energy sector was the dominant contributor of emissions in 2014, however over the planning horizon oil products and solid fuels become the major contributor to the total CO_2eq emissions. Oil products are mostly consumed in the transport sector, while solid fuels are mostly consumed in the industry sector. This suggest a strong rationale for policy intervention in these two sectors and this article does this with a focus on the transport sector. The two alternative scenarios, KBS and GNH demonstrate the possibility of reducing the dependency on oil products and solid fuels through efficiency improvement in the industry sector and technological changes (switching to electric power) and modal shifting in the transport sector.

The emission trajectories under the four scenarios are shown in Figure 4. The emission level exceeds the sink capacity by 2037 and 2044 under the HGDP and BAU scenarios respectively, indicating the need for policy intervention in order to maintain carbon neutrality as the economy expands over the planning horizon. Under the KBS and GNH scenarios, which are the corresponding emission reduction measures for their parent scenarios, the emissions levels were contained below the sink capacity. Compared to their parent scenarios, cumulative emissions reduce by 34% and 22% under the KBS and GNH scenarios. However, such emissions reduction entails adopting efficient and cleaner technologies in the demand sectors with financial implications, which is discussed under sub-section 6.3 of this article.

Although the total emissions increases, the carbon intensity of the Bhutanese economy steadily declines

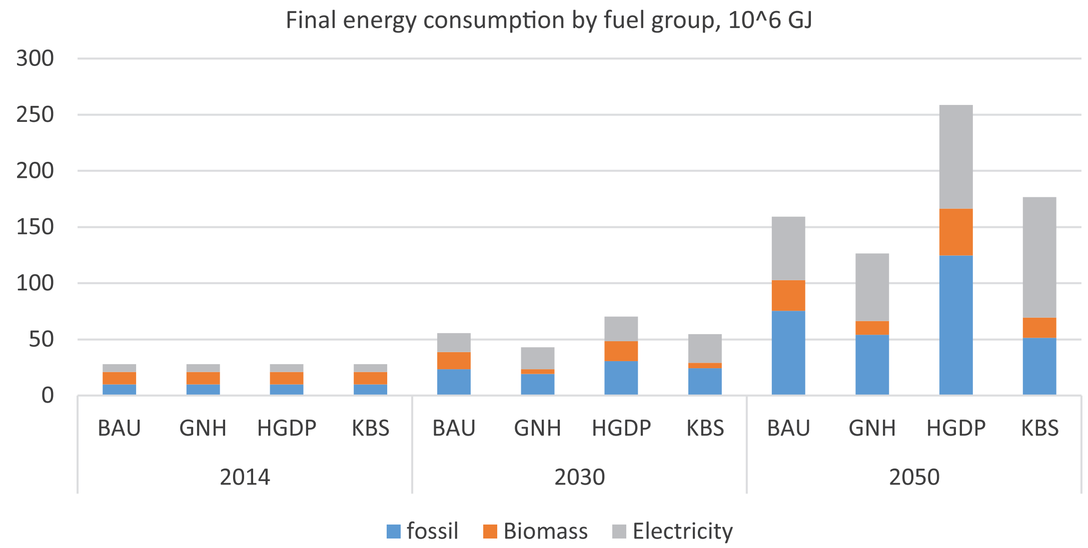

Figure 2. Energy consumption by major fuel group under four different scenarios. Note: BAU (Business as Usual); GNH (Scenario following GNH principle); HGDP (high economic outlook); KBS (knowledge-based society).

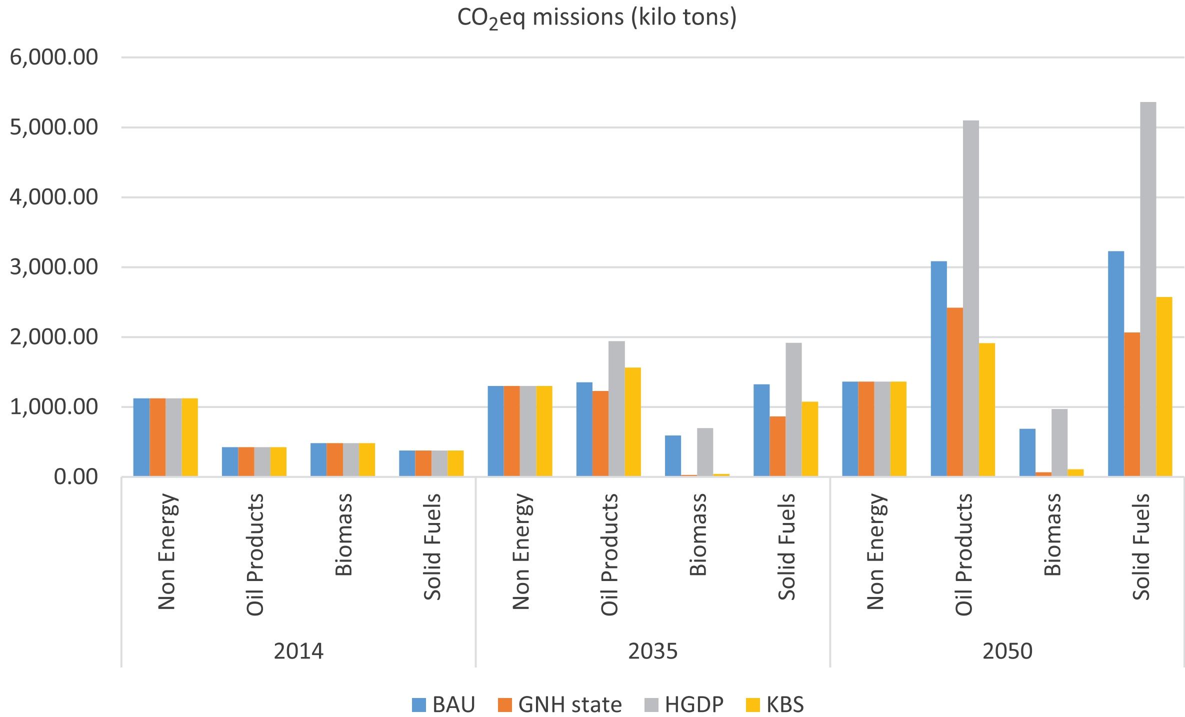

Figure 3. Emission variation by source under different scenarios.

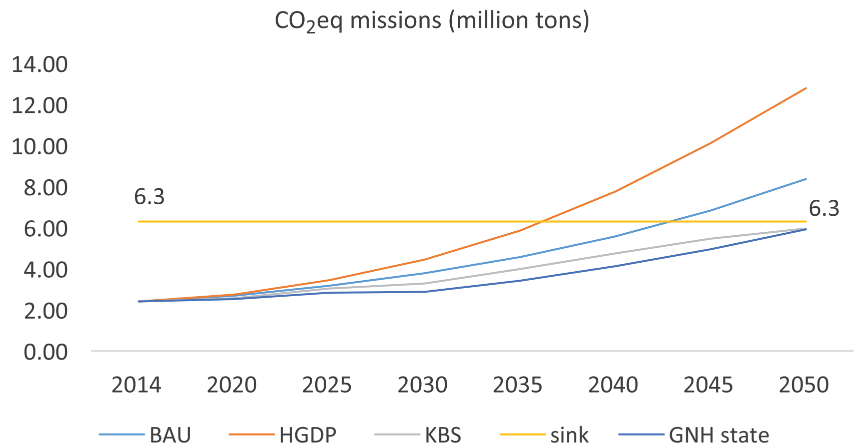

Figure 4. Scenario based CO_2eq emission in Million tonnes.

as shown in Figure 5, demonstrating the potential for a relative decoupling of GDP from environmental pressure, though absolute decoupling will require entirely replacing fossil fuels with renewables-based transport and industry. For instance, under the KBS scenario the carbon intensity of the economy decreases from 2.68kgCO_2eq/US$ in 2014 to 0.47kgCO_2eq/US$ by 2050, showing an improvement of 4.7%/year over the planning period. Such rapid reduction in the carbon intensity is following global trends (Newman, Beatley, & Boyer, 2017) as well as including new technologies in the energy mix as discussed in Sub-Section 6.1.

6.3. The Cost of Taming the Rising Carbon

As discussed in Sub-Section 6.2, the KBS scenario limits the total CO_2eq emission below the sink capacity despite high economic growth, similarly the GNH scenario holds the emission levels from a BAU pathway below the sink capacity. However, they entail transitioning to an efficient industrial production and preferences towards gradual electrification of the transport sector. But it comes with financial implications; there is a cost of carbon mitigation under the KBS scenario and savings from carbon mitigation under the GNH scenario relative to their parent scenarios, which were obtained from the cost-benefit summary report in the result module of LEAP. Table 2 shows the total discounted system cost and the cumulative CO_2eq emissions under the four scenarios. The system cost comprises a demand cost, transformation cost and the net resource cost (cost of export less cost of import). Relative to their parent scenarios, under the two alternative scenarios cost incurred in the demand sector increases, while the cost of resource

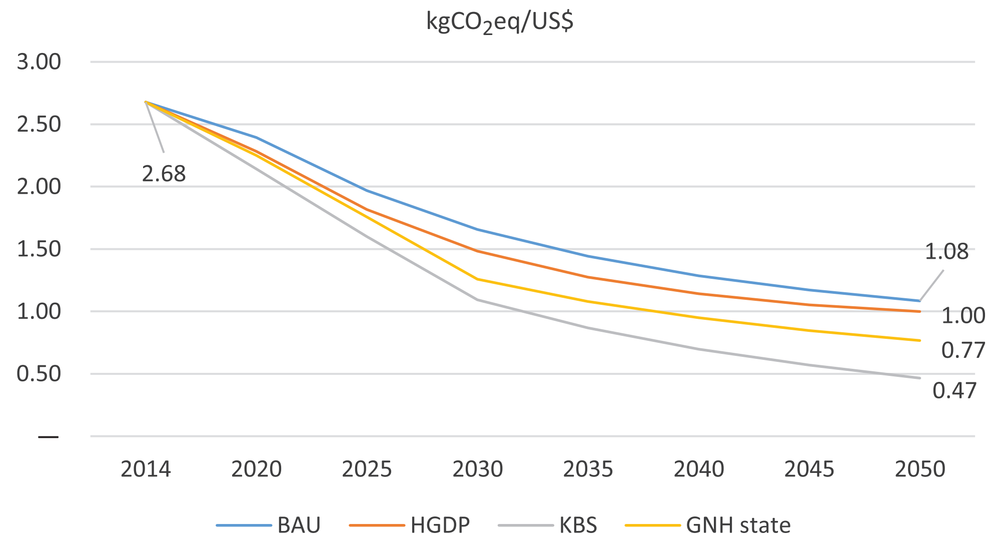

Figure 5. Carbon intensity of the Bhutanese economy.

import decreases. This leads to financial saving of US\$ 15.05/tCO_2eq under the GNH scenario relative to its parent scenario, BAU. This portion of the result indicates that Bhutan can live up to its carbon neutral pledge with cleaner and advanced technological choices at no cost.

However, under the KBS scenario, the cost of carbon mitigation relative to its parent scenario (i.e., HGDP scenario) amounts to US\$ 2.67/t CO_2eq. This translates to an additional cost of US\$ 5.55 million per year over the planning period, forming 0.043% of the GDP in 2050, which is lower than that estimated for India at 1.5% (GoI, 2014). The reason for the difference could be attributable to various assumptions in the model development and scenario characterisation. Notwithstanding this, pursuing a low carbon economy in India requires decarbonising their electricity sector, which is predominantly coal based, while in Bhutan clean hydropower is already the baseline electricity generation. With regard to the marginal abatement cost of carbon, a previous study conducted by the Asian Development Bank (Shrestha et al., 2013) for the South Asian countries showed that it varies from a saving of \$72.8/tCO_2eq to a cost as high as \$417.7/tCO_2eq depending on the fuel and the technology being substituted by their cleaner and more efficient counterparts. The additional cost under the KBS scenario suggests allocating the limited financial resources towards the carbon neutral goal that could compete with the budget for other pertinent socio-economic developmental needs. The result supports the viewpoint of Flagg (2015), who calls the carbon neutral pledge as a 'generous public good' (p. 209). However, in a carbon constrained world, where emission reduction targets are being accelerated following the Paris Agreement (UN Framework Convention on Climate Change, 2016), such additional costs could be met through the global carbon market.

6.4. Cost of Mitigation Measures in the Transport Sector

The KBS and the GNH scenarios assume that light rail meets 30% of passenger travel demand by 2050. However, electric vehicles were assumed to follow a different penetration rate in the two scenarios (see Table 1) to contain the corresponding emissions level below the sink capacity. In the GNH scenario, without calling in policies like developing an electric transport system, efficiency improvement in the four industry subsectors along with phasing out of dirty fuels in the residential and service sectors were found inadequate to limit the emissions level within the sink capacity. This is therefore suggesting the crucial role of electrifying the transport sector in Bhutan to live within their net zero carbon budget.

To examine the possible role of light rail transport in supporting the carbon neutral goal, model runs with a 'no LRT case' and 'LRT case' were compared under both the KBS and the GNH scenarios. The model results show that in the 'LRT case' there is a cost saving of US\$51.42/tCO_2eq and US\$ 5.07/tCO_2eq under the KBS and GNH scenarios respectively, while maintaining the emissions level below the sink capacity. This also

Table 2. Social Cost and CO_2eq emission.

Scenario	BAU	GNH	HGDP	KBS
Total discounted system cost, 10^9 US\$	52.78	52.24	66.70	66.90
CO_2eq emission, Million tons	167.43	131.33	219.04	143.67
Mitigation cost (US\$/t CO_2eq) relative to BAU	—	(−15.05)	—	—
Mitigation cost (US\$/t CO_2eq) relative to HGDP	—	—	—	2.67

demonstrates the attractiveness of light rail transport, attributable to its longer operational life and higher passenger carrying capacity despite its high upfront cost. The results show the promises of light rail transport in decarbonising the transport sector thereby leveraging the carbon neutral goal of Bhutan. Furthermore, with a dedicated right of way, light rail can decongest road traffic. A prefeasibility study initiated by UNCRD also found light rail to be promising for urban Bhutan (Hargroves et al., 2017). Furthermore, a detailed project level costs and feasibility are being undertaken in an on-going parallel research activity. LRTs were also found to become cheaper than bus based transport when travel demand grows (IUT India, 2012). The case of transport electrification can also be useful for other emerging countries where oil imports represent a high burden on their GDP.

7. Concluding Remarks and Policy Implications

The long term Bhutan-LEAP modelling exercise provided crucial insights into the carbon neutral goal of Bhutan and its implications for urban planning. The results showed that if Bhutan follows the 2014 BAU energy-economy pathway, the associated emissions will exceed the sink capacity by 2044 and the aspiration for a high economic outlook can potentially derail Bhutan's carbon neutral path as early as 2037 if a similar BAU energy economic system gets locked-in. This is suggesting the need for policy intervention if Bhutan is to live within its carbon neutral budget.

The urban planning implications are that electrification of transport is needed and this requires some interventions such as those outlined by (Newman, Davies-Slate, & Jones, 2017). The model results indicate that there is economic benefit arising from introducing environmentally beneficial policies to maintain its carbon neutral status following a BAU pathway. Furthermore, even under the high economic outlook, the cost of carbon mitigation to hold the rising emissions is US$ 2.67/tCO_2eq only. Nonetheless, Bhutan's hydropower-based electricity generation along with extensive forest cover seem to be the comparative advantage at present and together provide a future bastion of hope to uphold its carbon neutral goal. The hydropower provides clean electricity and the forest cover provide ecosystem support as well as acting as a carbon sink. These features will need to be preserved into the future.

This study could be useful for the Bhutanese policy makers as the country strives to mainstream its low carbon strategy while it pursues a GNH paradigm and aspires to a better living standard. The article could be useful for emerging countries with similar aspirations to that of Bhutan to grow their economy with less emissions, though Bhutan pursuing GNH is unique in that it has shaped its policy making towards social and environmental goals as well as economic development. This article shows that GDP, GHG and GNH can be integrated under scenarios that also invite intervention, especially with electrified transport options. The article suggests there are hopeful scenarios that can be developed for emerging nations like Bhutan to meet the 1.5 °C agenda along with the SDG's.

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Conflict of Interests

The authors declare no conflict of interests.

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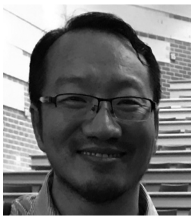

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Annex

A1. Data source

The base year energy consumptions were referred from the Bhutan Energy Data Directory (Department of Renewable Energy, 2015b). In case of techno-economic parameters of demand technologies, Bhutan specific data were used wherever available and the remaining data requirements were surrogated and adapted from the wider literature. For instance, data for transport sector were adapted from: City Bus Service (2015), Department of Renewable Energy (2015b), DoE (2010), Kołoś & Taczanowski (2016), the Ministry of Information and Communications (2015), Shafiei et al. (2017) and Zhu, Patella, Steinmetz and Peamsilpakulchorn (2016). Data for industry sector were obtained from: DoI (2015), Huisingh, Zhang, Moore, Qiao and Li (2015), Kero, Grådahl and Tranell (2016), Liu et al. (2011); Morrow et al. (2014), and NEC & TERI (2016). Similarly data for residential and the commercial sectors were sourced and adapted from: Department of Renewable Energy (2012, 2015a, 2015b) and UNDP (2012). Techno-economic data for existing hydropower plants and on-going hydropower projects were obtained from relevant stakeholders (Druk Green Power Corporation, 2014; Indian Embassy, 2016; MHPA, 2016). Data for wind power plant was imputed from Bhutan Power Corporation Limited (Personal communication, November 21, 2016) and for solar it was imputed from TERI (2015). Learning rates were imputed from Rubin, Azevedo, Jaramillo, and Yeh (2015) and Shafiei et al. (2017).

A2. Data sets for Bhutan-LEAP model

Table A1. Electricity sector key feature, based on BPC (2015).

Particulars	GWh		US cents/kWh*
Export	5179.3		3.36
Import	187.6		3.77
Generation	7166.3		
T&D loss		3.87%	

Notes: *authors' calculation based on BPC (2015). T&D stands for transmission and distribution.

Table A2. GDP and population projection under the BAU scenario.

Year	GDP, 10^6 US$*	Population**
2014	902	745,153
2020	1,324	809,397
2025	1,822	850,976
2030	2,508	886,523
2035	3,453	931,745
2040	4,753	979,273
2045	6,542	1,029,226
2050	9,005	1,081,727

Notes: US$ stands for the U.S. dollar. *See table 1 in the main text for the assumed growth rate; **data for 2014–2030 is from the National Statistical Bureau (2015); from 2035 to 2050, 1% growth rate was assumed.

Table A3. Power plant techno-economic data.

Plant	Capacity, MW	Capital cost (US$/kW)*	Data source
Existing hydropower plant			
CHP	360	646.57	Druk Green Power Corporation, 2014; Department of Renewable Energy, 2015b
Kurichu	60	1517.62	
Basochu	64	828.51	
Tala	1020	657.72	
Dagachu	126	1577.75	
Hydro_Micro	8.20	6952.00	
Candidate hydropower plant			
PHPA I	1200	1270.40	Indian Embassy (2016)
PHPA II	1020	1162.22	
MHPA	720	1088.16	MHPA (2016)
Tangsibji	118	1648.06	Druk Green Power Corporation. (2014)
KHP	600	1048.51	
Mega_hydro	4000	1173.60	This study
Other power plant			
Solar	0.12	1626	Department of Renewable Energy (2015b); TERI (2015)
Wind	0.60	4848.85	BPC, Personal Communication, November 21, 2016
Diesel Generator Set	10.7	2500	Department of Renewable Energy (2015b); Oladokun & Asemota (2015)
WTE	3.4	2746	Department of Renewable Energy (2015b)

Note: *authors' calculations based on the available data sources.

Table A4. Monthly electricity generation and consumption in 2014 based on Druk Green Power Corporation (2014) and BPC, Personal Communication, January 2017.

Month	Generation (GWh)	% Peak Generation*	Consumption (GWh)
Jan	243.7	20.3%	169.8
Feb	178.9	14.9%	154.6
Mar	211.4	17.6%	161.7
Apr	232.6	19.4%	166
May	458.9	38.2%	172.5
Jun	785.1	65.4%	167.6
Jul	1187.5	98.9%	155.9
Aug	1200.8	100.0%	164.3
Sep	1162.6	96.8%	157
Oct	767.9	63.9%	168.7
Nov	411.5	34.3%	175.1
Dec	306.1	25.5%	191.7

Note: *authors' calculations to construct hydropower availability curve.

Table A5. Cooking and heating end-use technology in the residential and service sectors UNDP (2012); Yangka & Diesendorf (2016).

Device	US$/device	Life (years)	Efficiency
Wood cook stove	5.69	5	10
Efficient wood cook stove	135.45	5	25
LPG/biogas stove	46.34	5	85
Electric stove	43.9	5	90
Efficient wood heating stove	189.66	5	75
Electric heater	57.98	5	90
Kerosene heater	203.25	5	45
Wood heating stove	56.90	5	12

Table A6. Household electric appliances, based on Department of renewable Energy (2015a, 2015b).

Device	US$/Device*	Life
Fridge 2-star	268.29	5 years
Fridge 3-star	284.55	5 years
Washing m/c semi-auto	240.65	5 years
Washing m/c auto	256.91	5 years
60Watt incandescent lamp	0.16	1200 hours
14Watt CFL	1.95	10000 hours
42Watt Fluorescent lamp	4.55	10000 hours
7Watt LED	7.31	50000 hours

Notes: *authors' calculation derived from the referred data sources. CFL — compact fluorescent lamp; LED stands for light emitting diode.

Table A7. Cost of passenger vehicle (IUT India, 2012*; RSTA, Personal Communication, October 19, 2016; Zhu et al., 2016).

Vehicle	Cost (US$)
Electric-cars	20,488
Light vehicle_gasoline	7,073.17
Light vehicle_diesel	29,268.29
Electric-bike	945.59
Diesel bus	39,204.75
Electric-bus	300,000.00
Light rail* (30 years life; 0.3MJ/pkm; 242 persons/coach)	1.62 million US$

Table A8. Transport sector technology characteristics, based on DoE (2010), Ministry of Information and Communications (2015), Yangka and Diesendorf (2016) and Zhu et al. (2016).

Passenger transport				
Vehicle type	**Fleet**	**km/litre**	**Occupancy (person/vehicle)**	**mp-km/year**
2-wheeler	9988	53.8	1.6	36.1
Taxi	4109	15	2.93	297.6
Light	41924	15	2.55	524.8
Bus	354	3.27	18.85	696.0
Freight transport				
Vehicle type	**Fleet**	**km/litre**	**Average capacity (tonnes/vehicle)**	**mt-km/year**
Heavy	8120	3.7	6	1933.78
Medium	1392		3	392.73

Note: mt-km stands for million tonnes kilometre; mp-km stands for million passenger kilometre.

Table A9. Freight transport technology, based on DoE (2010) and ETSAP (2010).

Freight vehicle	Diesel heavy truck	Heavy electric-truck*	Diesel light truck	Light electric-truck*
MJ/vehicle-km	7.46	−76%	3.92	−77%
Capital cost	32,000	406%	20,292	297%
kWh/vehicle-km		0.49		0.49
O&M cost	0.13	−82%	0.0561	−76%

Note: *authors' calculation based on ETSAP (2010).

Table A10. Transformation processes other than power generation, data imputed based on DoI (2015), Department of renewable Energy (2015a) and DRE & UNDP (2014).

Process	Capital cost	O&M cost	Life (years)	Production in 2014 (tonnes)	Resource potential
Coal Mining	49.59 (US$/ton)	82.62 (US$/ton)	50	121,891.00	1.9 Mt
Biogas production	18.96 (US$/GJ)	NA	30	898.45	633,756.19 GJ
Briquette making	4.05 (US$/GJ)	5% of capital cost	20	367.40	6,832.80 GJ

Table A11. Industry sector techno-economic data.

			US$/tonnes*			
Industry	SEC (kWh/tonnes)	Production (tonnes)	Capital cost	O&M cost	Life (years)	Data source
Cement	132.71	525,240.00	113.04	60.39	20	DoI (2015),
BCCL	5,340.58	32,340.48	812.38	842.76	20	Department of
Steel	825.50	196,172.22	46.07	335.40	20	Renewable Energy
Ferro Alloys	9,000.00	105,050.00	660.98	895.05	20	(2012, 2015a)

Note: *authors' calculation based on the listed data sources.

A3. Demand Projection

LEAP expression builder allows creating expressions for linking one branch to the other. For instance, the following expression syntax

GrowthAs(Branch:Variable, Elasticity)

relates the current branch (containing the above expression syntax) to the other branch which contains the independent variable that is assumed to drive the growth of the dependent variable in the current branch within the elasticity value specified by the modeller. In the Bhutan LEAP model, the above expression syntax translates to the following equation when invoked to project demand in the demand branches.

$$\text{Demand}(t) = \frac{\text{Demand}(t-1) * \text{driver}(t)}{\text{driver}(t-1)} \qquad \text{(Eq. (A.1))}$$

The driver is the chosen macroeconomic parameter (such as GDP, per capita GDP, population, number of households, etc.) provided under the 'key assumption' branch.

Table A12. Projected demand.

Sector	Unit	2014	2020	2025	2030	2035	2040	2045	2050
Transport sector									
Passenger travel	bp-km	1.93	2.84	3.91	5.39	7.43	10.24	14.11	19.45
Freight travel	bt-km	2.34	3.67	5.34	7.77	11.31	16.46	23.97	34.89
Industry sector									
BCCL	kt	32.3	40	57.6	81.7	113.7	155.7	209.4	276.9
Ferro Alloys	kt	106.8	132.1	190.4	269.7	375.6	514.1	691.6	914.5
Iron and Steel	kt	196.2	242.7	349.7	495.4	689.8	944.2	1,270.30	1,679.80
Cement	kt	525.2	649.8	936.3	1,326.30	1,847.00	2,528.10	3,401.30	4,497.60
Residential and Service sector									
Residential	Thousand HH	164.13	175.27	185.12	195.53	206.52	218.13	230.4	243.35
Service	Million US$	320.56	502.57	731.63	1,065.08	1,550.52	2,257.20	3,285.98	4,783.64

Table A13. Fuel price projection, based on Department of Renewable Energy (2015a) and US Energy Information Administration (2016).

Fuel	Unit	2014	2020	2025	2030	2035	2040	2045	2050
Diesel	US$/lt	0.82	1.29	1.49	1.74	2.00	2.31	2.67	3.09
Gasoline	US$/lt	0.95	1.49	1.72	2.01	2.31	2.67	3.08	3.56
Kerosene (Domestic)	US$/lt	0.21	0.34	0.39	0.46	0.52	0.61	0.70	0.81
Kerosene (Department of Industry)	US$/lt	0.77	1.22	1.41	1.64	1.89	2.18	2.52	2.92
Aviation Turbine Fuel	US$/lt	1.00	1.58	1.82	2.12	2.44	2.82	3.26	3.77
LPG	US$/kg	0.42	0.67	0.77	0.90	1.03	1.19	1.38	1.59

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Article

Neighborhood "Choice Architecture": A New Strategy for Lower-Emissions Urban Planning?

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Abstract

Recent advances in the field of behavioral economics offer intriguing insights into the ways that consumer decisions are influenced and may be influenced more deliberately to better meet community-wide and democratic goals. We demonstrate that these insights open a door to urban planners who may thereby develop strategies to alter urban-scale consumption behaviors that may significantly reduce greenhouse gas (GHG) emissions per capita. We first hypothesize that it is possible, through feasible changes in neighborhood structure, to alter the "choice architecture" of neighborhoods in order to achieve meaningful GHG reductions. We then formulate a number of elements of "choice architecture" that may be applied as tools at the neighborhood scale. We examine several neighborhoods that demonstrate variations in these elements, and from known inventories, we generate a preliminary assessment of the possible magnitude of GHG reductions that may be available. Although we acknowledge many remaining challenges, we conclude that "neighborhood choice architecture" offers a promising new strategy meriting further research and development.

Keywords

behavioral economics; choice architecture; climate change mitigation; greenhouse gas emissions; neighborhood planning

Issue

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1. Introduction

It is increasingly recognized that urban form plays an important role in greenhouse gas (GHG) emissions—by at least one measure, directly affecting up to 30% of all GHG emissions (Hoornweg, Sugar, & Trejos Gomez, 2011; Mehaffy, 2015). However, the ability to vary emissions through changes in urban form has been the subject of considerable controversy by investigators (Dodman, 2011). For example, a paper issued by the National Academy of Sciences (2009) held that the factors of urban form that can be feasibly varied by planners do not offer significant magnitudes of reduction, individually or in combination. Furthermore, the authors held that significant GHG reductions from alterations in urban form are not even feasible in the near term, since urban form changes slowly.

A rebuttal by Ewing, Nelson, Bartholomew, Emmi and Appleyard (2011) argued that the magnitudes of individual factors were under-stated, and that the paper ignored their significant cumulative effects over time. Moreover, precisely because urban form changes slowly, the effects of actions now will persist and accumulate for many decades, magnifying the long-term effects of changes in urban form in the short term.

It is also clear that the variation in GHG emissions per capita varies enormously by country and by city, and it is difficult to explain such magnitudes without recognizing the central role of often dramatic variations in urban form. For example, data assembled by the World Bank (summarized in Figure 1) shows that per-capita inventories of emissions assembled under UNFCC protocols vary between Stockholm, Sweden and the average in the USA by over six-fold. Although the USA is clearly a more geo-

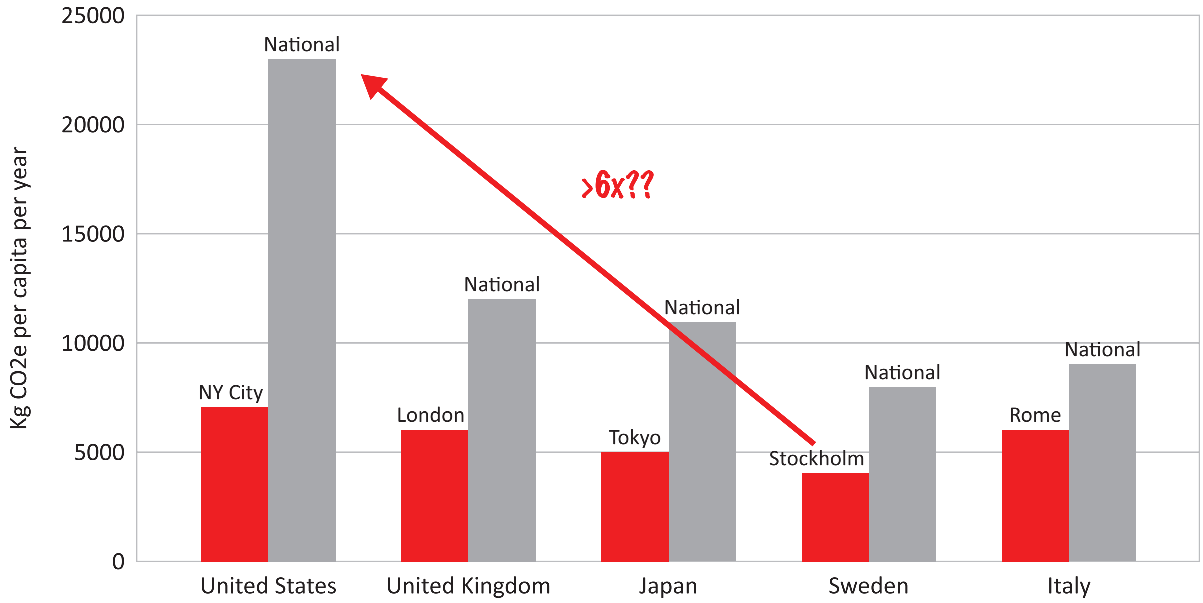

Figure 1. Dramatic differences are revealed between country (gray) and city (red) GHG emissions per capita, reflecting national consumption-based inventories gathered from 2005–2007 and assembled under UNFCC standards. Source: World Bank (2011). The differences do not correlate well with income, climate, national geography, or other factors—but the factors of urban form do show a strong correlation (Mehaffy, 2015).

graphically dispersed country, most emissions occur in activities within cities, not between them (UN-Habitat, 2011), and so it is the form of the cities—not their pattern of dispersal—that is suspect. If we could capture even a portion of that variation, it would represent a sizable reduction in greenhouse emissions per capita.

The role of urban form appears all the more important given that the world is currently experiencing an unprecedented period of rapid urbanization, with potentially profound impacts on emissions (Olivier, Janssens-Maenhaut, Muntean, & Peters, 2013; UN-Habitat, 2011). It seems clear that any significant changes in urban form that can be linked to changes in emissions rates will have a profound effect on emissions in the future.

At the same time, the dynamics of how urban form affects rates of emissions, and how these changes can be altered to achieve significant reductions of emissions, are undeniably complex (Dodman, 2011). Particularly important is the question of consumption behavior and demand. One of the promising topics of investigation has been the opportunity to achieve significant reductions through changes in behavior and consumption, with a notable focus on the household scale (Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Gowdy, 2008).

Going beyond the household scale, we might ask the same question at the neighborhood scale, and more broadly speaking, the scale of urban form. Do people tend to consume more energy-intensive, high-emissions products when they live in some types of urban forms than in others, all other things held equal? We already know that they tend to drive more in neighborhoods that are less dense and have more car-dependent transportation systems, for fairly self-evident reasons (Cervero & Murakami, 2010). Can the same logic be extrapolated to other higher-emissions behaviors?

One significant problem is that consumption demand is a highly elastic variable, and a problematic one when it comes to predicting outcomes. For example, the predicted levels of energy-efficient buildings have been shown to vary significantly from their actual performance, in part because anticipated demand has varied far more than expected (Montanya & Keith, 2011; Newsham, Mancini, & Birt, 2009).

One significant problem is the phenomenon of "induced demand". Demand and choice are not static but elastic, and demand can increase as the result of increased efficiency, tending to erase the gains. In transportation, for example, widened roads initially result in smoother traffic flow, but the faster paths draw more drivers, and create "induced demand", erasing the traffic flow benefits of widening projects. In addition, the creation of new route choices, rather than speeding flow, can actually increase congestion, the result of a phenomenon known as "Braess' Paradox" (Sorrell, 2009; Steinberg & Zangwill, 1983).

Similarly, more resource-efficient technologies (like more efficient automobiles) can also produce induced demand and "rebound effect" (Sorrell, 2007). Closely related, the well-known Jevons' Paradox states that as efficiency goes up, cost tends to go down, which tends to result in increased consumption demand. This phenomenon has been observed as an unintended consequence of increased energy efficiency (Polimeni, 2008). From a GHG emissions perspective, the result is often an increase in emissions that erases part or all of the expected gains (Sorrell, 2009).

No less problematic is the inability to deal with behavior in isolation, apart from systemic and cultural influences including psychological and sociological influences (Moloney & Strengers, 2014; Strengers, 2012). Such effects have proven ineffective in the past, leading authors like Strengers to call for a more comprehensive application of theories of social change and policy.

The lesson for those seeking GHG emissions reductions is that variables of urban form, like other variables affecting emissions, cannot be treated in isolation, but need to be treated as part of a comprehensive "systems" approach, sensitive to rebound effect, and Braess-like network influences. We must consider not only urban form, and not only lifestyle and consumption behaviors, but how urban form interacts with and shapes those behaviors in complex and subtle ways.

The challenges posed by these interactive effects may seem overwhelming, but they are hardly without precedent. Medical doctors routinely deal with similarly complex challenges, and over time they have developed successful and efficacious approaches. Indeed, the biological similarities of "organized complexity" in urbanism were described memorably by Jane Jacobs in the last chapter of her landmark *The Death and Life of Great American Cities*, titled "the kind of problem a city is" (Jacobs, 1961). Our challenge, too, is to iteratively develop more effective approaches, looking for successful methodologies that we can apply, refine and further develop (Mehaffy, 2015).

2. Contributions of Behavioral Economics

In a similar way, the more specific challenge of shaping behavior and demand is also a daunting one, but also not without precedent. Those who study complex economic interactions and the psychology of consumer choices have made substantial headway in facing similar challenges in recent years. Most relevant have been the notable advances in the area of behavioral economics and choice (Camerer, Loewenstein, & Rabin, 2011).

Economists, unable to explain behaviors that are not predicted by the "efficient market hypothesis" and other standard economic models, have increasingly turned to psychology for new models (Sent, 2004). In that field it has been found that human beings often must use limited information to make choices, and their ability to make what we might regard as rational decisions are similarly limited—as the Nobel Prize-winning psychologist and polymath Herbert Simon (1956) famously observed. The implication is that the limits of human cognition will distort choices—and the boundaries of these limits, according to Simon, can readily be observed in the psychology of experience, and the structure of the environment in which that experience takes place. Simon (1956) termed this phenomenon "bounded rationality".

The psychologists Daniel Kahneman and Amos Tversky took this work on bounded rationality much further in the intervening years, establishing a robust set of findings in the consequences for decision-making and choice from the limits of cognition, the effects of environmental "availability", and related insights—also garnering a Nobel Prize (Kahneman, 2002).

Building on those insights, in 2008 the behavioral economist Richard Thaler and two colleagues introduced the concept of "choice architecture" (Thaler, Sunstein, & Balz, 2010). They described the importance of the structures in which choices are pre-configured in shaping the actual choices made. This finding (once again the subject of a Nobel Prize) opens the way for those who seek changes in the outcomes of consumer choices to make alterations in the "choice architecture" to do so.

The primary focus of this work to date has been in the area of public policy and consumer choice—for example, influencing healthier eating choices—and in fact, a number of investigators have begun to explore the implications for sustainable resource use and GHG reduction (Johnson et al., 2012; Kallbekken & Sælen, 2013). Some researchers have examined specific tools to apply choice architecture to sustainable transport (Bothos, Mentzas, Prost, Schrammel, & Röderer, 2014). Most famously, the UK government has begun applying so-called "nudge" policies to achieve these and other public policy goals (Young & Middlemiss, 2012). Thus far, however, as far as we are aware, there has been little attention to the potential for application of these tools at an urban scale—the topic we take up here.

In a sense, one can readily observe that commercial businesses already frequently exploit these dynamics, as for example when they place brightly colored candy packaging at the checkout line of a store. On a broader environmental level, retailers and retail consultants have compiled extensive knowledge about the factors that influence decisions of consumers driving or walking past a store to choose to shop there, including display visibility, signage color and the like (Gibbs, 2011). While these urban-scale design changes do not formally exploit concepts of "choice architecture", they exhibit a similar approach to a similar problem.

It must be noted that there is considerable debate about choice architecture and its top-down, potentially manipulative aspects (Selinger & Whyte, 2011). At the same time, many choice architects state that their aim is not to manipulate consumers in hidden ways, but to apply open community decisions about public policies—ideally including the same people who will be affected by those policies, within a democratic and participatory context—and then to find ways to make implementation easier through behavioral economic strategies (Sunstein, 2015). Again, the public policy of healthier eating is a relevant example (Johnson et al., 2012).

More tantalizing for our purposes, behavioral economics suggests a possible path to a shared community goal of GHG reductions from urban form—the opportunity we investigate here. Can we look at the entire neighborhood as a tableau of choice architecture for the residents, amenable to a democratic process of pre-structuring by planners and stakeholders? Can such a strategy be employed to achieve reductions of emissions? If so, what are the potential magnitudes of reductions, and how can they be achieved in practice?

3. Methodology

To explore this possibility, we first examine a number of the most important key concepts of choice architecture, and their current applications within the field. We then consider how these concepts may translate into urban planning methodologies. Next, we consider how such methodologies may be translated into specific emissions-lowering actions at the neighborhood scale. Based upon the prospects for changes to known sources of emissions (e.g., passenger car use), we make an initial assessment of the possible magnitude of reductions based upon available evidence. Finally, we examine concrete examples, in the form of three neighborhoods with known characteristics of urban form, also known GHG inventories. We consider their variations in emissions using the conceptual model of choice architecture, asking whether the model might help to explain some of the currently unexplained variation. We find encouraging (but not conclusive) evidence for that hypothesis. We conclude with a discussion of the promise and pitfalls of choice architecture as a new conceptual strategy for these purposes, and the likely next steps in its subsequent development as a methodology in practice.

4. Elements of Choice Architecture

Thaler and other authors have articulated at least six major tools of choice architecture (Johnson et al., 2012) that might be applied to the planning of neighborhood structure. We list them here, along with their possible application to neighborhoods.

4.1. Create Defaults

Because of the cognitive limits of short-term decision-making, and the "bounded rationality" of human consciousness, humans are prone to choose "default" options that are more cognitively accessible (Kahneman, 2002; Smith, Goldstein & Johnson, 2013). For choice architects, this means that defaults should be established as more prominent and immediate options (Johnson et al., 2012).

Defaults may include both visually prominent features, and features that are more cognitively "available" because they have attention-getting or appealing aesthetic characteristics. This means that visual appeal is one of the important tools in a neighborhood choice architect's toolbox—no less than it is with a product marketer who uses beautiful models to sell its products.

4.1.1. Urban Planning Methodologies

a) Increase visual prominence and visual appeal of a default option. For example, create pedestrian pathways that are larger and more beautiful;
b) Increase cues that signal the default option. For example, add signage, or prominent gateway;
c) Decrease prominence of non-default options, without removing them from a rational decision-making process. For example, place parking lots at the rear of stores, in visually less prominent locations.

4.2. Reduce "Choice Overload"

Consumers are not helped when choices are too numerous to allow a careful evaluation and selection of alternatives (Schwartz, 2004). At the same time, too few alternatives may prevent consumers from finding a truly optimal choice for their varying circumstance. Therefore, an optimal choice architecture would present a range of meaningful choices most likely to meet consumer needs, without overwhelming consumers with irrelevant options (Johnson et al., 2004).

4.2.1. Urban Planning Methodologies

a) Limit the availability of multiple confusing choices, including confusing visual cues. For example, reduce the clutter of automobile-related signage, and make existing pedestrian and bike-related signage more prominent;
b) At the same time, assure a meaningful range of choices based on actual likely need. In the case of automobile-related signage, of course there is likely to be a continuing need for some signage, but it should be as limited as possible;
c) Present the choices in clear and comprehensible forms. Make designs "legible". Make signs clear, simple and easy to read. Place preferred and default choices in clear and visible locations.

5. Increase the Availability of Future Costs and Benefits in the Present

Consumers tend to focus on more cognitively available impacts in the present (Kahneman, 2002; Shu, 2008). Therefore, long-term costs or benefits, such as higher prices or better environmental benefits, must be presented in a near-term form that is more recognizable, e.g., immediate tolls, or awards for environmental achievements, offering immediate tangible benefits (Johnson, et al., 2004).

5.1. Urban Planning Methodologies

a) Provide for immediate payments or economic benefits. For example, increase toll charges, congestion charges, discounts, passes, "green" rewards, and similar financial incentives and disincentives. Reduce delays for public transit users, bicyclists and pedestrians;

b) Make long-term positive actions easier, more convenient, less burdensome or dangerous in the short-term relative to more negative ones (e.g., reduce "switching costs" and "search costs", and other barriers to a change toward more beneficial activities);
c) Make long-term positive actions more pleasurable and more immediately rewarding aesthetically in the short term. For example, provide greater aesthetic pleasures in the moment for walking and cycling, thereby making more "available" the benefits of these long-term low-carbon activities in the short term.

6. Partition Options into More Easily Understood Groups

Consumers are influenced by the way that attributes are grouped or "partitioned", and they tend to pay less attention to attributes that are grouped together (Fox & Rottenstreich, 2003). Therefore, to increase selection of more important attributes, itemize them, while aggregating less important ones (Johnson et al., 2004). For example, the nutritional content of foods might be listed in partitioned groups, with the most beneficial or least beneficial ones listed individually, and relatively inconsequential ones listed under "other ingredients". In addition, complex information can be made more cognitively accessible by partitioning into more easily comprehended units. (See also number 5, "translate attributes into cognitively accessible forms".)

6.1. Urban Planning Methodologies

a) Itemize costs and benefits of activities that have a direct connection to consumer behavior. For example, apply congestion charges per unit of driving distance. Provide simple, direct rewards to those who choose biking or walking, such as specially designed bike racks and pedestrian entrances;
b) Aggregate costs (including time costs) that might otherwise seem more costly. For example, coordinate and combine delays in waiting for transit so that delay times overlap and optimize walking times to coordinate with transit times;
c) Highlight costs and benefits that have important consequences by providing an immediate economic reward or charge in a prominent form. For example, provide a toll road for cars, but a special no-toll path for bicycles and transit.

7. Translate Attributes into Cognitively Accessible Forms

The benefits of a consumer choice may be more visible if the attribute is presented in a "translated" way, i.e., a clearer and more comprehensible way that requires less cognitive effort (Johnson et al., 2012). This may also include translating the attribute into a metric that is more meaningful for the consumer, e.g., a direct pocketbook cost instead of an abstract environmental benefit.

7.1. Urban Planning Methodologies

a) Create pricing mechanisms that translate abstract attributes into direct and simple economic costs and benefits, e.g., tolls, parking charges, congestion charges, etc.;
b) Create aesthetic benefits that reward consumers in the short term for choosing actions with long-term benefits (see, also, section 5: "Increase the availability of future costs and benefits in the present");
c) Provide signage and wayfinding that is clearer and presents alternatives in easier to understand forms, e.g., displaying slow travel times for automobile traffic.

8. Evaluating Potential Emissions Reductions from Choice Architecture at the Neighborhood Scale

We previously published a preliminary evaluation of the features of a neighborhood that relate to the concept of choice architecture, and the potential magnitude of emissions reductions suggested in previous research (Mehaffy, 2015). Here we review these features and assess the potential of choice architecture tools to achieve these reductions.

8.1. Altering the Choice Architecture of Existing Car-Dependent Neighborhoods

We began our earlier assessment by identifying a mature body of research documenting the contribution of vehicular transport (notably personal automobile transport) as significant factors in global per-capita GHG emissions, particularly so in developed countries (Dodman, 2009). As we noted, this factor appears likely to gain in significance as countries like China and India continue to develop car-dependent urban forms (Calthorpe, 2013). To the extent that the "modal split" (the percentage using different forms of travel) can be shifted away from vehicle use and towards walking and/or bicycling, there is a concrete opportunity to achieve measurable reductions in energy and resource consumption, and in GHG emissions per capita, in combination with other opportunities (Pacala & Socolow, 2004).

In addition, the embodied energy and materials in automobiles and infrastructure further increase the average emissions per unit of distance (Mehaffy, 2013). This is because greater vehicle operation and Vehicle Miles Travelled (VMT) on average requires manufacture of a greater number of automobiles, and more construction, maintenance and operation of roadways, all of which contribute to resource consumption and GHG emissions. In addition, roadways and other infrastructure generally remove vegetation and pervious cover, further exacerbating the problem.

We previously cited evidence to suggest that the potential reduction in GHG emissions from feasible changes to transportation behaviors was in the range of 10% (Mehaffy, 2015). This potential reduction occurs primarily as the result of lower driving and more use of walking and transit, or what is known as "modal split". Therefore, if changes to neighborhood choice architecture can have a significant effect on modal split, then such a strategy may assist with achieving per-capita reductions of GHG emissions of this magnitude. But before we can examine changes, let us assess the current choice architecture of *existing* neighborhoods, and the places where changes might be made in accordance with a choice architecture methodology.

It is well known that many existing neighborhoods are "car-dependent", that is, they are designed so that almost all trips are expected to be taken by private automobile (Sohn & Yun, 2009). Under these conditions, it is difficult to avoid increased use of automobiles, and encourage use of alternative modes. In choice architecture terms, these neighborhoods have "created a default" for automobile-based modes of travel. It is very difficult for consumers to switch to another mode, unless this default is altered through an alteration of choice architecture.

The economic literature provides evidence of this phenomenon at work. In work on the effect of "search costs" (Smith, Venkatraman, & Dholakia, 1999) it was shown that consumers may not have adequate information about the full costs versus benefits of continuing a "search" (e.g., pursuing an alternative mode or destination) and may therefore default to the current choice.

In economic literature, the phenomenon of "switching costs" poses a similar barrier: the costs to the consumer of time and opportunity in searching for parking, in maneuvering and securing the car, are generally well known, whereas the benefits of making the switch are often unknown, with the result that the switch is less likely (Dobbie, 1968). The options are *partitioned* in a way that makes the auto-based choices more cognitively available.

We can also see a strong default created within the infrastructure system that is designed to accommodate the automobile and make its use more convenient and pleasurable: the service station "convenience" stores, drive-to shopping centers, drive-in fast-food restaurants, and other related facilities. It is perhaps not surprising that they also exploit the opportunity to present a choice architecture of high-consumption activities to a captive market, using sophisticated behavioral psychology to do so (Chandon & Wansink, 2010; Smith, 2004). There are undoubtedly additional implications for GHG emissions, although this subject is beyond the scope of the present study.

Lastly, we can ask what is the unintended choice architecture of a car-dependent neighborhood on other modes of transportation. There is ample evidence that the engineering changes needed to accommodate automobiles can (and often do) conflict with the safety and comfort of pedestrians and bicyclists (Pucher & Dijkstra, 2003). In turn, there are negative impacts on public transit users, who must walk or bike to and from transit stops. This negative impact increases with the degree of car dependency and use, resulting in an increasingly dangerous and uncomfortable environment for non-auto users. Put differently, auto dependency tends to produce more auto dependency within a feedback cycle. The cycle is accelerated via the reinforcing influences of a changing neighborhood choice architecture.

What are the changes to choice architecture within existing car-dependent neighborhoods that might encourage other modes of travel? We list several here:

a) Provide more *visually prominent walking and bike paths*, with lower burdens and higher aesthetic benefits and pleasurability;
b) Create *pricing mechanisms* that make the costs of automobile travel more cognitively available to consumers, e.g., parking meters, congestion charges;
c) Create more *attractive* and *convenient* transit stops, with more attractive bike and walking paths to them;
d) Where possible, restrict new drive-through facilities and auto-dependent shopping centers, which make driving more *convenient* and a more *attractive default*;
e) Create *economic rewards* for behavior change, including transit passes, discounts, etc.

8.2. Altering Choice Architecture in New Neighborhoods toward More Walkable, Bikeable, Transit-Served Neighborhoods

As the previous discussion suggested, there is evidence that neighborhoods with higher rates of walking and biking show a reduction of longer-distance automobile travel (Ewing & Cervero, 2001). This in turn implies reduced GHG emissions per capita on the order of approximately five percent, an implication that is supported by other studies on city GHG emissions (Cervero & Murakami, 2010; Ewing & Rong, 2008). It thus appears that increasing walking and biking trips through changes in neighborhood choice architecture would serve as a useful GHG reduction strategy (Pacala & Socolow, 2004).

As might be expected, research has demonstrated higher rates of walking in neighborhoods where the design creates a more *convenient* and *attractive default*, even adjusting for other factors such as self-selection (Frank, Saelens, Powell, & Chapman, 2007). In particular, the literature shows a strong correlation between rates of walking and short blocks with high intersection density (Berrigan, Pickle, & Dill, 2010; Leslie et al., 2005). Short blocks lessen the average distance between any two destinations, lowering the barriers to walking. In addition, shorter blocks present a more varied and visually interesting path for walkers and bikers, with more frequent changes of vistas, as compared to longer, unbroken blocks. On the other hand, so-called "dendritic" street patterns can make walking nearly impossible because of the excessively long paths for most trips (Figure 2).

Short blocks and high intersection densities are also associated with greater rates of bicycle use, for the same evident reasons (Winters, Brauer, Setton, & Teschke, 2013). A "permeable" street network shortens average trip distances, and also gives bicycle users a greater opportunity to use alternate streets that are safer and with less traffic. Moreover, such a permeable network is likely to reduce the concentrations of traffic overall and reduce the number of areas of dangerous traffic with which a bicycle might have to contend, further reinforcing the attractiveness of bike travel and its status as a more likely default choice (Mehaffy, Porta, Rofe, & Salingaros, 2010).

Another factor is the importance of well-designed "attractive" and "convenient" sidewalks and bike lanes. Nelson and Allen (1997) showed a correlation between total length of lanes and rates of bicycling. Cao, Mokhtarian and Handy (2007) showed a correlation between safe and well-designed sidewalks and bike lanes, and increased rates of walking and biking with reduced rates of driving.

Following the logic of choice architecture, we must also consider the *aesthetic character* of the streetscape itself, including vegetation, interesting small-scale details, and *pleasurable* user experiences of beauty. As we have seen, a more appealing aesthetic character makes a choice more cognitively available. Following that hypothesis, Cerin, Saelens, Sallis and Frank (2006) presented research that presence of vegetation is associated with higher rates of walking. Other researchers found similar results for both walking and biking (Saelens, Sallis, & Frank, 2003; Wahlgren & Schantz, 2012). Wahlgren and Schantz (2012) also found that user experiences of beauty and greenery both served independently as stimulating factors for bicycle commuting. Since buildings are part of the scenery of bike commuters, this finding suggests that beauty in buildings (as experienced by users)

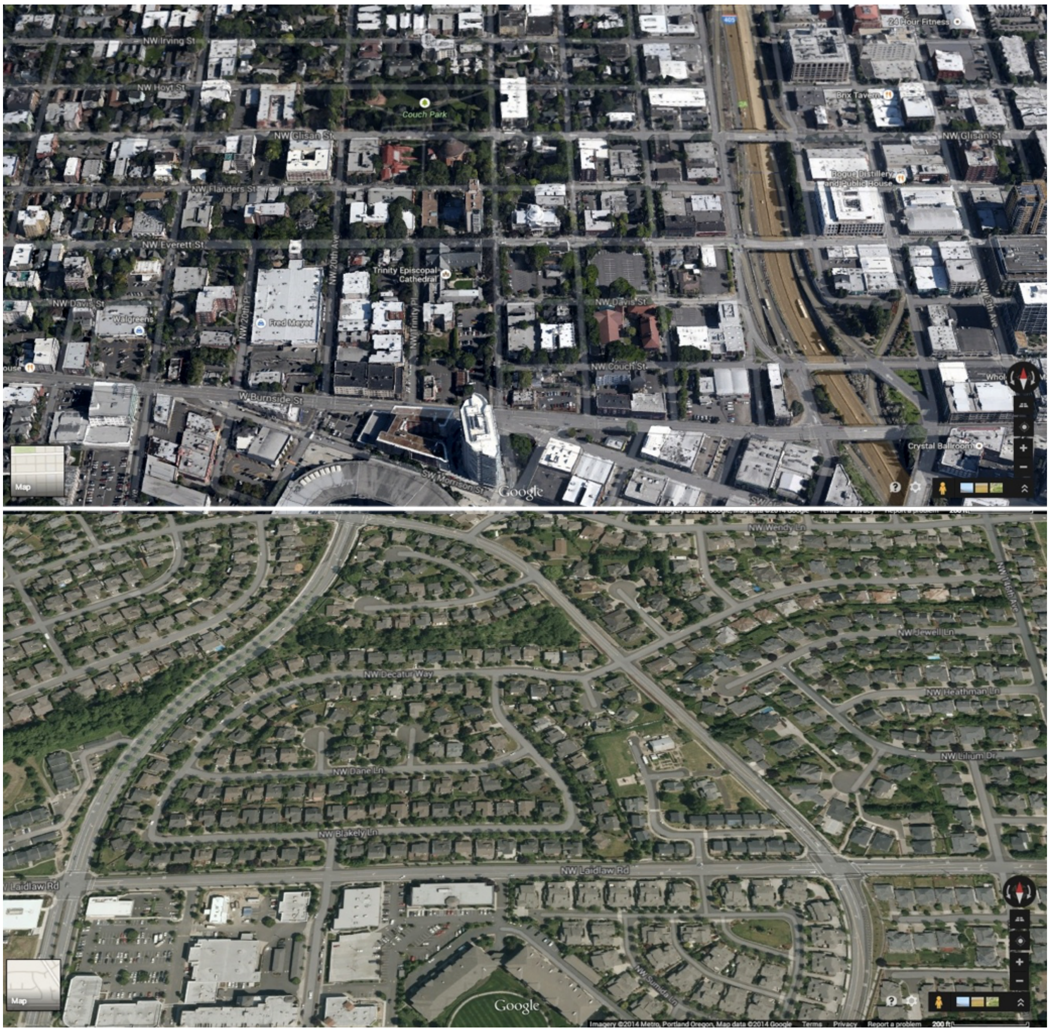

Figure 2. Two very different street patterns shown at the same scale. Above, short blocks and a high density of intersections invites walking. Below, long uninterrupted blocks and "dendritic" or tree-like street patterns make walking unappealing and difficult for most trips (Source: Google Maps).

as well as natural areas can improve the choice architecture to favor bicycle use.

Of course, the question of what specific design characteristics a walker or bicyclist is most likely to find beautiful must also be considered. Cold (1998) surveyed literature concluding that such environmental preferences are not subjective but are rooted in evolutionary history. In particular, the perception of beautiful environments is strongly associated with environments that combine coherence with complexity. This combination affords curiosity, enticement and an opportunity to penetrate hidden layers. Following this logic, neighborhoods with these factors are indeed associated with measurably higher rates of walking and bicycling (Saelens et al., 2003).

In addition, we must consider the influence of environmental affordances as a related concept. For Gibson (1979) we are cognitively more aware of the capacities that are afforded to us by an object in the environment—for example, the "affordance" of a flight of stairs to climb. It follows that the more we make cognitively available the affordances of, say, an attractive walking path, to get to a desired destination, the more likely will be its use. In this sense, Gibson's (1979) theory of affordances is complementary to the theory of neighborhood choice architecture.

In this same vein, we can also ask what are the characteristics of neighborhood choice architecture that will tend to encourage public transit use. There is strong evidence that increased transit use also results in lower per capita GHG emissions, again in the order of perhaps 5% (Mehaffy, 2013; Poudenx, 2008).

A key factor is the walkability or bikeability of pathways to transit stops, which helps to create a default option and *lower barriers*, affecting the willingness of residents to make the initial journey to the transit stop (Cervero & Radisch, 1996; Frank & Pivo, 1994). Also important for "convenience" and "barrier-reduction" is the average distance to the transit stop from possible points of origin for pedestrians (Zhao, Chow, Li, Ubaka, & Gan, 2003).

A second factor affecting transit use, though one that gets little attention, is the attractiveness of the transit facilities and vehicles and themselves. It seems likely that a part of the relative stigmatization of bus travel in particular is in its aesthetic character, and the identity it carries of a "second-class" form of transportation, sometimes disparagingly referred to as a "loser cruiser" (Audirac & Higgins, 2004; Poudenx, 2008). This makes it much harder to establish bus travel as a default option that is *pleasurable*.

Lastly, we found evidence that the immediate environment of the transit stop is important. If it contains other adjacent uses—particularly services that are likely to attract waiting passengers and provide greater safety and "attractiveness"—it is likely to be more frequented (Kim, Ulfarsson, & Hennessy, 2007; Schmenner, 1976). In addition, if there is shelter from inclement weather, this amenity *signals* to potential riders that they will be "comfortable" while awaiting their transport (Law & Taylor, 2001).

As in other areas, these findings lend support to the concept that modifications to the choice architecture of a neighborhood can have substantial impacts on the actual choices made to use public transit.

What are the elements of a strategy of choice architecture for the design of new neighborhoods?

a) *Barriers* to walking and cycling should be lowered, by making smaller blocks, permeable streets and pathways, and a high intersection density. "Dendritic" street patterns should be avoided;
b) *Defaults* should be established for walking and biking, by creating *attractive*, *pleasurable* pathways;
c) The choice of automobile use (or other vehicle to accommodate large loads, the inform, etc) may be preserved as a *non-default option*, while signaling the default of walking and biking with *visually prominent features*;
d) Bus and other transit shelters should be *attractive* and well-planned adjacent to *convenient and safe* active uses, with *prominent signage* indicating the benefits of transit use. Pathways to transit facilities should be prominent, attractive and convenient.

8.3. Other Applications of Neighborhood Choice Architecture

8.3.1. Parks and Recreation

For new neighborhoods as well as existing ones, active outdoor recreation is an inherently low-carbon activity, particularly when it replaces other activities—for example, walking, jogging or using parks, in replacement of driving or performing sedentary activities that consume energy and resources within the home (i.e., watching television, eating snacks, etc.).

There is also evidence that the presence of "attractive" nearby parks, in addition to making convenient recreation available, increases the likelihood of park use (Groth, Miller, Nadkarni, Riley, & Shoup, 2008). Conversely, the absence of such facilities within the neighborhood, even when residents have the means to access more distant ones readily by vehicle, is associated with lower active recreation by residents (McCormack, Rock, Toohey, & Hignell, 2010). By definition, these more distant parks also require more distant travel, often by automobile.

Therefore, to increase the use of parks and recreation as a low-carbon strategy, neighborhood choice architecture might include the following strategies:

a) Create many *convenient* nearby parks that can be *easily reached* by walking or bike;
b) Make them *visually prominent* and *attractive*;
c) Reduce the number of large remote parks that require extensive travel to access. Consider charging *user fees* and/or *parking meters* for their use.

8.3.2. Neighborhood Housing Types

As we noted in our previous research, the design of neighborhoods inevitably affects and limits the design of housing, in part from the size of lots, the provision for attached housing, and indirectly, the size of homes. In turn, these factors may greatly affect domestic consumption patterns, as we discuss below. This is an immature promising area for further research.

First, we can find abundant evidence that the size of homes and lots plays a major role in consumption demand (Ewing & Rong, 2008). In addition to the evident reduction of space required to light, heat and cool the home, residents also have more limited space in which to install high-consumption household and backyard goods. Residents who "downsized" homes do have a lower demand profile (Erickson, Chandler, & Lazarus, 2012).

A related finding is that residential water use is significantly lower in more compact neighborhoods with smaller homes (Chang, Parandvash, & Shandas, 2010; House-Peters, Pratt, & Chang, 2010). Larger-lot suburban residents often have large areas of lawn requiring watering, and they may also have other behaviors associated with high water consumption, e.g., washing of cars (Corbella & Pujol, 2009). The use of water carries implications for GHG emissions in two ways: a) water pumping, storing and purifying requires energy that typically generates GHG emissions; and b) rates of water use tend to correlate with rates of energy used in activities that consume water, such as clothes washing, water heating, lawn care, and other household activities.

At the same time, more work is needed to integrate models of household sources of consumption in relation to regional sources of production (Baynes, Lenzen, Steinberger, & Bai, 2011). For now, it seems very likely that the home itself creates its own "domestic choice architecture" favoring greater per capita consumption and greater GHG emissions (Høyer & Holden, 2003). The lesson for our purposes is that neighborhood form creates the context in which this household-scale choice architecture occurs, and shapes it through a number of ways (including, most obviously, the process of development and the consumer choices it generates).

8.3.3. Neighborhood-Scale Food Consumption

Lastly, we should mention intriguing evidence that the structure of a neighborhood has a notable influence on the pattern of food consumption by residents. In turn there are implications for resource intensity of the food consumed, the amount of waste packaging, and contributions to landfills—all of which drive GHG emissions per capita.

We have already discussed the presence of auto-dependent design as a neighborhood default, and the system of shopping that is auto-oriented. There is also evidence that increased driving can in turn create a "cycle of dependence" (Handy, 1993) in which more distant regional "volume" shopping centers, "big box", fast-food and other "drive through" convenience retailers, eventually displace smaller, more local retailers. As we noted in previous research, the larger facilities benefit from a captive automobile-based market, in the form of buyers who must, if they are not satisfied with the selection, go to the trouble of returning to their automobiles and initiating the cumbersome process of driving to another facility (Mehaffy, 2015). For this captive market, businesses have become adept at utilizing brightly colored packaging and signage, and high concentrations of salt, fat, sweets and processed foods, which entice buyers to engage in high-consumption purchases (Chandon & Wansink, 2010; Smith, 2004).

We previously discussed examples of positive choice architecture in sidewalk-facing markets that present appetizing healthy food in a way that is visible to pedestrians and bicyclists, creating a very different choice architecture (Figure 3). Of course, it is possible to present unhealthy foods in the same way, but it is notable that the close proximity of the food to pedestrians and bicyclists in effect "levels the playing field" and allows fresh fruit and produce to be shown in a most appealing way.

The link between neighborhood choice architecture and food choice is the most indirect, and therefore the least well established in the research literature. It must be noted that other factors may also work to counter the benefits of more compact, walkable neighborhoods—for example, if their residents have a propensity to eat in restaurants with high levels of food waste. However, the indications are intriguing enough that we believe this topic is worth considering for further research and development.

9. Looking at Actual Neighborhoods and Their Relative Emissions

Finally, we will examine three neighborhood examples with contrasting characteristics of urban form as well as comparative baseline inventory data. Each of the three neighborhoods exhibits distinctly different choice architecture in its urban form. The comparison will help us to see how the conceptual model can be applied to interpret actual variations. It is important to note that other factors certainly contribute to the variations in performance (such as sheer density, for example) but they also illustrate in concrete form how neighborhood choice architecture, at the least, offers us an intriguing hypothesis to account for additional reductions from behavior.

The neighborhoods are included in a study by Nichols and Kockelman (2015) that examined operational and embodied energy for five different neighborhoods in Austin, Texas. The authors used a number of inventory methodologies and data sources to produce a combined inventory of energy consumption. Their study did not include household goods or food consumption, but it did consider transportation, household energy and other forms of consumption.

Figure 3. The choice architecture of healthy food on a street in Oslo, Norway. This urban form assures that many people coming into close contact with the appealing display of food (Photo Credit: Author).

The authors also did not measure actual GHG emissions, but rather, rates of energy consumption. Because energy is a primary driver of emissions, and direct measurements of emissions are generally harder to measure at the neighborhood scale, we use the data on energy here as a reasonable proxy for the magnitudes of differences that we may be able to affect with neighborhood choice architecture, in concert with other strategies. Specifically, we will consider the reductions of energy consumption as they are correlated with neighborhood choice architecture.

For simplicity, we consider three of the neighborhoods from the Nichols and Kockelman (2015) study, which span the widest range of difference in urban form. Since they are all in the central or western Austin area, their socio-economic status, climate, legal and political systems, local energy technologies and building codes, and other factors that might generate variations in consumption patterns, are all comparable or even identical. The only major identifiable variable is urban form.

Figure 4 shows Westlake, a western suburb of Austin where the choice architecture is a very strong example

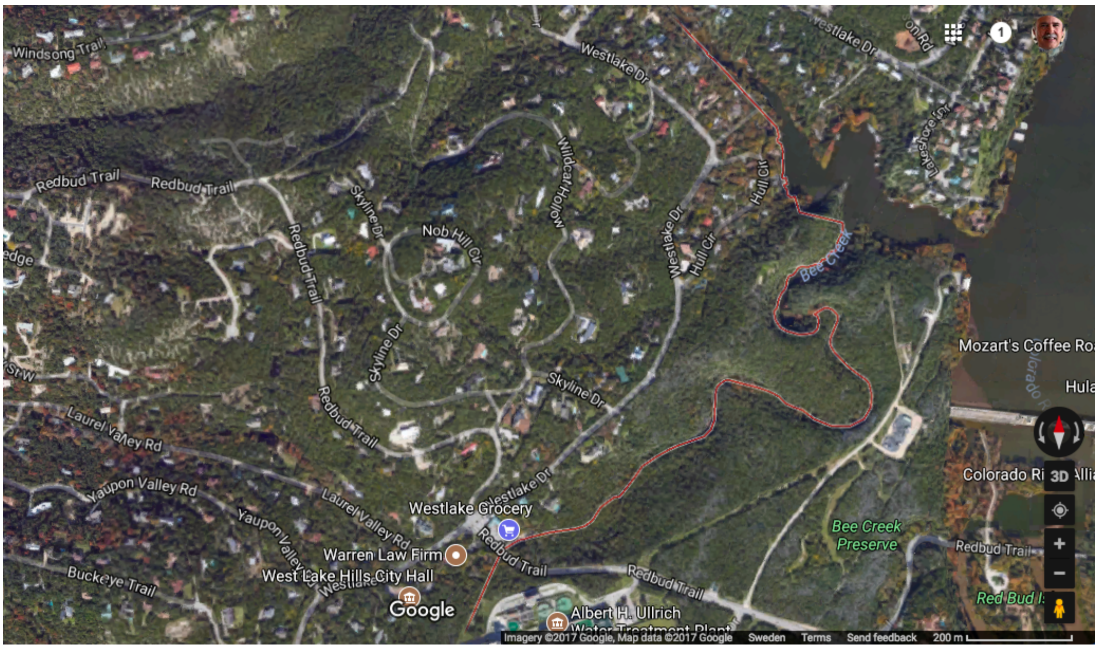

Figure 4. The Westlake neighborhood of Austin, Texas, USA. (Image: Google Maps).

of auto-dependent default. Streets are fragmented and "dendritic", blocks are very large, and there is a low density of intersections. There are no sidewalks, and few people can be observed walking except for recreation. There are no bike paths, and bike users must contend with automobiles on winding, sometimes dangerous roads. Transit service is infrequent and inconvenient, with large distances between stops, and there are no adjacent uses or attractive shelters. Shopping is remote and generally requires extensive driving; from the center of this neighborhood, the closest major shopping facility is approximately 4 miles, and the "Walkscore" website (which measures proximity to shopping among other factors) scores the neighborhood a dismal "4" out of 100 for walkability (Walkscore, 2018). There are no small neighborhood-scale parks. Houses are almost all large detached buildings on large lots.

Figure 5 shows Hyde Park, a more central historic suburb of Austin where the choice architecture is a more mixed example. Streets are inter-connected with a relatively high intersection density, blocks are relatively small, and there are ample sidewalks. Many people can be observed walking and using bicycles. Transit service is convenient and frequent, with large distances between stops, and no adjacent uses or attractive shelters. Shopping is relatively close by, and it is feasible (though not very practical) to shop without a car. There are numerous small neighborhood-scale parks within walking distance. Houses are generally detached, but smaller than typical Westlake houses and in significantly smaller lots on average.

Figure 6 shows the downtown area of Austin, where the choice architecture is the most extreme in the opposite direction from auto-dependent. Blocks are the smallest of the three examples, and there is a very high density of intersections. There are ample sidewalks, and many people can be observed walking and biking. Transit service is frequent and convenient, and many adjacent uses and/or attractive shelters. Shopping is very close by and generally does not require driving. There are many small neighborhood-scale parks nearby, and a large riverfront bark that is also close by to most downtown residences (since it expends in a linear pattern along the river). Houses are almost all large attached apartments or condominiums, and average home size is the smallest of the three neighborhoods.

According to Nichols and Kockelman's (2015) research, the embodied and operational energy of the three neighborhoods is as follows:

As Table 1 shows, the difference between Westlake and Hyde park is almost 30%, and the difference between Westlake and downtown is an eye-popping 53%. Although it is not possible at this point to conclude that neighborhood choice architecture by itself is a causative factor of the bulk of this magnitude—or even to quantify its relative contribution—we can begin to see from this case study how choice architecture, as a conceptual strategy, offers promise as a more integrated method of emissions reduction. At the same time, it is clear that further research is needed within specific neighborhoods, and using more direct comparisons of a range of specific choice architecture techniques.

10. Conclusion

In summary, we have explored the outlines of a framework conceptual strategy for achieving GHG reductions at the urban and neighborhood planning scale, com-

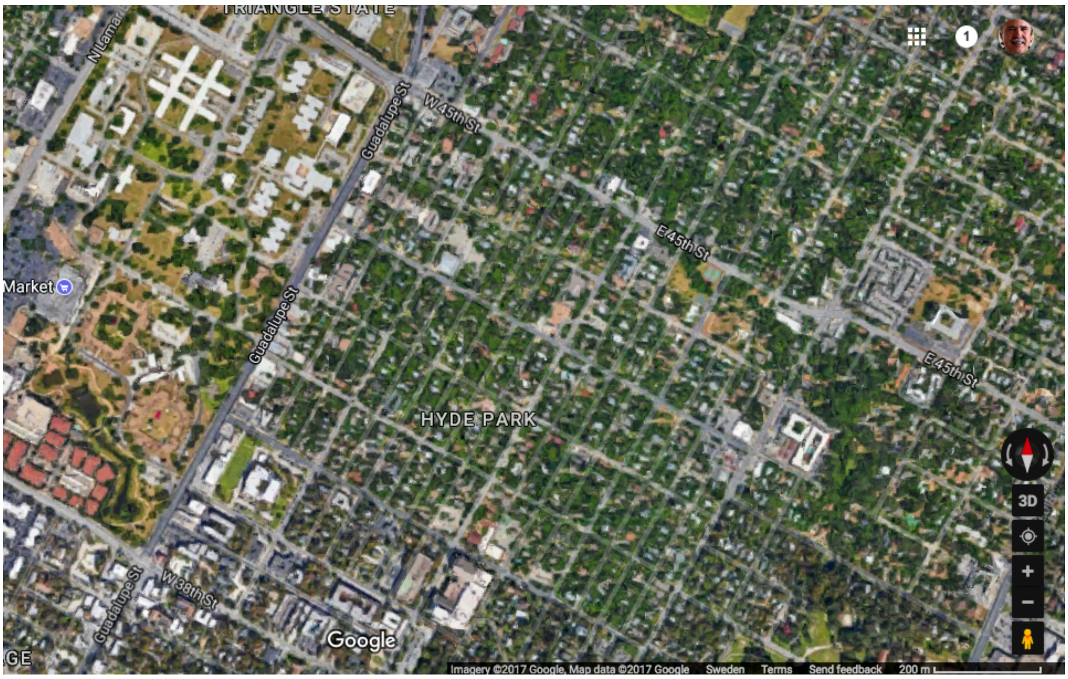

Figure 5. The central Austin, Texas, USA, neighborhood of Hyde Park (Image: Google Maps).

Figure 6. The downtown neighborhood of Austin, Texas, USA (Image: Google Maps).

Table 1. Variation of energy consumption by neighborhood in Austin, Texas, considering transportation and household energy (not including food or household goods). Source: Nichols and Kockelman (2015).

Neighborhood	Operational	Embodied	Combined	Reduction
Westlake	101.0	23.99	124.99	0.00%
Hyde Park	77.18	11.99	89.17	28.66%
Downtown	54,67	3.78	58.45	53.24%

bining the insights of behavioral economics, environmental psychology, urban planning, and public policy. This proposed strategy is aimed at overcoming the well-described limitations of current approaches in treating factors in isolation, and at achieving a more joined-up response between public policy, rational personal choice, and environmental influences in reinforcing desired and necessary day-to-day behaviors.

Although it is too early to verify the potential efficacy of the strategy, this discussion is intended to outline a potential magnitude of benefit sufficient to establish a rationale for further research aiming to provide additional cycles of development, refinement, verification, and wider application. Next steps would include further articulation of individual tools of choice architecture, together with a further strategy for their evaluation, refinement and more widespread implementation. Certainly, a number of significant hurdles remain, including the lack of neighborhood-scale data needed for verification. It will be necessary in further investigation to address these challenges with innovative solutions (for example, "big data" methods of measuring household-scale emissions as part of a research agenda).

It should be noted that this conceptual strategy may also prove effective in achieving other urban planning goals, including promotion of public health, resource conservation and the like. We focus here on GHG emissions reduction, both because it is an urgent issue in its own right, and because it poses most of the same kinds of challenges—complexity, political barriers, economic disincentives—as the other shared policy goals. In all these cases, what is needed is a more unified and effective way of connecting public policy goals to broad changes in individual and city-scale behavior, through the medium of urban form and its choice architecture.

Lastly, the evidence presented here also tells us that, whether we recognize it or not, the choice architecture of *existing* neighborhoods has no less profound impacts – particularly those that are configured around automobile-dependent transportation systems. At the same time, the lens of choice architecture makes us more aware of the impacts of our *own* choices as planners, and the hidden "choice architecture" of professional models and assumptions. Whatever the specific methodologies adopted, it will be a very good thing if we become more conscious of the often-obscure impacts of neighborhood choice architecture—and the often-obscure architecture of our own choices, about the neighborhoods of the future.

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Conflict of Interests

The author declares no conflict of interests.

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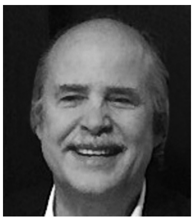

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Article

The Dilemmas of Citizen Inclusion in Urban Planning and Governance to Enable a 1.5 °C Climate Change Scenario

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Abstract
Cities around the world are facilitating ambitious and inclusive action on climate change by adopting participatory and collaborative planning approaches. However, given the major political, spatial, and scalar interdependencies involved, the extent to which these planning tools equip cities to realise 1.5 °C climate change scenarios is unclear. This article draws upon emerging knowledge in the fields of urban planning and urban climate governance to explore complementary insights into how cities can pursue ambitious and inclusive climate action to realise 1.5 °C climate change scenarios. We observe that urban planning scholarship is often under-appreciated in urban climate governance research, while conversely, promising urban planning tools and approaches can be limited by the contested realities of urban climate governance. By thematically reviewing diverse examples of urban climate action across the globe, we identify three key categories of planning dilemmas: institutional heterogeneity, scalar mismatch, and equity and justice concerns. We argue that lessons from urban planning and urban climate governance scholarship should be integrated to better understand how cities can realise 1.5 °C climate change scenarios in practice.

Keywords
climate change; collaboration; inclusion; public participation; urban climate research; urban governance; urban planning

Issue
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1. Introduction

Cities are increasingly spearheading climate change action and pursuing innovative strategies both individually and collectively through transnational networks (Hughes, Chu, & Mason, 2018). While more top-down approaches may be suitable in certain circumstances, inclusive planning and governance is generally needed to concurrently realise multiple ambitious goals, including those established under the 2015 Paris Agreement (i.e., a maximum 1.5 °C long-term temperature increase), the UN Sustainable Development Goals, and the UN Habitat New Urban Agenda. Stakeholder engagement is crucial because cities are heterogeneous, complex, and often at least quasi-democratic in nature, necessitating broad buy-in before actions can be taken (Susskind, Rumore, Hulet, & Field, 2015). As climate risks and impacts are often experienced at the local level, the inclusion of different local actors is essential to ensuring the adequate representation of diverse voices and needs (Bulkeley & Betsill, 2005). However, planning efforts are often contentious and hampered by miscommunication, misunderstanding, low civic capacity, and unresolved competition between interests and values.

Over time, urban planning scholarship and practice have developed a wide range of tools and approaches to address long-term multi-sectoral problems. For example, ideas about 'wicked problems' have been highly influential in debates around the complexity of public policy and planning processes (cf. Head & Alford, 2015; Rittel & Webber, 1973). In response, different planning approaches have facilitated the inclusion of diverse stakeholders in ways that acknowledge differing interests, facilitate engagement across institutional boundaries, and support action in the face of uncertainty. Yet to what extent are these existing tools and approaches capable of dealing with the urgent challenge of achieving 1.5 °C trajectories in cities across diverse contexts?

To reflect on this question, we must take stock of the strategies that cities have in their repertoires. However, comparing planning approaches across the globe is fraught with methodological difficulties (Robinson, 2016). These may include challenges with comparing across political economic arenas (such as between the Global North and South); drawing meaningful trends from individually situated actions, strategies, and experiments; and defining key concepts like citizen engagement, participation, and inclusion across social, cultural, and spatial contexts. While recognising these methodological constraints, we pursue a qualitative synthetic review approach that uncovers and interprets emblematic examples to understand particular phenomena (cf. Grant & Booth, 2009). Our goal is not to systematically or comprehensively review the literature; instead, we pursue a synthetic reading of recent scholarship to enable a thematic analysis of key dilemmas encountered in the context of inclusive and participatory climate change planning and governance approaches in cities.

We apply a qualitative synthetic review method to explore linkages and tensions between two vast bodies of literature—urban climate governance and urban planning—and ask: how do existing planning tools equip cities to realise 1.5 °C climate change scenarios given the major political, spatial, and scalar interdependencies involved? To address this question, we first review emblematic examples of consultative approaches, co-creative participation, and planning support tools to thematically identify and analyse key institutional, scalar, and spatial priorities associated with cities taking action towards 1.5 °C trajectories (Section 2). We then situate these within the literature on urban planning and governance and explore how they differ across cities in the Global North and South (Section 3).

We argue that scholars of climate change governance stand to benefit greatly from the accumulated insights of urban planning. Conversely, urban planning scholars and practitioners can learn from the conceptual insights offered by researchers of climate governance, especially since planning increasingly faces similar 'wicked' challenges such as fragmented institutional arrangements, political inertia, limited resources, and mismatching boundaries. Furthermore, by branching beyond the methodological criticisms levelled against single case studies and the instrumental orientation of most discussions on planning barriers and successes (see Adger, Arnell, & Tompkins, 2005), our analysis of planning dilemmas (cf. Jordan et al., 2011) offers a novel critical approach to cross-examining experiences from different urban contexts. Ultimately, we aim to articulate practical, policy-relevant decision-making entry points in support of more ambitious and inclusive planning processes to meet the urgent challenge of achieving 1.5 °C trajectories in cities.

2. Climate Change Planning: Tools and Approaches

Climate change planning has emerged as a distinct enterprise for cities and regions to formally establish and chart pathways for achieving their emissions mitigation and climate change adaptation goals. Advocacy by prominent global networks, institutional isomorphism, and shared roots in traditional planning practices have yielded some commonalities. Key players such as ICLEI–Local Governments for Sustainability, C40 Cities, and more recently, the 100 Resilient Cities network have spearheaded the dissemination of best practices. That said, cities have nonetheless exhibited entrepreneurship and experimented with different arrangements and approaches, leading to heterogeneity in responses across the globe (Anguelovski & Carmin, 2011).

Climate change planning has often, although not always, emphasised stakeholder engagement, with a focus on identifying audiences, message framings, and engagement channels (Moser, 2006). Early on, this was important because general understanding and acceptance of climate change was relatively low (Sterman, 2011). For instance, entrenched ideological differences shaped public opinion in the USA (McCright & Dunlap, 2011), while public debates in the UK pitted emissions reduction targets and economic priorities as zero-sum trade-offs (Lorenzoni, Nicholson-Cole, & Whitmarsh, 2007). This revealed a need to improve levels of awareness and relate climate change to personal experiences and knowledge (Lorenzoni & Pidgeon, 2006). Planning efforts subsequently emphasised persistent risks posed by climate change and appealed to the societal values of ecological integrity and well-being (van der Linden, Maibach, & Leiserowitz, 2015). Public engagement, in this context, aimed to facilitate behavioural, organisational, political, and other types of social change consistent with identified mitigation and adaptation goals (Moser, 2014). While these engagement objectives persist, an increasing recognition of the importance of non-state actors—including NGOs, businesses, and academics—and of the multiple agencies with a stake in climate action has precipitated the development of more complex engagement strategies that bridge institutions and foster wider consensus.

In this section, we apply the qualitative synthetic review method to highlight three broad categories of participatory and inclusive climate change planning in cities, including consultative science-policy dialogues, co-creative participatory learning systems, and the use of support tools such as joint fact-finding, scenario planning, and 'serious games'. We note that these three categories are not mutually exclusive—efforts often draw upon or extend across two, or even all three. Nonetheless, we highlight several emblematic examples and illustrate how their selective implementation can help urban actors shape priorities collectively in ways that facilitate political acceptance, buy-in, and leadership. However, we also note that questions remain around whether such approaches genuinely equip cities to realise 1.5 °C climate change scenarios.

2.1. Consultative Approaches

Climate change planning often involves enabling strategic partnerships, representative networks, alliances, expert committees, and citizen coalitions. These forums bring together public demands with government agencies, non-profit associations, and private entities (Agranoff & McGuire, 2004). Many of these partnerships are ad hoc, such as in the case of adaptation planning in the Bergpolder Zuid neighbourhood of Rotterdam in the Netherlands, where local stakeholders came together to synthesise climate projections, bridge sectoral interests, and uncover suitable actions (Groot, Bosch, Buijs, Jacobs, & Moors, 2015). Similarly, the Cambridge Climate Emergency Congress in Massachusetts, USA, brought together a cross-section of citizens and officials for a series of meetings to devise recommendations (Edelenbos, van Meerkerk, & Schenk, 2018). Ad hoc participatory processes such as these reflect particular strategic needs and are goal oriented.

Some consultative forums have also been institutionalised into decision-making. A good example of this is the New York City Panel on Climate Change (NPCC2), which was established in 2013 to assess future temperature, precipitation, sea level change, and coastal flood risks. Reports were drafted by scientists, decision-makers, and other stakeholders, working through thematic working groups that met throughout the planning process (Rosenzweig & Solecki, 2015). Not only were these deliverables further integrated into public policies, many of the relationships established through the NPCC2 have subsequently been drawn upon for other planning purposes—including in the case of New York's recent 1.5 °C Report (City of New York, 2017). Similar examples include the London Climate Change Partnership, Toronto Climate Change Network, Southeast Florida Regional Climate Change Compact, San Diego Regional Climate Collaborative, and, in the Global South, the Quito Panel on Climate Change in Ecuador and Surat Climate Change Trust in India. These consultative approaches focus on formalising cross-sector collaborations and help to improve learning and capacity development within and across city boundaries (Chu, Anguelovski, & Carmin, 2016)

A significant challenge with many consultative approaches is that they assume adequate representation and that all participants have an equal say. Another is that the links between consultation and decision-making are often tenuous. Furthermore, planning is susceptible to elite capture, including disproportionate influence from private actors who may have divergent interests from other stakeholders. As a result, the convening of consultative panels does not inherently guarantee inclusive outcomes, social empowerment, or the expression of democratic citizenship (Burton & Mustelin, 2013; Cooke & Kothari, 2001; Few, Brown, & Tompkins, 2007). For example, in many cities in the Global South that receive external capacity and finance for climate change actions, participation is often an item on a donor checklist rather than a genuine learning process that builds local capacity (Carmin, Dodman, & Chu, 2013; Ensor & Harvey, 2015).

2.2. Deliberative and Collaborative Approaches

Many constraints to climate change action are not scientific in nature but rather are political and policy challenges (Mearns, 2010; Moser & Ekstrom, 2010). These challenges are rooted in divergent interests, priorities, and values. Issue framing, risk assessment, and the evaluation of options are all value-laden and influenced by participants' interests, which makes the engagement of the diverse range of stakeholders critical (Folke, Hahn, Olsson, & Norberg, 2005; Preston, Rickards, Fünfgeld, & Keenan, 2015). In this section, we highlight the role of deliberative and collaborative processes to address uncertain risks and vulnerabilities.

There is a rich history of collaborative planning in the public sector (see, for example, Innes & Booher, 2010). Well-organised collaborative processes bring together stakeholders to collectively define the problem, evaluate information, and identify creative solutions that are fair, efficient, stable, and wise (Susskind & Cruikshank, 1987). They can bridge institutions and integrate voices from diverse communities, including those that are marginalised. Collaborative efforts can take different shapes and forms. Consensus building approaches focus on the formal convening of representatives in face-to-face meetings (Susskind, McKearnan, & Thomas-Larmer, 1999). Neutral facilitators provide process support and help parties maximise their deliberative potential. Other approaches to collaborative planning are similar in that they emphasise broad engagement, rich deliberation, and the pursuit of collaboratively rational outcomes.

Deliberative approaches focus on building understanding and ultimately achieving consensus among heterogeneous groups. Quick & Feldman (2014) emphasise the productive work that can and should occur across boundaries, highlighting their value as junctures for translating across, aligning among, and decentring differences. Theoretically, productive boundary work involves the pursuit of an inter-subjective, collaborative rationality arrived at through deliberation (Habermas, 1991; Innes & Booher, 2010). Collaborative rationality is contingent on having the diversity of interests represented; a degree of interdependence among them to motivate genuine engagement; and a deliberative space in which the parties are empowered to speak, interrogate, and access relevant information (Innes & Booher, 2010). When these conditions are met, participants may find creative ways to concurrently meet their needs and build stronger relationships.

Specific to climate change, collaborative boundary work can facilitate inter-institutional arrangements for sharing information, reassembling capacities and resources, and articulating and addressing distinct needs and actions. Deliberative approaches can play a role in designing, implementing, and monitoring climate change interventions (Chu et al., 2016). In many cities across the Global South, community-based planning is an important approach that simultaneously addresses local climate vulnerabilities, improves livelihoods, reduces social inequities, and facilitates development (Ayers & Forsyth, 2009). While communities have intimate knowledge of local environmental changes, they are often less aware of the wider causes and effects of climate change. Hence, community-based initiatives use co-learning approaches in which local and external scientific knowledge about climate change complement each other (Nay, Abkowitz, Chu, Gallagher, & Wright, 2014; Reid & Huq, 2014). For instance, in Indore, India, a city vulnerable to water scarcity during droughts, the municipality—through a 'shared learning dialogue' exercise—has proactively engaged local women's groups and slum-dwellers associations to promote awareness and envision alternative ways of water management (Chu, 2017). In Bergrivier Municipality, South Africa, community-based interventions spearheaded by unemployed urban youth brought renewed awareness of the connections between ecology, social networks, and economic opportunities (Ziervogel, Cowen, & Ziniades, 2016). Such examples show that promoting climate resilience through knowledge cogeneration can engage stakeholders in a proactive problem-solving process to enhance social capital.

In the Global North, co-learning forums are often referred to as collaboratives or collaborative processes. Multi-stakeholder planning approaches enable processes of analysing and framing the situation, collecting information, and identifying and evaluating possible solutions in the pursuit of those that are both robust and widely supported (Innes & Booher, 2010; Margerum, 2011). While tailored to local needs, collaboratives tend to include assessments of stakeholder interests, face-to-face 'active inquiry' sessions, the pursuit of consensus-based pathways, and a reliance on professional neutral parties to provide process support (Forester, 1999). There is substantial evidence demonstrating how collaborative processes can lead to better outcomes and enhance the adaptive capacities of cities when the conditions are right (Hobson & Niemeyer, 2011). For example, experiences with coastal communities in the Northeastern, USA, suggest that collaborative approaches can help groups engage in smarter and more effective deliberation around climate change (Susskind et al., 2015).

Collaborative approaches often involve community-level efforts to address differential capabilities, so grassroots discourse and deliberation play central roles in defining impacts and prioritising responses (Schlosberg, 2012). Peer-to-peer or citizen-led techniques can facilitate novel partnerships that focus on locally appropriate solutions. However, public deliberation in a decentralised political sphere can be messy and driven by dynamic and contentious streams of knowledge (Cheema & Rondinelli, 2007). The production of community knowledge can be an arduous and time-consuming process, especially when it involves significant complexity and uncertainty. As a result, some citizen-initiated processes fail to achieve their goals. For example, the Cambridge Climate Emergency Congress (see Section 2.1) struggled to balance its advocacy and governance roles, concurrently maintaining legitimacy in the eyes of public authorities, reflecting a diverse range of interests, and bringing about concrete climate change action (Edelenbos et al., 2018). These challenges notwithstanding, community-generated knowledge can ultimately increase the legitimacy of decisions, redress socioeconomic inequalities, and improve the likelihood of achieving locally appropriate outcomes (Ensor & Berger, 2009; Forsyth, 2013).

2.3. Planning Support Tools

In this section, we discuss three support tools that can be employed in climate change planning: policy experiments, joint fact-finding, and role-play simulation (RPS) exercises. These three are representative of a wider range of tools that planners might employ in practice and are illustrative of how such tools are typically embedded within deliberative, collaborative, or consultative processes. By employing these tools, policy-makers and other stakeholders are partners in the planning process, collectively analysing and interpreting knowledge and its implications for potential interventions. Such processes can address knowledge deficits by focussing on joint knowledge production, building trust in science, clarifying uncertainties, bridging values, and facilitating co-learning (Karl, Susskind, & Wallace, 2007; Nay et al., 2014).

Many cities have designed experiments in climate change planning to bridge local knowledge deficits (Bulkeley, Castán Broto, & Edwards, 2015; Chu, 2016b). Experiments involve short-term, relatively low cost initiatives to test innovative approaches before they are adopted more widely (Bulkeley & Castán Broto, 2013). Increasingly applied to low-carbon transition policies, for example, experiments promote overall decision-making effectiveness and help to generate new governance capacities. Methodologically, experiments can support evidence-based policy-making by supplying robust evaluations and opportunities to redesign existing approaches (Stoker & John, 2009). Experiments can therefore be seen as 'laboratories' of learning and sharing best practices (Karvonen & van Heur, 2014), which allow diverse actors to embed emerging needs and priorities into urban plans (Evans, 2011). In practice, experiments allow stakeholders to implement pilot projects, reframe objectives, and monitor and evaluate outcomes (Cárdenas, 2009). For example, communities in London were able to incorporate their own needs and interests into different low-carbon energy infrastructure projects (Bulkeley, Castán Broto, & Maassen, 2014). Low-income communities in Indore, India, were also able to use experiments to test implementation pathways, prioritise climate actions, and evaluate overall project benefits (Chu, 2016b). Although some have challenged their external validity and replicability, experiments have been shown to be a good approach for encouraging intensive dialogue and small-scale innovation (Stoker & John, 2009).

RPS allow for a different type of experimentation by providing safe and inexpensive sandbox-like simulated environments for exploring climate change scenarios and potential responses (Schenk & Susskind, 2014). RPS exercises are a form of 'serious game', within which stakeholders are asked to take on particular roles and solve fictional challenges within clear parameters (Rumore, Schenk, & Susskind, 2016). Such exercises played a prominent role in the New England Climate Adaptation Project, which involved four coastal communities in the Northeastern USA. By providing a lens through which they could assess their own situations, RPS exercises helped communities identify future risks and build support for collaborative efforts to manage them (Susskind et al., 2015). In another example, the Institutionalizing Uncertainty project engaged stakeholders in Singapore, Rotterdam, and Boston to consider how they might integrate uncertain risks into their infrastructure planning (Schenk, 2018). Serious games come in a wide range of styles and levels of complexity and are being used in a wide variety of situations around the world. For example, the Red Cross/Red Crescent Climate Centre is using games to convey complex climate science in simple and powerful formats to audiences ranging from delegates at international climate conventions to farmers in rural villages (Mendler de Suarez et al., 2012).

Joint fact-finding is another process used to engage stakeholders, with the aim of arriving at shared sets of acceptable data for planning purposes. Joint fact-finding is used in the context of climate change to help stakeholders make sense of the risks (and opportunities) posed, as well as to seek consensus around how to respond (Ehrmann & Stinson, 1999; Schenk & Matsuura, 2017). In Boston, for example, the development of the city's Climate Action Plan involved a series of facilitated workshops that employed joint fact-finding to help stakeholders come to a shared understanding of the sources of greenhouse gas emissions, as well as to devise shared goals and evaluate options for meeting those goals (Raab, 2017). When groups recognise the dynamic and persistently uncertain nature of the 'facts' in complex situations, joint fact-finding can help to devise 'facts for now' and 'facts for use' (Schenk, 2017).

To summarise, our synthetic review suggests that the emergence of various methodologies to promote dialogue and knowledge co-production between policy-makers and citizens can transform climate change planning in cities. Ultimately, however, the degree to which experiments, serious games, and other tools and approaches like joint fact-finding will be successful—especially in the context of enabling a 1.5 °C climate change scenario—often depends on the institutions and actors involved, contents of dominant discourses, presence of rules, and availability of resources. As a result, such tools require careful design and execution to harness their potential.

3. Dilemmas in Inclusive Climate Planning

Significant action is required to enable 1.5 °C climate change scenarios, and many have noted the importance of truly transformative approaches to decarbonisation that involve interconnected technical, economic, social, and political changes (Patterson et al., 2018; Pelling, O'Brien, & Matyas, 2015). Though cities can play a unique role in facilitating deep societal change (Bernstein & Hoffmann, 2018), climate transformations will place unprecedented demands on them. In light of this, urban planning scholarship and practice can offer insights into how planners and policy-makers can engage with local constituents to facilitate behaviour change, alter local economic production systems, engender local awareness, and offer alternative visions of development.

We previously illustrated different inclusive planning approaches that have emerged to enable urban climate change action. The synthetic review highlighted efforts to explore interests and account for disparate priorities, seek consensus, understand complex data, and facilitate strategic outcomes. A series of priorities for advancing inclusive approaches are summarised in Table 1. Despite the advances made, our thematic analysis in this section illustrates that the ambitious potential of such approaches are often constrained by factors such as fragmented governance arrangements, political inertia, limited resources, and mismatching jurisdictional boundaries. Drawing on terminology used by Jordan et al. (2011), these issues can be seen as reflecting various key dilemmas–institutional, scalar, and spatial—that cities face while pursuing climate actions. In this light, questions arise about the extent to which existing inclusive planning approaches can genuinely equip cities to realise 1.5 °C climate change scenarios.

Table 1. Key dilemmas faced by cities in advancing ambitious and inclusive climate action.

Category	Procedural aspects	Structural aspects
Institutional	• Gaining issue recognition from powerful local departments. • Bringing stakeholders with diverse values and interests. • Facilitating decentralised decision-making and the separation of duties. • Addressing capacity and resource constraints.	• Overcoming the rhetoric of 'environment versus development'. • Confronting powerful investment and speculative behaviours in development. • Bridging elite political interests, entrenched ideological, and value differences. • Breaking the 'siloed' nature of urban planning.
Spatial/Scalar	• Determining how responsibilities are divided across different levels of government. • Addressing spatial and political fragmentation within and across cities. • Planning across ecosystem, landscape, and cross-jurisdictional scales.	• Addressing the multi-scalar and multi-level nature of climate change priorities. • Overcoming conflicting social and political interests across jurisdictions. • Designing adequate plans when public sector functions are constantly eroded.
Equity/Justice	• Facilitating adequate representation and inclusion of diverse stakeholders. • Ensuring that planning outcomes are equitably distributed. • Recognising the needs and interests of marginalised and vulnerable communities.	• Confronting elite or entrenched political and economic interests. • Reframing climate change action as a collective and socio-ecological priority. • More equitably redistributing the procedures, responsibilities, and beneficiaries of planning.

3.1. Institutional Dilemmas

Cities experience substantial uncertainty that affects their ability to identify the most appropriate mitigation and adaptation actions. External uncertainties are compounded by entrenched urban political dynamics, funding pressures, and economic interests that constrain the structure of planning processes. Institutional heterogeneities and disparities—which manifest as diverging sectoral interests, uneven governance capacities, and conflicting policy mandates—shape the ad hoc and context-dependent nature of urban climate change planning.

Scholars have long noted that discussions of the reflexive turn in urban planning must include analyses of power, the state, and political economy (Healey, 1996). These power differentials are particularly visible when science is driving public policy debates because science itself is so often contested and value-laden (Layzer, 2011). Although the literature suggests that collaborative processes can help address uncertainty, many public discourses have been subsumed by powerful actors that hold their own vested interests. For example, a study of several Australian cities highlighted the disproportionate role private property developers played in driving local climate change agendas (Taylor, Wallington, Heyenga, & Harman, 2014). Although cities like Durban, South Africa, and Toronto, Canada, are considered early leaders of climate action, they also face push-back from property speculators, unsupportive legal environments, and occasional climate denialism among their local leadership (Carmin et al., 2013). Finally, in the USA, cities in Florida, North Carolina, and elsewhere are discouraged from using the language of climate change due to ideologically driven state mandates (Shi, Chu, & Debats, 2015). Ambiguities around how to frame climate change against powerful interests have constrained the degree to which existing plans can engage and be straightforward with the broader public.

In some cities, priorities across municipal agencies are vastly divergent and often not conducive to cooperation on large multi-scalar issues like climate change. In Durban, for example, climate change priorities are spearheaded by the Environmental Planning and Climate Protection Department (EPCPD), which began seriously thinking about the issue in the early 2000s (Roberts, 2010). However, many projects have been constrained by internal conflicts, particularly when relationships were tenuous between a relatively minor department such as the EPCPD and more prominent energy, infrastructure, and economic development departments (Chu, Anguelovski, & Roberts, 2017). These challenges reflect the prioritisation of economic development over climate protection.

A final institutional dilemma relates to the human capacity deficiencies found in many cities. Uncertain climate projections and scenarios can impede the coherence of climate change messages aimed at redirecting planning priorities (Patt & Dessai, 2005; Whitmarsh, 2011). Furthermore, planning departments often face deficiencies in financing, technical skills, staffing capacity, and legal provisions, which constrain their abilities to work beyond day-to-day tasks (Carmin et al., 2013). In some cases, cities have rejected new sources of data and finance because of the anticipated additional paperwork, reporting burdens, or expertise. The main challenge, therefore, is often not the availability of climate science, but internal limitations, scepticism, and mismatches in capacity, funding, and institutional responsibility.

3.2. Spatial and Scalar Dilemmas

Cities typically oversee infrastructure and public services, are directly accountable to local electorates, and are first-responders during hazard events. As a result, the spatial concentration of people, production, and consumption behaviours presents many opportunities for climate action (Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). For example, the literature on low-carbon transitions shows that the concentration of population and infrastructure in cities can foster innovative approaches to renewable energy consumption and other grassroots mitigation technologies (Bulkeley, Castán Broto, Hodson, & Marvin, 2011). Even so, such innovations are rarely straightforward due to mismatches between jurisdictional and ecological boundaries (Bai, McAllister, Beaty, & Taylor, 2010).

Most climate actions require collaboration across jurisdictional boundaries; however, many cities are fragmented across space, with political boundaries dividing what are otherwise contiguous metropolitan regions (Bollinger et al., 2013). Governance theories note that coordinating climate change actions across diverse landscapes and populations is challenging due to geographically specific risks and impacts, which are determined by particular sociocultural contexts, political or legal jurisdictions, and ecological conditions (Adger, Barnett, Brown, Marshall, & O'Brien, 2013). For example, changing mobility behaviours by incentivising public transportation usage or transit-oriented development is critical for reducing emissions, but such actions rely on coordinating across transportation networks that transcend political boundaries (Bollinger et al., 2013). In Boston, USA, a state agency is responsible for the public transportation system while different local agencies are responsible for the road network, which weaves through more than 100 separate municipalities. Moreover, the way that communities are spread across space—which involves issues of zoning and land use planning—affects travel demands, vehicle dependency, and emission levels (Dulal, Brodnig, & Onoriose, 2011). Therefore, any planning process designed to change transportation behaviours must address larger patterns of mobility and settlement across city-regions, together with individual behaviours and consumption preferences (Chapman, 2007).

The transboundary nature of infrastructure networks also influences how cities coordinate adaptation and risk management actions (Davoudi, Crawford, & Mehmood, 2009). For example, Surat, India, is vulnerable to flooding during monsoon seasons (Chu, 2016a). In the early 2010s, Surat built several large-scale infrastructures to reduce flood risks; however, this infrastructure is functional only if coordinated with the upstream dams managing discharge from the larger regional watershed (Bhat, Karanth, Dashora, & Rajasekar, 2013). In another example, Medellín, Colombia, is building a 46-mile-long green belt to manage growth while also protecting urban forests, providing access to green spaces, and reducing urban heat island effects (Anguelovski et al., 2016). Such a large-scale 'green' infrastructure project requires coordination between regional transport authorities and the different municipalities in charge of housing and public services (Chu et al., 2017). These examples highlight how cities cannot tackle climate change as standalone stressors in specific locations (Hallegatte, 2009), but rather must do so as portfolios of systemic risks on infrastructure networks and land use patterns that stretch across boundaries.

In terms of the multi-scalar nature of climate change, scholars note that planning and management boundaries are crossed horizontally—i.e., across political boundaries—and vertically among hierarchies of government (Hooghe & Marks, 2003). For example, climate action around water issues in Dutch cities is largely the responsibility of regional water boards, but municipalities are responsible for interrelated land use planning decisions, and provincial and national agencies for higher-level water system planning and decision-making (Uittenbroek, Janssen-Jansen, & Runhaar, 2013). In another case, energy production and consumption policies in cities in the UK and Germany are contingent upon directives from national and European Union authorities, while local authorities often manage incentive programmes (Kern & Bulkeley, 2009). At a more local level, the Tokyo Metropolitan Government in Japan must coordinate climate actions across 23 wards that are functionally separate from each other (Hijioka et al., 2016).

Control over many climate change responsibilities is devolved to non-state, network, or extra-local actors. For many cities in the Global South, transnational networks provide the capacities and resources necessary for climate action. Examples include C40, ICLEI, and 100 Resilient Cities, all of which have their own agendas and interests that shape their engagements with cities (Andonova, Betsill, & Bulkeley, 2009). Private and informal sectors also play a variety of roles. For example, water and electricity systems are often privately owned or managed, and yet they are both integral to communities and intertwined with other infrastructure systems. In the case of Mumbai, India, and Lagos, Nigeria, different informal or private neighbourhood tankers help supply clean water to rapidly urbanising areas that are yet to be served by formal municipal pipelines (Gandy, 2006; Graham, Desai, & McFarlane, 2013).

The multiple scales of governance add layers of actors, networks, and institutions to any urban planning process. The interconnectedness of networks across space is compounded by the fragmentation of governance scales and jurisdictions, resulting in numerous agencies and authorities with distinct yet highly interconnected roles and responsibilities (Hughes et al., 2018). In order to balance the scope of climate change actions, public authorities must share decision-making arenas with equally powerful and informed actors.

3.3. Equity and Justice Dilemmas

As we noted in Section 2.2, deliberative planning processes can enable broad knowledge sharing, leading to collaboratively rational actions (Habermas, 1991; Healey, 1996). However, the combination of high levels of public indecisiveness, apathy, uncertainty over sources of scientific data, and the intransigence of many urban interests can also result in significant disagreement. Intractability and the absence of many voices—together with opportunities for elite capture—can exacerbate inequity and injustice. Here we examine how cities must contend with entrenched power differentials that affect the ambition and inclusiveness of planning outcomes.

Procedural inclusiveness requires the explicit engagement of traditionally marginalised communities in the policy process. For example, in the late 2000s, Quito, Ecuador, established a citizen's climate change panel with representation from youth groups, indigenous communities, and local women's associations, which helped to prioritise actions that balanced climate and development needs (Anguelovski, Chu, & Carmin, 2014). Similarly, cities that participated in the Rockefeller Foundation's Asian Cities Climate Change Resilience Network (ACCCRN) embarked on a series of 'shared learning dialogue' workshops that brought together diverse stakeholders to design appropriate actions (Kernaghan & da Silva, 2014). Such programmes have been prevalent in the USA as well, where New York City (Rosenzweig & Solecki, 2010), Chicago (Coffee, Parzen, Wagstaff, & Lewis, 2010), and San Francisco (Ekstrom & Moser, 2014) have all advocated for broadly representative approaches. The objectives of these programmes were to improve citizen awareness, develop civic capacity and knowledge, and legitimise prospective planning decisions.

Although inclusive processes are critical, they must be accompanied by a recognition that facilitating equitable outcomes is equally important (Meerow & Newell, 2016; Shi et al., 2016). Some scholarship suggests that targeted political mobilisation from elites and advocacy groups can be more influential than broad participatory processes (Brulle, Carmichael, & Jenkins, 2012). The issue of who has power over the process is critical because it affects how priorities enter the public consciousness. For example, though scientific and technical experts from abroad helped to design inclusive forms of climate adaptation in Santiago, Chile, the planning process played out against complex and intersecting urban political interests (Krellenberg & Katrin, 2014). In Jakarta, Indonesia, large engineering firms based outside the country guided much of the decision-making around climate infrastructure (Anguelovski et al., 2016). Both these examples raise questions about the interplay between external and local interests, the extent to which local priorities and marginalised groups are addressed, and the relationship between local climate and development agendas.

The decentralisation of decision-making in cities has led to a proliferation of arenas for participation and deliberation. However, this political restructuring has uncovered more fundamental questions about who has control over climate change planning processes and outcomes. Here we highlighted corresponding procedural and distributive equity priorities, which, when combined with the other institutional and scalar dilemmas, point to complex webs of values, ideologies, and practices that characterise climate change action in cities. As Table 1 summarised, these intersecting priorities often lead to contentious questions and even uncomfortable trade-offs. A recognition of these dilemmas therefore contributes to uncovering specific decision-making parameters around evaluating and prioritising capacities and resources to realise 1.5 °C climate change scenarios in practice.

4. Conclusion

In this article, we synthetically reviewed literature on participatory planning and urban governance in the context of climate change, identifying key institutional, scalar, and spatial dilemmas associated with cities taking action towards 1.5 °C scenarios. A key finding is that the ability to plan for climate change in cities is contingent on being able to mobilise across spaces and scales. Inclusive tools can enable collaborative processes that acknowledge the interests of different stakeholders, facilitate engagement across boundaries, and address uncertainty. However, these tools must be structured to reach across space and scale. Questions remain around whether existing approaches to inclusive planning can actually facilitate the sorts of ambitious actions required to meet the 1.5 °C target. Planning processes often face dilemmas between procedural orientations—i.e., embedding climate change into existing practices—versus more structural orientations to transforming underlying urban political and economic functions (including addressing existing social and environmental injustices in cities). Overall, there remains significant opportunity in interrogating the overlap between planning and governance scholarship.

The findings highlight entry points for evaluating experiences in pursuing 1.5 °C scenarios across different urban contexts, as well as generating comparative insights despite the locally specific nature of many climate change plans and policies. The dilemmas identified in Table 1 offer insights on competing decision criteria and trade-offs associated with pursuing ambitious and inclusive climate action. An awareness of these dilemmas can thus enrich and inform ways of articulating, framing, conducting, and evaluating practical approaches amidst diverse citizen voices and political priorities. This approach acknowledges but also moves beyond familiar catalogues of internal limitations, scepticism, and mismatches in capacity, funding, and policy responsibility that prevent cities from pursuing more ambitious and inclusive actions. In particular, we contribute to reflections on: (1) how to cultivate urban institutions that can enable adaptable and collaborative forms of governance that are also aligned to global climate change imperatives; (2) how to navigate spatial and scalar dilemmas through a critical awareness of the complex networks of actors and institutions; and (3) how to deal with equity and justice issues, such as through multidimensional mechanisms that include intersectional class, gender, ethnic, racial, and age-related priorities to evaluate the processes and outcomes of climate change planning.

Overall, we argue that scholars of climate change governance stand to benefit from the accumulated insights of urban planning, and conversely, urban planners and practitioners stand to benefit from the insights offered by climate governance. Drawing together insights from both perspectives is crucial for enhancing the likelihood of realising ambitious and inclusive climate action to enable 1.5 °C climate change scenarios within complex urban planning and governance settings.

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Conflict of Interests

The authors declare no conflict of interests.

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