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CLIMATE EMERGENCY | URBAN OPPORTUNITY

HOW NATIONAL GOVERNMENTS CAN SECURE ECONOMIC PROSPERITY AND AVERT CLIMATE CATASTROPHE BY TRANSFORMING CITIES

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Annex 1: The technically feasible mitigation potential in cities

Analysis conducted by Derik Broekhoff and Taylor Binnington (Stockholm Environment Institute)

Scope of analysis

This analysis assesses the climate mitigation potential from nearly 700 specific urban areas with a 2015 population of at least 750,000. It also assesses the climate mitigation potential of several thousand other urban areas with a 2015 population of less than 750,000, which we aggregated together within each region. In this analysis, all mitigation actions were assumed to start in 2020.

This analysis updates and expands upon a study conducted by the Stockholm Environment Institute (SEI) in 2014.[1] The 2014 study estimated the global greenhouse gas (GHG) abatement potential from actions specifically targeting urban energy use and emissions, in the buildings, transport and waste sectors. The new analysis presented in this report uses more recent data on urban populations and urban energy consumption. The reference or baseline scenario in the updated study recognises new policy commitments under the Paris Agreement, as well as new technological learning and new economic assumptions, and therefore has lower emissions than the 2014 analysis.

Moreover, the updated analysis expands the scope of the original study in three ways:

1. It expressly focuses on mitigation outcomes in line with a "below 2°C" pathway, rather than the 2°C pathway considered in the prior study. [At the time that this report was published, the IEA had not published a 1.5°C pathway.]
2. It includes estimates of GHG reductions associated with reduced material use in urban infrastructure, including urban buildings, road and rail networks, and vehicles. These reductions could result from many of the same abatement measures that were included in SEI's prior analysis (e.g. building codes and compact urban development) but were not evaluated last time.
3. It includes potential GHG reductions that would be difficult for local governments to deliver alone but could be achieved by or in partnership with higher levels of government. Relevant areas for abatement include decarbonisation of electricity supplied to urban areas, shifts to low-carbon fuels, and waste prevention.

Because of this increased scope, the feasible abatement potential identified in this report constitutes a larger percentage of the total reductions needed for the world to stay "well below" 2°C of warming than the 2014 analysis.

Data and approach

We estimated global urban GHG abatement potential using a bottom-up assessment of mitigation options, a widely used approach in energy and climate modelling.[2] Our approach quantified the emission reductions that can be achieved in urban areas across four sectors – buildings, transport, waste, and material use in urban infrastructures – by comparing emissions at five-year intervals under two sets of scenario assumptions running from 2015 to 2050.

Our reference scenario assumes no further climate action in cities is projected beyond current trends and commitments. It was based on energy consumption and emissions projected in the 2017 *Energy Technology Perspectives* (ETP2017) from the International Energy Agency (IEA),[3] specifically the Reference Technology Scenario (RTS). This provides data for the major world regions listed in Table A.1. The reference scenario takes into account recent national policies and commitments – including commitments reflected in countries' Nationally Determined Contributions (NDCs) under the Paris Agreement.

We downscaled the IEA's forecasts to urban areas only, making adjustments to energy consumption in each region and sector based on urban-focused research by the Global Buildings Performance Network,[4] the Institute for Transportation and Development Policy[5] and others.[6] We adopted urban population data from the United Nations' *World Urbanization Prospects*,[7] which follows the latest definition used in each country. These definitions are generally established by national statistical offices and used to carry out the national census. When the definition used in the latest census was not the same as in previous censuses, the data were adjusted whenever possible so as to maintain consistency. All details are available online.

Table A.1. Regions and countries modelled in ETP2017

Association of Southeast Asian Nations (ASEAN)
Brazil
China
European Union
India
Mexico
Russia
South Africa
United States
Other OECD
Other non-OECD

Source: IEA, 2017.[8]

Following the reference scenario, we developed a mitigation scenario by applying a set of aggressive technology and practice assumptions to curb urban energy use and emissions. Where possible, we used the IEA's Beyond 2°C Scenario (B2DS) as a guide, so that the urban mitigation scenario is consistent with a future that limits global temperature change to well below 2°C. The IEA has not yet modelled a 1.5°C scenario.

Our analysis was founded on a simple activity analysis, where GHG emissions were calculated as the product of three key drivers: a measurement of each sector's requirements for energy services (the activity of a sector), the fuel consumption per unit of activity (the energy intensity), and the GHG emissions per unit of fuel consumption (the emissions intensity of energy). In each sector, we assumed that activity levels depend linearly on urban population, so that population growth and urbanisation are important drivers of change in emissions for all sectors. In Tables A.2, A.3, A.4 and A.5, we present the sector-specific data and assumptions used for each of these three drivers, for both reference and mitigation scenarios.

Table A.2. Data and assumptions for the buildings sector

Reference case activity levels	Reference case energy intensity	Reference case GHG-intensity of energy	Mitigation actions
Square metres of residential and, separately, commercial floor space per capita were derived from United Nations' *World Urbanization Prospects*[9] and IEA estimates.[10] We assumed that residential floor space per capita is the same in both urban and rural areas, while for commercial floor space, we followed the assessment of the Global Buildings Performance Network that 90% of commercial floor space is in urban areas.[11]	In OECD countries, we assumed that the energy intensities of both residential and commercial buildings in urban areas follow national averages, where energy and technology access is similar in rural and urban areas. In developing countries, we adjusted IEA's national averages based on data concerning the rural/urban splits of electricity access and traditional biomass use.[12] For all urban areas, the energy intensity of heating and cooling demand was adjusted linearly from population-weighted national averages[13] to city-specific heating-degree days and cooling-degree days, respectively, as reported between 2011 and 2014 on degreedays.net.	Emission factors for fossil fuels, in CO_2-equivalent terms, were derived from ETP2017.[14] Emissions associated with the production of electricity in each region were calculated per kWh of consumption, from the RTS of the same source. We further adopted IEA's assumption that biomass, waste and commercial heat are assigned zero GHG emissions.	New building standards set at "passive house" levels; deep energy retrofits of building shells on 1.4% of 2015 building stock per year in early years, 3% in later years.[15] Heat pumps installed in all new and retrofitted buildings where average heating degree days are between 2,000 and 5,000/year; half of new and retrofitted buildings in nearby regions. Aggressive implementation of efficient lighting and appliances as in IEA's B2DS.[16] GHG intensities of energy follow IEA's B2DS, including for electricity. Increased adoption of rooftop and building-integrated solar photovoltaics (PV).[17]

Table A.3. Data and assumptions for the transport sector

Reference case activity levels	Reference case energy intensity	Reference case GHG-intensity of energy	Mitigation actions
Reference case urban motorised travel activity (passenger-km (pkm) and tonne-km (tkm)) was derived from the RTS of ETP2017,[18] with the urban component identified using data in IEA (2013) and (2016).[19] Reference case travel intensity for each mode (pkm/tkm per capita) was calculated by dividing urban travel demand estimates by urban population estimates.	Vehicle energy intensities (MJ/pkm or tkm) for all modes follow the same regional trends found in the RTS of ETP2017.[20]	Fuels used to power passenger and freight transport are predominantly gasoline and diesel (or GHG-emitting biofuels) for the duration of reference case. Fuel mixes and share of electric vehicles estimated from the RTS of ETP2017.[21] GHG intensities of fuels and electricity derived from the RTS of ETP2017. For biofuels, we assumed a gradual transition to advanced carbon-neutral fuel by 2050. Fossil fuel emission factors were based on well-to-wheel lifecycle estimates derived from multiple studies.[22]	Motorised travel intensity (pkm and tkm/capita) substantially reduced through logistics improvements for freight,[23] a combination of national and local policies driving reduced passenger and freight travel demand[24] and rapid expansion of cycling and public transit.[25] Improvements in fuel economy and high penetration of electric vehicles (EVs), following IEA B2DS. Decarbonisation of electricity (following B2DS), leading to further abatement from EV adoption. Faster transition to carbon-neutral biofuels (by 2040).

Table A.4. Data and assumptions for the waste sector

Reference case activity levels	**Reference case energy and GHG intensities**	**Mitigation actions**
Urban waste generation over time followed trends projected through 2050.[26] Quantities of waste generation, in tonnes per capita, were based on IPCC Waste Model defaults for different world regions.[27]	Energy and GHG emissions were based on fraction of waste collected, were assumed constant, and were managed via recycling (including composting) or landfilling. Recycling (and composting) rates assumed to converge everywhere to current best practice[28] by 2050. For landfilling, the share of methane captured – through an increasing number of methane capture facilities and increased capture efficiency at these facilities – grows faster in developing countries (3.1% per year) than in OECD countries (1.0% per year). The proportion of landfills that use methane to generate electricity remains constant. Stored carbon in landfills increases with higher waste generation and decreases with paper recycling and food composting. Other factors affecting carbon storage were assumed constant, including collection rates, degradable organic content (DOC) and the fraction of DOC that decomposes.[29] For recycling, emissions avoided represent a share of the emission intensities (tCO2e/t product) of production for paper, steel, aluminium and plastics, derived from the RTS of the ETP2017.[30] As new product efficiencies improve over time, avoided emissions from new production decrease.	Waste prevention efforts reduce waste generation per capita by 15% from 2020 levels by 2030, and 30% by 2050, in all regions. Waste collection rates converge to 90% in all regions by 2050. Methane capture efficiency – at landfills that capture methane – improves significantly. The number of landfills that capture methane also increases rapidly. Electricity generation from landfill gas increases in all regions, with a 3% annual growth rate in methane capture facilities that also generate grid electricity. Recycling rates increase to 80% of recyclables from collected waste in all regions by 2050. Avoided production energy and GHG intensities follow the same trends as in the reference case.

Table A.5. Data and assumptions for material use

Reference case activity levels	Reference case energy intensity	Reference case GHG-intensity of energy	Mitigation actions
Production levels for cement, steel and aluminium used in buildings, vehicles, and road and rail construction were taken from the RTS in Pales et al. (2019).[31] Total production levels for buildings, vehicles, and road and rail construction were allocated to urban areas based on population (applying the ratio of urban to total population in each ETP2017 region).	Energy intensities for the production of steel, cement and aluminium were derived from global energy use per tonne of production found in the RTS of ETP2017.[32]	GHG emissions intensities of coal, oil, natural gas and electricity used in the production of steel, cement and aluminium were all derived from the ETP2017,[33] with adders applied to account for upstream emissions from fossil fuel extraction. Process emission rates for cement and aluminium were calculated from ETP2017 emission data, after subtracting emissions associated with fossil fuel use.	Improved building design and material use efficiency, combined with compact, transit-oriented development yield significant reductions in the need for materials production to supply urban infrastructure. Steel used in buildings derived from the materials efficiency (MEF) scenario in Pales et al. (2019);[34] cement used in buildings and roads, steel used in vehicles and rail infrastructure, and aluminium used in vehicles all derived from the Pales et al. (2019) Clean Technology Scenario (CTS).[35] National-level policies drive reductions in the energy intensity of production for steel, cement and aluminium production, following IEA's B2DS. Reductions in process emissions derived from the B2DS, using the same methods as applied in the reference case.[36]

Limitations

Projections for the reference and mitigation scenarios in this analysis are anchored in the IEA's RTS and B2DS scenarios. The reference scenario represents one possible future; abatement potentials against this reference should be seen as indicative. Likewise, assumptions derived from the B2DS, such as electric vehicle penetration rates and energy intensities of end uses, represent one possible forecast. As indicated above, we apply results from a range of different studies to calibrate assumptions for our own mitigation scenario. Though we checked to ensure broad consistency with other low energy-demand scenario analyses,[37] our results are not the product of a single, consistent techno-economic forecasting model. Finally, in various instances, we had to make assumptions about the data underlying IEA projections, including fuel mixes for different end uses. Uncertainties also arise from the assumptions used to assign activity levels and associated energy consumption to urban areas.

Annex 2: Urban sprawl and emissions: case studies of Pittsburgh and Stockholm

Analysis conducted by Leah Lazer (Coalition for Urban Transitions)

Scope of analysis

This analysis is intended to provide a visual demonstration of how space per person in a city is not necessarily correlated with quality of life. To do this, it shows a dense, liveable city alongside a sprawling city that has room for improvement. It was conceived to support the report's description on the benefits of compact cities, to help mitigate public misperceptions of and aversion to dense city living. It could be seen as a complement or update to Alain Bertaud and Harry Richardson's comparison of Atlanta and Barcelona.[38]

Data

The spatial footprint for each city reflects its functional urban area, not its administrative boundaries. This more accurately encompasses the city's actual population and degree of sprawl. Although the metropolitan area might give the most complete picture of the full functional size of the city, density differences don't show up as strongly at that scale, as peripheral land is typically low in density across different contexts. The definitions for the urban boundaries of each case study city are below.

The urban boundary used for Pittsburgh was its "urban area" as defined in the 2010 United States Census. Data sources were:

- Pittsburgh map shapefile: U.S. Census Bureau, 2010. TIGER/Line® Shapefiles: Urban Areas[39]
- Pittsburgh area and population: U.S. Census, Urban Areas, 2010[40]
- Pittsburgh gross value added (GVA) (for city administrative boundary): Oxford Economics, 2012 (constant 2012 prices)[41]
- Pittsburgh emissions (for city administrative boundary): derived from Oxford Economics, 2012, as outlined in Floater et al., 2014[42]

The urban boundary used for Stockholm was its "urban area" as defined by Statistiska centralbyrån (the Swedish national statistics agency) in 2015. Data sources were:

- Stockholm map shapefile, population and area: Statistiska centralbyrån, Open Geodata for Localities, 2015[43]
- Stockholm GVA (for metropolitan area): Oxford Economics, 2015 (constant 2012 prices)[44]
- Stockholm emissions (for metropolitan area): derived from Oxford Economics, 2015, as outlined in Floater et al., 2014[45]

Approach

City selection criteria

- Cities with similar populations AND very different areas of urban extent; and
- Definition of similar population: within ~250,000 for smaller cities with populations under 2 million, within ~400,000 for cities with populations over 2 million; and
- Aimed for pairs where both cities had international name recognition, and the denser one was known for being dynamic, liveable, prosperous, and/or sustainable, while the less dense one had a less favourable reputation. We recognise that these criteria are subjective.

Year selection criteria

All shapefiles used were the most recent available data for that geography. For that reason, the years for population, urban extent, city GVA and city emissions were selected to match the year of that city's shapefile, or the closest year to that shapefile for which data were available.

To calculate density (residents per square mile), we divided the population by the urban extent, using figures that referred to the same boundaries, to ensure like-for-like comparison.

All maps were generated from shapefiles that were publicly available from the sources listed in this methodology. All mapping was performed in QGIS. No changes were made to the shapefiles besides selecting the Coordinate References System (CRS). Both maps are shown in the World Mollweide CRS (ESPG 54009). This is an equal-area, pseudo-cylindrical map projection, usually used for global maps or night sky maps. The Mollweide projection trades accuracy of angle and shape for accuracy of proportions in area. This means it is best suited to accurately represent the relative areas of different places, although the shapes may appear distorted. This projection was selected because this analysis focuses on comparing total areas, whereas the shapes and angles of city boundaries are less relevant. The scaling on the map pair was selected to allow the larger city to fill the frame allotted.

Additional data

To calculate GVA per capita and emissions per capita, we used the Oxford Economics dataset.[46] That dataset referred to the *city administrative boundary* for Pittsburgh and the *metropolitan area* for Stockholm. However, the shapefile, population and area used in the rest of the analysis referred to the *urban area* of both Pittsburgh and Stockholm. This created a dilemma for calculating GVA per capita and emissions per capita, since it would not be accurate to divide the GVA or emissions of the *administrative boundary* or *metropolitan area,* by the population of the *urban area.* Therefore, we used the population from the Oxford Economics dataset. This enabled us to divide the Pittsburgh *administrative boundary* GVA and emissions by the corresponding *administrative boundary* population, and similarly the Stockholm *metropolitan area* GVA and emissions by the corresponding *metropolitan area* population. We determined that this would give a representative approximation of the emissions per capita and GVA per capita of the city's urban area or metropolitan area. However, if we had been able to use urban area or metropolitan area for all parts of the analysis, it is possible that the emissions per capita might be higher, due to larger homes, longer driving distances, and factories or industry located in peripheral areas. Although the city-level data is technically GVA, the results and graphic refer to it as gross domestic product (GDP), to make the results intelligible to a wider audience.

Limitations

The data for each pair of cities were from the closest possible year, but it was not possible to use the same year in all cases. Since the shapefiles were the most difficult data to locate, all shapefiles are the most recent available data for that geography, then the year for population, urban extent, city GVA and city emissions were selected to match the year of that city's shapefile, or the closest year to that shapefile for which data were available.

The boundaries used to calculate GVA per capita and emissions per capita are based on administrative boundary (for Pittsburgh) and metropolitan area (for Stockholm), not urban area as used for the map, population and area, which might somewhat skew the results.

Annex 3: Proportion of urban residents and urban land less than 10 metres above sea level

Analysis conducted by Deborah Balk (CUNY Institute for Demographic Research, City University of New York), Gordon McGranahan (Institute of Development Studies), Kytt MacManus (Center for International Earth Science Information Network, Columbia University) and Hasim Engin (CUNY Institute for Demographic Research, City University of New York)

Scope of analysis

The overall goal of this analysis was to update estimates of the population living at risk of coastal hazards, using the basic methodology established in McGranahan et al. (2007).[47] Expanding upon that research, here we also aim to make some additional distinctions in the understanding of differential risk and degrees of urbanisation. Therefore, we distinguish between populations at high risk (living below 5 metres contiguous to coast) and those at medium risk (living at 5–10 metres contiguous to coast); and we distinguish between dwellers of cities and other types of urban and quasi-urban areas (such as peri-urban outlying areas and smaller towns). We also describe changes in the past 25 years, from 1990 to 2015.

Data

In the 10 years since the 2007 study, many new renderings of urban areas have become available. We have selected data from the Global Human Settlement Layer (GHSL) project suite produced by the Joint Research Center (JRC) of the European Commission.[48] At its core are more than 40,000 Landsat scenes, which have been processed in a consistent manner across countries and over time using advanced machine learning algorithms. The data, GHS-BUILT described in Table A.6, are binary, indicating either the presence or absence of a built structure in each 30-metre grid cell, and aggregated to 250 metres to represent the fraction of built-up land in each pixel. Data are available for four time periods (1975, 1990, 2000 and 2015), of which we used from 1990 to 2015 here. (We do not have population data at a spatial resolution that make analysis of 1975 meaningful.) This dataset has been cross-validated or analysed with census-designated classes of urbanisation in the recent studies of the U.S., and this process generally confirmed the accuracy of the GHSL algorithms, except perhaps in very sparsely settled rural regions.[49]

A second derived data product, GHS-SMOD, was used to construct a "degree of urbanisation" grid.[50] This modelled surface uses built-up area (GHS-BUILT) along with population data (GPW v4.11 input data reallocated) in the form of GHS-Pop (described momentarily) and a set of density and proximity criteria to classify population and land area into seven classes along a rural-to-urban continuum. This new data product has not yet been cross-validated in the peer-reviewed literature, but such studies are under way. We felt that it was important to use a refined measure of urban locations rather than a simple dichotomy for this study, but owing to the validation under way, we reduced the seven classes to three as indicated in Table A.7. In broad strokes, these represent: cities; other urban and quasi-urban locations (such as towns, peri-urban locations); and rural areas.[51] We also used GRUMP, and simple built-up thresholds from GHS-BUILT, as a type of sensitivity analysis on the urban classifications.

Table A.6 identifies the data used to construct the various estimates detailed above. In an important departure from earlier studies,[52] the data used here to construct the low elevation coastal zone (LECZ) represent recent advances in the processing of the underlying data. The underlying data, from the Shuttle Radar Topography Mission (SRTM), have known vertical errors, whereby some low-lying vegetated areas are erroneously estimated – what is known as tree-height bias. Corrections to the SRTM have been made in a new database, the Multi-Error-Removed Improved-Terrain DEM (MERIT), and it is that dataset that is the basis of the LECZ exposure used here.[53] We used the original SRTM data for the sensitivity analysis.[54]

Table A.6. Data sources

Theme	Dataset	Abbreviation	Spatial resolution	Reference
Elevation	Shuttle Radar Topography Mission elevation data	SRTM	90m	ISciences (2003)[55]
	Multi-Error-Removed Improved-Terrain DEM	MERIT	90m	Yamazaki et al. (2017)[56]
Urban rural classifications	Global Human Settlement – Settlement “degree of urbanisation” Model Grid	GHS-SMOD	1km	Florczyk et al. (2019)[57]
	Global Human Settlement – Built-up Grid	GHS-BUILT	300m	Pesaresi et al. (2018)[58]
	Global Rural Urban Mapping Project	GRUMP	1km	CIESIN et al. (2017)[59]
Population	Global Human Settlement – Population Grid	GHS-Pop	300m	EC/JRC (2018)[60]
	Gridded Population of the World, v.4.11	GPW v.4.11	1km	CIESIN (2018)[61]

NB: Grey-font refers to data used in sensitivity analysis only.

For population data, we used the GHS-Pop data as our primary data, and GPW v.4.11 (an earlier version of which was used in the original McGranahan et al. study[62]) for the sensitivity analysis. The GHS-Pop data apply the GPW v.4.11 inputs and reallocate population to GHS-BUILT areas. In this way, population from large, sparsely populated administrative units is moved towards the detected built-up area rather than being assumed to be evenly distributed throughout the entire polygon.

Since the population data and the urban extent data both use GHS-BUILT to reallocate population and then classify those areas in varying degrees of urban, they are internally consistent. For this reason, we used these as our basic data product for the production of our new LECZ estimates. These internally consistent data, however, may tend to somewhat over-concentrate population into areas that are obviously built-up, leading to somewhat more urban residents. Because GHSL is not as expansive as the night-time lights used in the 2007 study (which were very inclusive of core urban areas and their surrounding areas), we expanded smaller estimates of urban land than in the initial study.

Table A.7. Urban classifications according to GHS-SMOD data

code	Short formal description	Intuitive description	Formalisation
RUR	*rural grid cells*	*rural areas*	xpop <300 OR ∑xpop(4-conn cluster of xpop >300) <5000
LDC	*urban clusters*	*towns or suburbs*	xpop >300 AND ∑xpop(4-conn cluster) >5000, no generalisation step, AND not "urban centres"
HDC	*urban centres*	*cities*	{xpop >1500 OR xbu>0.5 } AND ∑xpop(4-conn cluster) >50000, followed by generalisation step: single cluster, iterative 3x3 kernel union-majority filter until idempotence, filling gaps (holes) < 15 square km

Approach

We used the above layers to estimate "zonal statistics" as described above. Table A.8 highlights the processing steps necessary to condition the data layers, make them compatible with one another, and overlay them in order to generate the estimates above. This includes re-projecting spatial layers, aggregating finely resolved data to compatible resolutions, and so forth. The data were all re-projected into World Geodetic System 1984 (WGS84) and aggregated or resampled to 300 metres resolution to conform with GHS-POP inputs. The analysis was undertaken in ArcGIS, python and R.

Table A.8. Summary of basic data processing steps

Data type/step	Processing decisions and steps
Elevation	
Aggregate MERIT-DEM	The MERIT-DEM elevation data were aggregated with a Majority Filter from approximately 100m to approximately 300m to conform with population and built-up inputs.
Create LECZ extracts	The aggregated MERIT-DEM data were extracted into 5m, and 10m zones.
Population, and Built-Up preprocessing	
Extract	GHS-POP was extracted by country and LECZ.
Extract and project	GHS-BUILT was extracted by country and LECZ, and projected from Mollweide into WGS84 to conform with the native projection of elevation data.
Resample and extract	GHS-SMOD, GPW v.4.11 and GRUMP were down-sampled to 300m and extracted by country and LECZ. GHS-SMOD was projected from Mollweide into WGS84 to conform with the native projection of elevation data.
Derivation of urban gradients	
Threshold GHS-BUILT	GHS-BUILT was transformed into two binary masks of Built-up/Not Built-up. The first mask assumed that any pixel greater than or equal to 1 pct Built-up was in the Built-up category. The second mask

	assumed that any pixel greater or equal to 50 pct Built-up was in the Built-up category.
Aggregate GHS-SMOD	GHS-SMOD was aggregated to produce two binary masks. The first mask combined SMOD into three classes: High Density Clusters (HDC), Low Density Clusters (LDC) and Rural Areas (RUR). The second mask combined SMOD into two classes: (HDC, LDC), and RUR respectively.
Zonal statistics	
Calculation	More than 100,000 individual zonal statistics tables were produced for every combination of inputs, by country and LECZ.
Compilation	The statistics were compiled into the master tables presented here.

Selected results

Table A.9 presents selected results from the analysis to provide more detail about countries that might be of particular interest.

Table A.9. Population and percent of national population in urban centres and quasi-urban clusters in the LECZ, for select countries of interest

Country	Total Population (2015) in Urban Centers in the 10m LECZ	Percent of Country Population (2015) in Urban Centres in the LECZ	Total Population (2015) in Quasi-Urban Clusters in the LECZ	Percent of Country Population (2015) in Quasi-Urban Clusters in the LECZ
Indonesia	34,804,741	13.5%	12,596,966	4.9%
China	129,506,529	9.4%	52,128,053	3.8%
India	55,216,398	4.2%	15,611,043	1.2%
Mexico	2,916,240	2.3%	1,508,959	1.2%
Ghana	541,916	2.0%	643,626	2.3%
Tanzania	236,783	0.4%	104,160	0.2%

Table A.10. Average Annual Population Growth Rate of the Urban Centre, Quasi-Urban Cluster, Rural and Total Population in the Low Elevation Coastal Zone (LECZ)

Elevation	Total Population Growth Rate	Urban Centre Population Growth Rate	Quasi-urban Cluster Population Growth Rate	Rural Population Growth Rate
0-5 m	1.41%	2.26%	0.67%	0.54%
5-10m	1.24%	1.85%	0.23%	0.32%
0-10m	1.30%	1.98%	0.41%	0.42%
non-LECZ	1.13%	1.62%	0.68%	0.78%

Limitations

The elevation data was produced and distributed in the WGS84 Geographic Coordinate System. The data from GHSL, however, were produced and distributed in the Mollweide Equal Area Projected Coordinate System (not including GHS-POP which is also released in a WGS84 version). In order to conduct analyses on these data sources it is necessary to harmonise their coordinate systems, but the projection of raster data is not without complications.

When a raster dataset is projected from one coordinate system to another, the registration and total number of pixels represented are altered. In other words, the number of pixels may change along with the location of those pixels relative to ground truth. We opted to maintain the projection of the elevation data source (WGS84) in order not to introduce uncertainties about the location of the LECZs. We therefore needed to project GHS-BUILT and GHS-SMOD to conform with the elevation source.

The thematic layers (GHS-BUILT, GHS-SMOD) were not simple to validate owing to the fact that there is no available alternative source for these data to compare with. We expect that any error introduced by projecting these data from Mollweide to WGS84 using a “nearest neighbour” approach is quite minimal; however, it should be noted that because of the fact that the LECZs represent small swathes of land area, they are also more sensitive to any apparent shifts of pixel locations. Although the projection issue does produce some uncertainty, it would not have been possible to use these data sources together without taking this approach.

Annex 4: Relationship between urban population density and economic performance

Analysis conducted by Yohan Iddawela and Neil Lee (London School of Economics and Political Science)

Scope of the analysis

The aim of this research is to investigate the assertion that urban population density is associated with economic dynamism. The primary research question we are attempting to address is: To what extent does urban density lead to innovation? We also examined the impact of increased urban population density on a number of other economic outcomes. We modelled these impacts in two separate contexts: (1) Europe; and (2) the United States. This analysis builds on a wide body of literature that investigates how urban forms can shape economic outcomes, by analysing the relationships between various urban forms or densities, and economic variables such as productivity, innovation or GDP.[63]

Data

Europe

We used European Union (EU) metropolitan regions as our unit of analysis. A metro region is defined as urban agglomerations (Nomenclature of Territorial Units for Statistics (NUTS) level 3 regions or groups of NUTS level 3 regions), where at least 50% of the population lives inside a functional urban area that is composed of at least 250,000 inhabitants.[64] Our dataset covers 277 metro regions across 29 EU countries from 2009 to 2012; data sources are listed in Table A.11.

Table A.11. Data sources and definition for the European region

Variable	Definition	Source
Patent intensity	Number of patents per 1,000 people	European Patent Office
GDP	GDP of metro region	Eurostat
Urban population	Population in metro region	Eurostat
Employment density	Employment per square kilometre in metro region	Author's calculation from Eurostat
R&D expenditure	R&D expenditure in metro region	Eurostat
Infrastructure	Index of road density (percentage of total metro region covered by roads) – authors' calculations	OpenStreetMap
Tertiary education rate	Percentage of population with tertiary qualifications	Eurostat
High-skilled Employment	Percentage of population in high-skilled employment	Eurostat

United States

We used metropolitan statistical areas (MSAs) as our unit of analysis. An MSA consists of one or more counties that contain a city of 50,000 or more inhabitants or contain a Census Bureau-defined urbanised area and have a total population of at least 100,000.[65] Our dataset covers 390 MSAs from 2001 to 2017; data sources are listed in Table A.12.

Table A.12. Data sources and definition for the U.S. region

Variable	**Definition**	**Source**
Patent intensity	Number of patents per 1,000 people	Authors' calculations using United States Patent and Trademark Office data
High-skilled worker share	Share of high-skilled workers in MSA	American Community Survey
Medium-skilled worker share	Share of medium-skilled workers in MSA	American Community Survey
Low-skilled worker share	Share of low-skilled workers in MSA	American Community Survey
Urban population	Population in MSA	American FactFinder
High-skilled employment rate	Employment rate of high-skilled workers	American Community Survey
Medium-skilled employment rate	Employment rate of medium-skilled workers	American Community Survey
Low-skilled employment rate	Employment rate of low-skilled workers	American Community Survey
Biotech workers	Share of MSA population working in biotech	American Community Survey
ICT workers	Share of MSA population working in ICT	American Community Survey
Manufacturing workers	Share of MSA population working in manufacturing	American Community Survey
Infrastructure	Index of road density (percentage of total MSA covered by roads) – authors' calculations.	OpenStreetMap
Universities	Number of universities in MSA	Homeland Infrastructure Foundational-Level Data

Approach

Europe

We employed a panel data model that incorporates year and NUTS 1 region fixed effects (FE). This was used to account for time-variant and region-invariant shocks (e.g. downturns in the global economic market and the emergence of new technology), as well as time-invariant and region-variant heterogeneities (e.g. distance to the coast).

We examined the impact of urbanisation on two different dependent variables: (i) patent intensity; and (ii) GDP levels.

Our analyses were based on variants of the following specifications:

$$(1)\quad lnPatent_{tm} = \alpha + \beta lnUrbanPopDens_{tm} + \mathbf{X}'_{tm}\varphi + \emptyset_t + \vartheta_r + u_{tm}$$

$lnPatent_{tm}$ is log patent intensity (patents per 1,000 people) at time t in metro region m. The main explanatory variable is l$lnUrbanPopDens_{tm}$, log of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects innovation levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_r represents region fixed effects, and u_{tm} is the error term.

$$(2)\quad lnPatent_{tm} = \alpha + \beta lnEmpDens_{tm} + \mathbf{X}'_{tm}\varphi + \emptyset_t + \vartheta_r + u_{tm}$$

$lnPatent_{tm}$ is log patent intensity (patents per 1,000 people) at time t in metro region m. The main explanatory variable is $lnEmpDens_{tm}$ which represents log employment density at time t in metro region m and country n. $\mathbf{X}$ is a vector of numerous covariates which affects employment density levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_r represents region fixed effects, and u_{tm} is the error term.

$$(3)\quad lnGDP_{tm} = \alpha + \beta lnUrbanPopDens_{tm} + \mathbf{X}'_{tm}\varphi + \emptyset_t + \vartheta_r + u_{tm}$$

$lnGDP_{tm}$ is log GDP at time t in metro region m. The main explanatory variable is $lnUrbanPopDens_{tm}$, log of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects GDP levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_r represents region fixed effects, and u_{tm} is the error term.

$$(4)\quad lnGDP_{tm} = \alpha + \beta lnEmpDens_{tm} + \mathbf{X}'_{tm}\varphi + \emptyset_t + \vartheta_r + u_{tm}$$

$lnGDP_{tm}$ is log GDP at time t in metro region m. The main explanatory variable is $lnEmpDens_{tm}$, log of employment density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects GDP levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_r represents region fixed effects, and u_{tm} is the error term.

Overall, our results show a robust positive effect of urban density on innovation, even when controlling for other factors, such as R&D spending. We need to be cautious in our interpretation, as we cannot say this is a causal relationship (it might be that innovative cities attract more people, leading to a spurious correlation with density).

United States

We examined the impact of urbanisation on four separate dependent variables: (i) log patent intensity; (ii) log high-skilled earnings; (iii) log medium-skilled earnings; and (iv) log low-skilled earnings.

For each of these models, we used a reduced form OLS model with fixed effects estimation that incorporates year and state fixed effects. This was used to account for time-variant and state-invariant shocks, as well as time-invariant and region-variant heterogeneities.

$$(1)\quad lnPatent_{ta} = \alpha + \beta lnUrbanPopDens_{ta} + \mathbf{X}'_{ta}\varphi + \emptyset_t + \vartheta_s + u_{ta}$$

$lnPatent_{ta}$ is log patent intensity (patents per 1,000 people) at time t in MSA a. The main explanatory variable is $lnUrbanPopDens_{ta}$log of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects innovation levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_s represents state fixed effects, and u_{ta} is the error term.

$$(2)\quad lnHiSkillWage_{ta} = \alpha + \beta lnUrbanPopDens_{ta} + \mathbf{X}'_{ta}\varphi + \emptyset_t + \vartheta_s + u_{ta}$$

$lnHiSkillWage_{ta}$ is log of average high-skilled earnings at time t in MSA a. The main explanatory variable is l$lnUrbanPopDens_{ta}$ og of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects wage levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_s represents state fixed effects, and u_{ta} is the error term.

$$(3)\quad lnMedSkillWage_{ta} = \alpha + \beta lnUrbanPopDens_{ta} + \mathbf{X}'_{ta}\varphi + \emptyset_t + \vartheta_s + u_{ta}$$

$lnMedSkillWage_{ta}$ is log of average medium-skilled earnings at time t in MSA a. The main explanatory variable is l$lnUrbanPopDens_{ta}$ log of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects wage levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_s represents state fixed effects, and u_{ta} is the error term.

$$(4)\quad lnLoSkillWage_{ta} = \alpha + \beta lnUrbanPopDens_{ta} + \mathbf{X}'_{ta}\varphi + \emptyset_t + \vartheta_s + u_{ta}$$

$lnLoSkillWage_{ta}$ is log of average low-skilled earnings at time t in MSA a. The main explanatory variable is $\beta lnUrbanPopDens_{ta}$log of urban population density for a city. $\mathbf{X}$ is a vector of numerous covariates which affects wage levels (see data table for a full overview). $\emptyset_t$ are time fixed effects, ϑ_s represents state fixed effects, and u_{ta} is the error term.

Overall, our results show a robust positive effect of urban density on innovation, even when controlling for STEM employment. As with the European results, however, we investigated the degree of association between variables. A clean identification strategy needs to be adopted to establish the causal relationship.

Selected results

Table A.13 presents results of the regression analysis performed on the European region and Table A.14 presents the results for the United States. Both contain the estimates of the fixed effects model. In results not shown here, we used random effects specifications for these models. These did not yield major differences in terms of the significance and magnitude of the effect.

Table A.13. Regression results for the European region

	(1)	(2)	(3)	(4)
Variables	Log patent intensity	Log patent intensity	Log GDP	Log GDP
Log pop density	0.107**		0.188**	
	(0.0448)		(0.0823)	
Log emp density		0.108**		0.0899*
		(0.0424)		(0.0465)
Log R&D	0.100***	0.114***	0.124*	0.146***
	(0.0345)	(0.0378)	(0.0696)	(0.0499)
Infrastructure	0.112	0.315	14.70***	14.58***
	(1.307)	(1.303)	(3.568)	(1.931)
STEM employment	-0.000962	-0.00698	0.0211**	0.0215**
	(0.00674)	(0.00747)	(0.0105)	(0.00832)
Tertiary education rate	0.0393***	0.0393***	0.0300***	0.0285***
	(0.00549)	(0.00524)	(0.00737)	(0.00543)
Constant	-6.153***	-5.922***	5.791***	6.253***
	(0.271)	(0.252)	(0.367)	(0.233)
Year FE	Yes	Yes	Yes	Yes
NUTS 1 FE	Yes	Yes	Yes	Yes
Observations	726	570	726	570
R-squared	0.873	0.885	0.731	0.706
Robust standard errors in parentheses				
*** p<0.01, ** p<0.05, * p<0.1				

Table A.14. Regression results for the U.S. region

	(1)	(2)	(3)	(4)
Variables	Log patent intensity	Log high-skill earnings	Log medium-skill earnings	Log low-skill earnings
Log population density	0.186**	0.0456***	0.0548***	0.0348**
	-0.0903	-0.00889	-0.00737	-0.014
High-skilled worker share	15.81***	0.37		
	-1.788	-0.264		
Employment rate of high-skilled workers	-0.112	-0.0229		
	-0.29	-0.0908		
Biotech worker share	7.45	1.555	0.344	-0.767
	-8.075	-1.18	-1.172	-1.443
ICT worker share	11.41**	1.241***	2.057***	-0.00848
	-4.274	-0.435	-0.392	-0.541
Manufacturing tech worker share	16.91***	0.513	0.54	0.791
	-3.887	-0.548	-0.641	-0.807
Infrastructure	-0.606	0.400**	0.943***	0.713***
	-1.027	-0.184	-0.161	-0.237
Universities	0.00531	0.0102	-0.0198**	-0.0249**
	-0.0629	-0.00865	-0.00744	-0.0101
Medium-skilled worker share			-0.168	
			-0.111	
Employment rate of medium-skilled workers			1.063***	
			-0.12	
Low-skilled worker share				0.272
				-0.341
Employment rate of low-skilled workers				0.233
				-0.139
Constant	-5.022***	11.01***	9.690***	9.690***
	-0.288	-0.0861	-0.148	-0.0363
Year FE	Yes	Yes	Yes	Yes
State FE	Yes	Yes	Yes	Yes
Observations	2,852	2,862	2,862	2,862
R-squared	0.713	0.443	0.712	0.285
Clustered standard errors in parentheses				
*** p<0.01, ** p<0.05, * p<0.1				

Limitations

This analysis does not prove a causal relationship between density and economic growth. A proper identification strategy would need to be implemented in order to do so.

Moreover, there is some debate about using MSAs as a unit of analysis. This is because some MSAs incorporate rural land areas, meaning that they are not perfect indicators of density. Given data-availability issues, we were not able to crop out rural areas from MSAs. Therefore, we would expect the magnitude of the effects to be larger if rural areas were accounted for. However, our results align closely with the mean elasticities related to the effect of urbanisation on patenting activity. For example, one meta-review of urbanisation literature finds that the mean elasticity of patenting activity's relationship with urbanisation is 0.21.[66] This is only .03 higher than our observed elasticities in this report. Given this, it is unlikely that this problem with MSA boundaries significantly affects the results.

Annex 5: Relationship between urban density and urban greenhouse gas emissions

Analysis conducted by Catlyne Haddaoui (Coalition for Urban Transitions)

Scope of analysis

This analysis looks at the relationship between urban population density and greenhouse gas emissions. It investigates whether greater compactness in cities can help fight climate change.

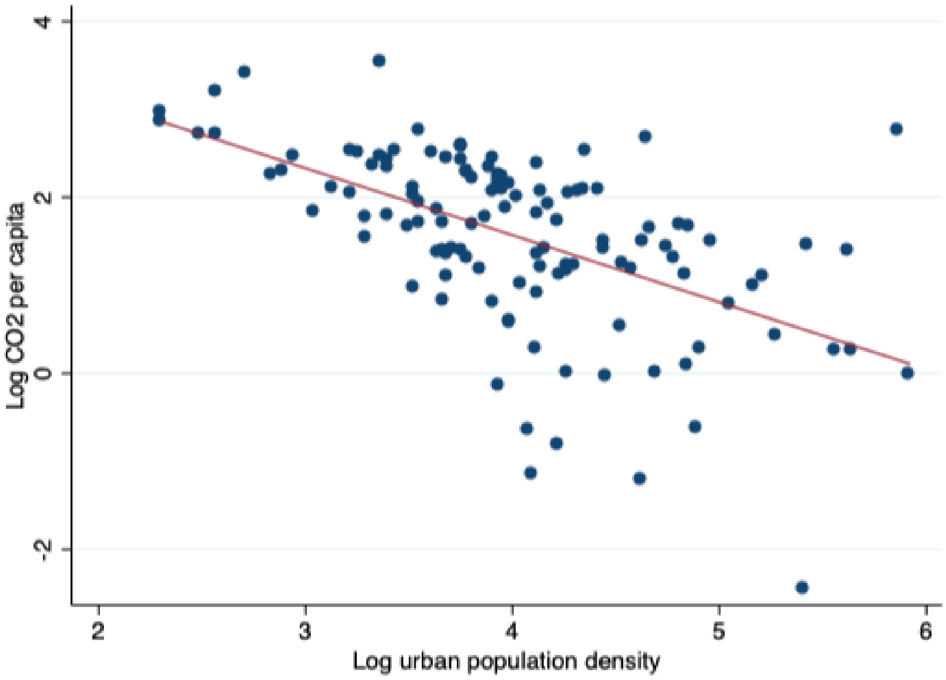
Data

Data on urban population density are from *Atlas of Urban Expansion*.[67] Data on urban density covers 199 cities worldwide at the metropolitan scale. The most recent data points for urban density for each city range from 2009 to 2015 (mostly 2013 and 2014). Gross value added (GVA) per capita data are for the year 2015 and are from Oxford Economics 750 Global Cities database.[68] Emissions per capita are also for the year 2015 and are derived from the Oxford Economics dataset, as outlined in Floater et al., 2014.[69]

Approach

Looking only at the correlation between log emissions per capita and log urban population density, we find a correlation of $r=-0.54$, with $p<0.01$ (see Figure A.1).

Figure A.1. Correlation between log urban population density and log CO_2 per capita



However, this negative relationship might be due to differences in the income levels of cities: specifically, higher-density cities may have lower incomes, which may explain why they consume less energy and produce fewer emissions.

Therefore, we ran a simple regression of CO_2 per capita emissions on urban population density, controlling for per capita GVA (all log scale).

Selected results

Table A.15 presents results of the regression of urban population density on CO_2 per capita, controlling for GVA per capita on a panel of 121 cities for the year 2015.

Table A.15. Regression results

Number of obvs = 121 F(2,118)=63.11 Prob > F=0 R-squared = 0.6025 Root mean square error = 0.63665						
Robust ordinary least squares						
Log CO_2 per capita	Coefficient	Standard error	t	P>|t|	[95% confidence interval]	
Log urban pop density	-0.1872431	0.0981461	-1.91	0.059	-0.3815991	0.0071129
Log GVA per capita	0.6384312	0.080734	7.91	0	0.478556	0.7983064
_cons	-3.716683	1.054193	-3.53	0.001	-5.804272	-1.629094

Based on a sample of 121 cities in 2015 and holding per capita GVA constant, a 1% increase in urban density is associated with a 0.2% decrease in CO_2 emissions (p=0.06).

Limitations

This relationship cannot be interpreted as causal. The estimation only controls for difference in GVA per capita. Moreover, emissions were measured at the production level, so the analysis does not take into account emissions from consumption.

Annex 6: Global conversion of land to urban purposes

Analysis conducted by Alejandro Blei, Shlomo Angel and Xinyue Zhang (Marron Institute of Urban Management, New York University)

Scope of the analysis

Urban population growth and the outward expansion of cities and towns entails the conversion of land from rural to urban use. Yet knowledge of the land cover changes that underlie urban expansion, whether the total amount of land or the type of land cover that is converted to urban use, such as areas that were formerly forest or cultivated land, remains poorly understood. While organisations such as the United Nations Population Division and the Food and Agriculture Organization (FAO) report time series data on the urban population in each country or on types of land cover in countries, these reports critically lack a spatial component. Indeed, a key obstacle to improving our understanding of the relationship between urban expansion and land cover change has been uncertainty surrounding the spatial representation of urban land. Definitive resolution to the urban question remains unsettled, but new global datasets make possible the quantification of land cover change due to settlement expansion in a spatially explicit manner. Moreover, the new data sources allow for a targeted focus on different types of settlements that can shed light on change due to urban settlement expansion specifically.

This analysis combines three global datasets and applies a settlement extent methodology developed for the *Atlas of Urban Expansion, Volume 1: Areas and Densities* to produce estimates of the total amount of land, and the relative shares of different land cover categories, that have been subsumed by two sets of settlement expansion over the 2000–2014 period, for all countries.[70] More specifically, we focus on settlement expansion that intersects the European Commission's Global Human Settlement Model Grid's (GHS-SMOD) urban layer, which contains two subclasses: urban centres and urban clusters. We produce estimates of settlement expansion and land cover change within these two subclasses. We report on changes associated with six categories of land cover: cultivated land, forest, grassland, shrubland, wetland and bareland. Our approach allows us to generate answers to the following questions:

1. Over the 2000–2014 period, how much settlement expansion was urban, belonging to either of the urban centres or urban clusters subclasses in 2014?
2. What types of land cover at the year 2000 were converted to urban use within these expansion areas?

The analysis is novel for its integration of datasets, spatial analysis methods, and for its geographic coverage. It generates new data with respect to the number and area of settlement extents over time and it provides spatially explicit estimates of land cover change associated with urban expansion at the country level. The analysis also raises a number of questions about how the results should be interpreted and what actions, if any, should be taken in response to the trends observed. Addressing these questions in a comprehensive manner lies beyond the scope of the present analysis and remains the focus of a subsequent study. That said, the land cover impacts of urban expansion, globally, have been relatively unknown until now. This analysis provides a first attempt at documenting this dynamic.

Data

A central concept throughout the analysis is the idea of settlement extent, which refers to a spatially explicit representation of human settlement. The basis for delineating settlement extent is a model created by the New York University Urban Expansion Program. This model was used to map and measure urban extent in *Atlas of Urban Expansion.*[71]

While the Atlas focused on mapping settlements with populations of 100,000 or more, the model can also be applied to settlements with very small populations. In theory, and in practice – for we have observed as much in this analysis – the smallest settlement extent our model produces is on the order of 0.03 square kilometres, or approximately three hectares. This does not mean that all settlements with areas greater than three hectares are output by the model. An isolated settlement of three hectares of contiguous built-up area, surrounded by open countryside in all directions, for example, would not meet the model's thresholds and would not be output as a settlement extent. We retain information about that settlement's built-up area, but it is not output by the model in a spatially explicit manner.

We ran the model using year 2000 and year 2014 data to obtain settlement extents over time. We subtracted the settlement extents of the earlier period from those of the latter period to obtain settlement expansion areas.

The fundamental input to the settlement extent model is the three-way classification of satellite imagery into: built-up area, open space (not built-up) and water pixels. Whereas the Atlas relied on human-assisted classification of 30-metre resolution Landsat satellite imagery to generate input data for 200 cities, this analysis relies on a relatively new global dataset. The European Commission's Global Human Settlement Layer (GHSL) built-up grid applies machine learning methods to Landsat satellite imagery to produce time series data on the presence of built-up area across the entire planet at a resolution of 38 metres.

The settlement extent model produces extents as large as several thousand square kilometres and as small as three hectares. Settlements may be more urban or more rural in character depending on a number of factors: the size and configuration of their built-up areas, their populations, the types of economic activities in which residents are employed, connections to neighbouring settlements, and many others. At this stage of the analysis, we were unable to assign names or populations to settlement extents across all countries in a systematic manner and we knew little about the economic activities associated with individual settlements. We therefore looked to other data sources to help us differentiate urban settlement extent from rural settlement extent, and, ultimately, to help us identify urban settlement expansion.

We turned to a second global data product produced by the European Commission, the GHS-SMOD, to help us distinguish urban from rural settlement. The GHS-SMOD is a spatially explicit product with a resolution of one kilometre. Grid cells refer to areas of urban settlement, rural settlement or no settlement. The urban class is further subdivided into urban centres and urban clusters. In broad terms, urban centres refers to cities or large urban areas, while urban clusters refer to towns and suburbs or small urban areas. Grid cell classification was generated by the OECD's degree of urbanisation model which integrates data from global built-up and population grids and it applies population and density thresholds, as well as spatial contiguity rules, to generate grid cell values.

We overlaid 2000–2014 settlement expansion on year 2015 urban centre and urban cluster grid cells to obtain the intersection of these areas. We interpreted these intersected areas to represent urban settlement expansion. The two classes of urban GHS-SMOD cells allowed us to distinguish between settlement expansion associated with urban centres and with urban clusters. Although GHS-SMOD cells have a spatial resolution of one kilometre, settlement extent, and by association settlement expansion, has a spatial resolution of 38 metres. Thus, the intersected area may be a very tiny portion of the one-kilometre urban grid cell or a very large portion of the one-kilometre grid cell, depending on the spatial relationships between these two datasets.

To assess land cover change due to urban settlement expansion, we identified a second land cover dataset with more detailed information for the open space category for the year 2000. We employed the GlobeLand30 (GL30) 30-metre dataset, created by the National Geomatics Center of China, to obtain information about six land cover categories: cultivated land, forest, grassland, shrubland, wetland and bareland. We overlaid urban settlement expansion for the 2000–2014 period on this year 2000 data. Aggregation of GL30 land cover data in this second intersected area provides information about the categories of land cover, their areas and their relative shares that were subsumed by urban expansion across the 2000–2014 period.

Approach

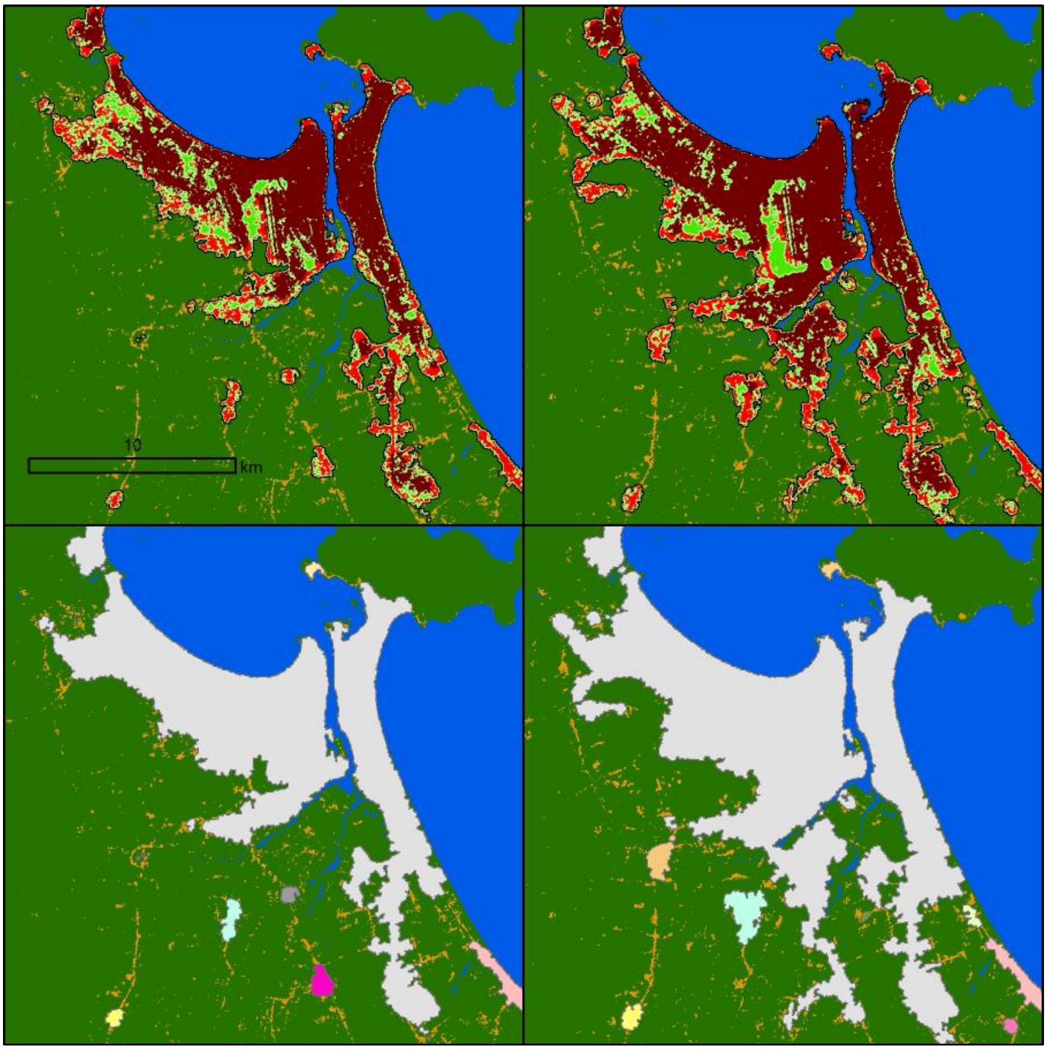
This study relied on secondary data sources that were global in coverage. We conducted additional analysis and interpretation of the datasets to generate new information about settlement expansion and urban settlement expansion specifically. The overall approach relied on spatial analysis techniques carried out in a GIS environment. Results may be summarised at the country, continental and global levels. Below, we describe the methodology and procedural steps in greater detail and use images to aid the reader's understanding of the input and output data.

While a built-up grid was a fundamental input for the generation of settlement extent, additional analysis was required to extract information that would allow for the segmentation and clustering of this data in a systematic manner. The first step of this information extraction procedure was to obtain the three-way classification of built-up area, open space and water pixels. One of the GHSL file formats already contained these divisions. The second step of this procedure was to create information for each built-up and open space pixel that would allow for their subclassification into one of three categories of built-up area: urban, suburban or rural; and one of three categories of open space: fringe open space, captured open space and rural open space.

Around each built-up pixel, we calculated the share of built-up area within its one square kilometre Walking Distance Circle, a circle with a radius of 584 metres, roughly a 10-minute walk. Cut-offs for the share of built-up area within this circle provide a measure of the spatial density of built-up area and defined the different categories of built-up area. If more than 50% of the circle was built-up, the target pixel was labelled urban; if more than 25% but less than 50%, the target pixel was labelled suburban; if less than 25%, the target pixel was labelled rural. Open space pixels within 100 metres of urban and suburban pixels are likely to be degraded by their proximity to development and were labelled fringe open space. Captured open space patches less than 200 hectares in area – patches that are completely surrounded by urban and suburban pixels – are likely to be degraded by their isolation from other open spaces and were labelled captured open space. Fringe and captured open space comprise urbanised open space. Open space pixels that are neither fringe nor captured were labelled rural open space.

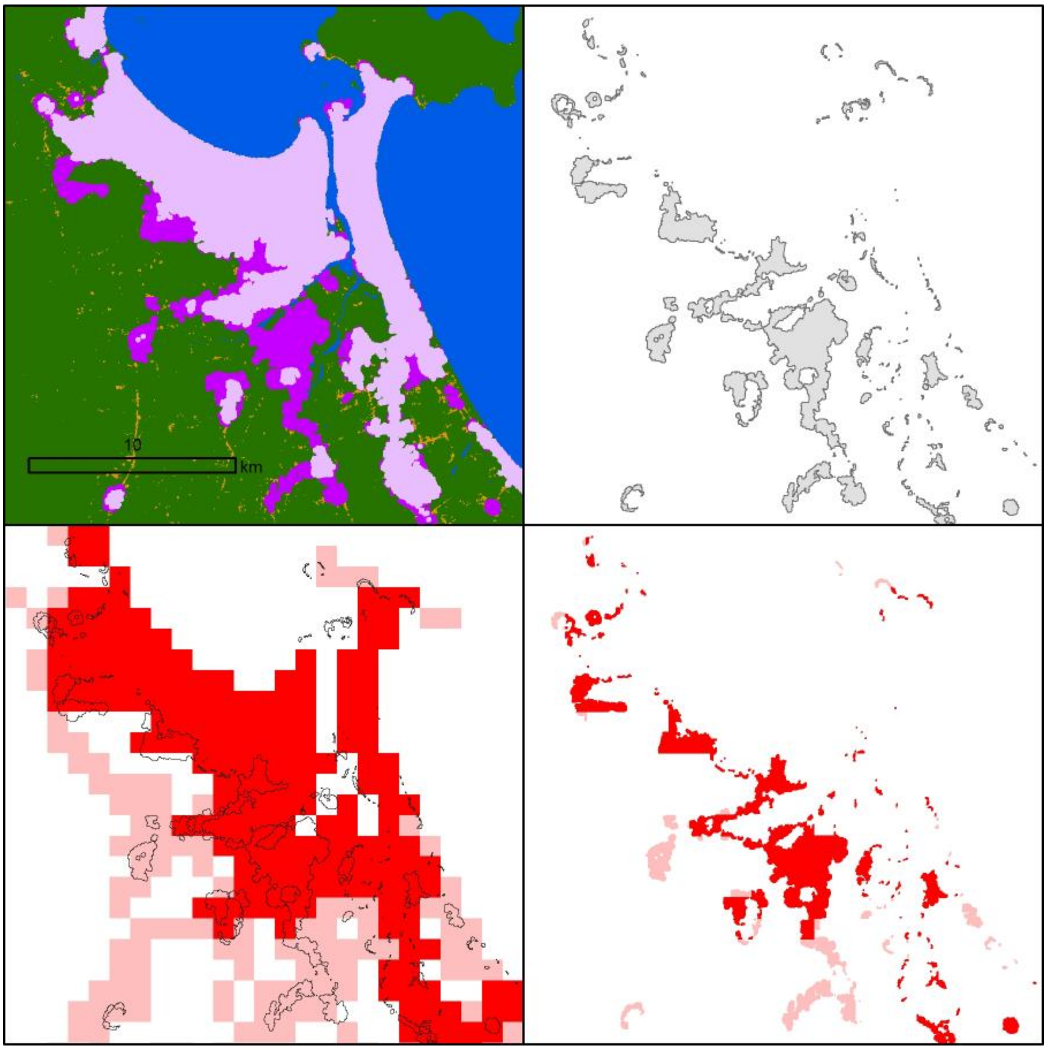
This differentiation of imagery pixels allowed for the third step of the procedure, or the identification of settlement clusters. These are discrete clusters of built-up area and urbanised open space pixels surrounded by rural open space. The fourth and final step of the procedure allowed for the grouping of settlement clusters into settlement extents. Discrete clusters of built-up area and urbanised open space may be grouped into the same settlement extent, a type of meta-cluster, depending on the size and geographic proximity of settlement clusters to each other. A settlement extent may be composed of a single, hundreds, or conceivably thousands of settlement clusters, depending on spatial relationships of clusters across the analysis area as seen in Figure A.2.

Figure A.2. Top row, left to right: The vicinity of Da Nang, Vietnam and the subclassifications of: built-up area into urban (dark red), suburban (red) and rural (ochre) pixels; open space into fringe (light green), captured (bright green) and rural open space (dark green pixels) for the years 2000 and 2014. Bottom row, left to right: total settlement extents (grey) in 2000 and 2014.



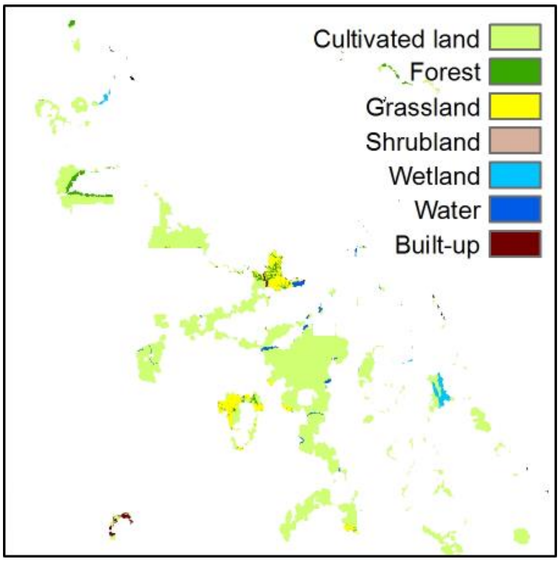
Repeating the procedure at 2000 and 2014 produced two sets of settlement extents across the country. Subtracting the 2000 data from 2014 resulted in the settlement expansion area. This area includes both built-up area and urbanised open space. To distinguish urban centre settlement expansion from urban cluster settlement expansion, we overlaid year 2015 GHS-SMOD data and obtained the intersections of these areas. In Figure A.3, bottom left, the GHS-SMOD layer appears much larger than the urban expansion area because it covers all settlements – not just newly urban and quasi-urban areas.

Figure A.3. Top row, left to right: Year 2000 settlement extent (light purple) and year 2014 settlement extent in the vicinity of Da Nang, Vietnam; 2000–2014 settlement expansion. Bottom row, left to right: GHS-SMOD urban centre cells (red) and urban cluster cells (pink); urban centre settlement expansion (red) and urban cluster settlement expansion (pink).



Assessing land cover change within the two types of urban settlement expansion is simply a matter of intersecting these areas with year 2000 land cover information. Figure A.4 depicts GL30 land cover within all urban settlement expansion in the vicinity of Da Nang, Vietnam. Land cover totals within urban centre expansion and urban cluster expansion individually may be obtained by aggregating GL30 pixels within these respective areas. The presence of built-up pixels in expansion areas, as shown in the bottom left corner of Figure A.4, may be explained by rural built-up pixels that were absorbed by the outward expansion of urban settlements. Since built-up is a GL30 category (labelled “artificial surfaces” in the GL30 dataset), it comprises a land cover category within expansion areas, although the interpretation of this category is rather nuanced, as described in the Limitations section.

Figure A.4. Year 2000 landcover within the 2000–2014 expansion area in the vicinity of Da Nang, Vietnam



Selected results

Tables A.16 to A.22 present selected results to provide more detail about countries and regions of particular interest.

Table A.16. Previous land cover of land that was converted to urban areas between 2000 and 2014, km² by continent and subregion

<note to typesetter: set landscape if necessary, but preferable portrait if you can>

	Cultivated land	Forest	Grassland	Shrubland	Wetland	Rural built-up areas	Water	Bareland	No Data	Total
Africa	**5,590**	**3,930**	**4,338**	**620**	**366**	**3,282**	**254**	**544**	**15**	**18,939**
Eastern Africa	1,642	541	830	50	26	705	21	15	2	3,832
Middle Africa	527	330	926	23	25	334	19	31	0	2,217
Northern Africa	1,427	50	257	98	3	691	36	407	7	2,975
Southern Africa	219	144	651	90	3	511	15	5	1	1,639
Western Africa	1,775	2,865	1,673	359	309	1,041	163	86	5	8,276
Asia	**39,833**	**3,852**	**2,996**	**420**	**212**	**11,678**	**1,973**	**658**	**53**	**61,676**
Central Asia	245	6	33	2	1	448	3	4	0	742
Eastern Asia	27,711	1,746	1,532	80	101	6,130	1,559	33	32	38,923
Southeastern Asia	3,202	773	138	10	42	697	129	3	7	5,002
Southern Asia	6,698	1,136	919	194	60	3,030	251	135	6	12,428
Western Asia	1,977	192	374	134	8	1,373	30	485	8	4,582
Europe	**7,334**	**791**	**202**	**154**	**36**	**2,959**	**177**	**34**	**16**	**11,704**
Eastern Europe	1,266	127	94	15	12	738	42	8	0	2,302
Northern Europe	618	117	20	15	3	418	16	3	5	1,215
Southern Europe	2,206	194	32	85	8	772	19	15	9	3,339
Western Europe	3,245	354	57	39	13	1,031	101	8	1	4,848
South America	**771**	**406**	**677**	**262**	**26**	**963**	**28**	**39**	**4**	**3,177**
South America	771	406	677	262	26	963	28	39	4	3,177
North America	**3,245**	**3,275**	**1,691**	**1,067**	**730**	**6,061**	**163**	**103**	**9**	**16,342**
Caribbean	81	193	99	3	4	83	2	9	2	476
Central America	652	247	220	315	11	738	12	6	1	2,201
Northern America	2,512	2,835	1,372	749	715	5,240	148	88	7	13,665
Oceania	**344**	**121**	**80**	**9**	**1**	**125**	**3**	**3**	**1**	**687**
Australia and New Zealand	291	102	78	7	1	104	3	3	1	591
Melanesia and Micronesia	53	19	1	1	0	20	0	0	0	96
Grand Total	**57,117**	**12,376**	**9,984**	**2,532**	**1,371**	**25,068**	**2,598**	**1,381**	**98**	**112,524**

Table A.17. The top five countries by area of cultivated land converted to urban areas, 2000–2014

Country	**Cultivated land converted to urban areas, km²**
China	25,495
India	5,591
USA	2,237
Japan	1,368
Italy	1,310

Table A.18. The top five countries by share of urban expansion converting cultivated lands to urban areas, 2000–2014*

Country	Share of country’s urban expansion that converted cultivated lands to urban areas, %
Nepal	89%
North Korea	81%
Taiwan	79%
Myanmar	79%
Slovakia	77%

* Includes only countries where at least 50 square kilometres of cultivated lands were converted to urban areas between 2000 and 2014.

Table A.19. The top five countries by area of forest converted to urban areas, 2000–2014

Country	Forest converted to urban areas, km^2
USA	2,762
China	1,539
Nigeria	1,327
India	928
Ghana	597

Table A.20. The top five countries by share of urban expansion converting forests to urban areas, 2000–2014*

Country	Share of country’s urban expansion that converted forests to urban areas, %
Liberia	80%
Cote d’Ivoire	73%
Sierra Leone	67%
Sri Lanka	64%
Senegal	60%

* Includes only countries where at least 50 square kilometres of forests were converted to urban areas between 2000 and 2014.

Table A.21. The top five countries by area of wetlands converted to urban areas, 2000–2014

Country	Wetlands converted to urban areas, km^2
USA	714
Nigeria	251
China	97
India	52
Ghana	27

Table A.22. Previous land cover of land that was converted to urban areas between 2000 and 2014, km^2 and %, select countries of interest

Country	Cultivated land	Forest	Grassland	Shrubland	Wetland	Water	Built-up rural areas	Bareland	NoData	Tot
Ghana	97	597	264	29	27	19	224	0	1	1,25

Indonesia	122	40	3	3	0	0	44	0	0	213
India	5,591	928	763	156	52	215	2,057	57	4	9,82
Mexico	552	157	138	308	9	10	641	6	0	1,82
Tanzania	100	33	161	4	2	1	102	0	1	404
China	25,495	1,539	1,468	47	97	1,517	5,628	18	21	35,8

Limitations

Studying spatially explicit land cover change requires careful consideration of the advantages and disadvantages of using different data sources. The desire for a globally comprehensive analysis required the use of datasets generated by automatic detection methods, for example, and gains in geographic coverage may have come at the expense of gains in accuracy that may have been attained by using more localised land cover data generated by more labour-intensive, human-assisted procedures. Overall classification accuracies are generally high across datasets, but aggregate classification accuracy may mask variation in regional accuracy, which may in turn render estimates for certain regions more accurate than others. In Bhutan, for example, our procedures did not yield a single settlement extent for either 2000 or 2014. Even though Bhutan is a small and sparsely populated country, we know it contained several human settlements. We failed to create settlement extents because the input data contained virtually no built-up pixels, and the ones that existed were too small in number and too sparsely arranged. This example highlights the difficulties of developing automatic detection methods that can be applied globally with high accuracy. Methods that are highly accurate in one landscape may be less accurate in another.

We limited the study period to 2000–2014 to make use of a consistent data source (GHSL) with a uniform spatial resolution, despite the existence of more recent global built-up datasets, some of which were released over the course of this analysis. The study window imposed a constraint on finer-grained data that could be used to assess the different land cover categories subsumed by urban settlement expansion. Namely, the window required locating a global dataset with fine-grained land cover information circa 2000. We integrated information from the GL30 dataset for this purpose. Combining the two datasets carried the potential for contradictions and we recognise that certain contradictions exist, perhaps an unavoidable consequence of integrating two different global datasets. For example, pixels that are classified as built-up in the year 2000 by GHSL may not be classified as built-up in GL30 in the year 2000 and vice versa. These differences may be at least partly explained by different assumptions built into each product’s classification algorithm.

Uncertainties surrounding thematic accuracies in each dataset means that the amount of urban expansion and the breakdown and totals of land cover categories within expansion areas must be treated as estimates. We were unable to determine the confidence intervals around these estimates at present, as doing so would require additional analysis at the country level that lay beyond the scope of this particular study. We also recognise that different definitions of urban will inevitably result in different estimates of the amount of urban expansion. We have focused on settlement expansion within GHSL urban centres and urban clusters to deepen our understanding of the impact that these two definitions have on outcome measures.

Annex 7: The economics of the technically feasible mitigation potential of cities

Analysis conducted by Jason Eis, Karishma Gulrajani, Naina Khandelwal, James Patterson-Waterston, Julian Tollestrup and Jacob Wellman (Vivid Economics)

Scope of analysis

The economics of the technically feasible mitigation potential of cities analysis aims to quantify the costs and benefits of interventions required to reduce emissions to a level in line with a below 2°C scenario in urban areas across the globe to 2050. The approach builds on a previous estimation of economic impacts of urban interventions required for a 2°C global warming scenario.[72] The update considers additional interventions required to achieve mitigation beyond 2°C, in line with the aims of the Paris Agreement on Climate Change.

Interventions included in this economic analysis correspond to the mitigation measures modelled by the Stockholm Environment Institute (SEI) for this report and span the transport, buildings and waste sectors (Table A.23). Deployment of interventions follows modelled deployment from 2015 to 2050. Impacts are calculated for the world's urban areas, as defined in the United Nations' *World Urbanization Prospects*,[73] and presented for 11 countries/regions (ASEAN, Brazil, China, European Union, India, Mexico, Russia, South Africa, United States, other OECD, and other non-OECD).

Table A.23. Urban mitigation interventions considered in this analysis

Sector	**SEI technical analysis**	**Vivid Economics economic modelling**
Buildings	New build at "passive house" levels Deep energy retrofits Heat pumps installed in new and retrofitted buildings as set out in Annex 1	Residential – deep efficiency Commercial – deep efficiency
	Aggressive implementation of efficient lighting and appliances	Residential – efficient lighting Residential – efficient appliances Residential – efficient cooking Commercial – efficient lighting Commercial – efficient appliances Commercial – efficient cooking
	Decarbonisation of electricity and increased adoption of rooftop and building-integrated solar PV	Residential – rooftop solar PV Commercial – rooftop solar PV
Transport	Freight logistics improvements	Freight – improved logistics

	National and local policies drive reduced passenger travel demand	Passenger – compact urban areas and system efficiency
	Rapid expansion of cycling and public transit	Passenger – modal shift to mass transit
	Improvements in fuel economy and high penetration of electric vehicles (EVs)	Passenger – fleet efficiency and electrification Freight – fleet efficiency and electrification
	Decarbonisation of electricity Faster transition to carbon-neutral biofuels	Rooftop solar PV is modelled in buildings sector
Waste	Reduced waste generation per capita and waste collection	Not modelled
	Methane capture efficiency and electricity generation from landfill gas	Landfill gas capture and utilisation
	Increased recycling rates	Not modelled
	Reduced demand for buildings materials Increased efficiency of production of cement, steel and aluminium	Reduced demand for cement and steel

Key outputs include total investment required to implement modelled interventions (by intervention); net present value of interventions from 2017 to 2050 (by intervention); total benefits in 2030 and 2050 (by intervention); and employment impacts of implementing modelled interventions.

Data

Key data sources used in the economic impact analysis vary across sectors and are laid out in Table A.24.

Table A.24. Data sources used in economic impact analysis

Sector	Intervention	Variable	Sources
All	All	Discount rates – assumed to be 3.5% in the central scenario, 1.4% and 5.5% in sensitivities	HM Treasury (2011)[74] Stern (2007)[75] Own assumption
Transport	Reduced travel demand from urban planning and modal shift	Costs associated with increased travel by e-bike	McDonald et al. (2015)[76] VTPI (2018)[77] Cherry et al. (2009)[78] IEA (2016)[79] Global Petroleum Prices (2018)[80]

Transport	Reduced travel demand from urban planning and modal shift	Costs associated with increased travel by public transit	U.S. Department of Energy (2017)[81] UK Department for Transport (2017)[82] UK National Infrastructure Commission (2018)[83] European Environment Agency (2017)[84]
Transport	Reduced travel demand from urban planning and modal shift	Benefits from reduced travel by personal vehicles and public transit, including fuel savings and avoided operating costs	Litman (2011)[85] Gouldson et al. (2015)[86] IEA (2016)[87] World Bank (2016a, 2016b)[88] Victoria Transport Policy Institute (2017)[89]
Transport	All	Regional scaling of transport costs and benefits	NUMBEO (2019)[90] WorldData.info (2017)[91] Reid and Chanda (2017)[92]
Transport	Fleet efficiency	Costs of increased fleet efficiency	IEA (2014)[93]
Transport	Fleet efficiency	Fuel savings from increased fleet efficiency	U.S. National Academy of Sciences (2010)[94]
Transport	Fleet electrification	Costs of increased fleet electrification	Brennan and Barder (2015)[95] Bloomberg NEF (2019)[96] Transport and Environment (2018)[97] IEA (2018)[98] IEA (2016)[99] Global Petroleum Prices (2018)[100]
Transport	Freight – system efficiency	Costs and benefits of urban consolidation centres	Transport Systems Catapult (2018)[101] BMVI (2010)[102]
Transport	Freight – vehicle efficiency	Costs of improved vehicle efficiency	ICCT (2017)[103] Hooper and Murray (2018)[104] IEA (2018)[105]IEA (2016)[106]
Buildings	Increased building shell efficiency	Costs of increased building shell efficiency	GBPN (2015)[107]

Buildings	Increased appliance and lighting efficiency	Costs of increased appliance and lighting efficiency	Thema (2018)[108]
Buildings	Increased solar power from rooftop photovoltaics (PVs)	Costs of increased solar power from rooftop PVs in urban areas	IRENA (2017)[109]
Buildings	All	Scaling of costs for buildings sector interventions across regions	Arcadis (2018)[110]
Waste	Increased methane capture and conversion to landfill gas	Costs of infrastructure to capture and convert landfill gas	U.S. EPA (2012)[111] Markgraf and Kaza (2016)[112] Global Methane Initiative (n.d.)[113] Arcadis (2018)[114]
Waste	Materials efficiency	Benefits of reduced steel and cement consumption	World Bank Commodity Price Database[115] Imbabi et al. (2012)[116]

Approach

The general cost–benefit approach is consistent across all interventions. First, the additional increase or decrease in demand for specific transport, energy or waste disposal services was calculated for the urban mitigation scenario, compared with a reference scenario, based on emissions modelling conducted by SEI. Second, the additional investment costs of interventions included in the urban mitigation scenario were calculated by multiplying change in demand by the marginal cost of adopting a lower-carbon option (adapted for regional cost variation). Third, the value of the benefits associated with the deployment of all units was calculated in the urban mitigation scenario relative to the reference scenario (adapted for regional cost variation). Finally, the additional investment costs and benefits generated in the period to 2050 were compared, to assess the overall economic case for each intervention, and net employment impacts were calculated from expected investment in each intervention.

Changes in demand for energy, transport and waste disposal in the urban mitigation and reference scenario are modelled by SEI. SEI's model provides reference and mitigation scenario emissions profiles, along with underlying demand factors that produced those profiles.

The following two assumptions apply to all the interventions:

1. Projections on future energy prices: an assumption of a real annual price increase of 2.5% was applied to 2014 energy prices in the central scenario, and sensitivities include annual energy price increases of 1% and 4%. The data for energy prices were obtained from the IEA Energy Prices and Taxes database[117] for the OECD countries, and World Bank pump prices database[118] for the non-OECD countries.

2. Sector-specific learning rates were applied to each sector to model cost reductions over time. These include 5% and 7% for the waste and transport sectors and 1.53% and 1.84% for the buildings sector. These assumptions are in line with learning rates used in previous analysis,[119] as well as in complementary sector analysis.[120] Variation in learning rates was also tested.

The costs and benefits included in this analysis have been limited to those that are directly monetizable. However, separate from the cost–benefit analysis, the impact of interventions on employment was also calculated. These estimates drew on a high-level literature review of low-carbon interventions across sectors to estimate the net jobs supported per million dollars invested (i.e. total project costs) for each intervention.[121] Net jobs were calculated by subtracting gross jobs associated with fossil fuel investments from gross jobs associated with low-carbon building, transport and waste interventions. To account for regional variation in the absence of other data, the analysis employed the methodology of McKinsey Global Institute.[122]

Limitations

Costs and benefits are calculated at the country/region level for 11 countries/regions. City-specific values may vary within these regions.

Economic benefits calculated did not consider non-market benefits which may be significant, especially for social welfare-maximising governments. These benefits include: (i) value of time saved through improved transport and waste infrastructure; (ii) health benefits from reduced air pollution, improved waste infrastructure, and more efficient buildings; (iii) additional productivity benefits related to more efficient buildings; and (iv) benefits associated with avoided carbon emissions (i.e. social cost of carbon).

Auxiliary infrastructure costs were not considered for: (i) electric vehicle charging; or (ii) increased use of buses for public transport. In both cases, the assumption is that required infrastructure would be developed in the reference case, but this may warrant further research.

Finally, the case for investment in modelled interventions can be further refined through identification of interventions at the region and sector level with a positive net present value at various discount rates. In addition, modelling reinvestment of net benefits into lower net present value interventions can provide a picture of portfolio investment.

Annex 8: Decoupling economic growth and carbon emissions: case studies of Montreal and London

Analysis conducted by Catlyne Haddaoui (Coalition for Urban Transitions)

Scope of analysis

This analysis aims to provide examples of cities that have decoupled economic growth from greenhouse gas (GHG) emissions. This analysis provides real-life examples of cities that managed to pursue economic prosperity while reducing their environmental impact, meaning that the city's gross value added (GVA) per capita has risen while the city's per capita CO_2 has remained stable or decreased.

Data

Montreal

Data for GVA are for the Montreal Metropolitan Area are from the Oxford Economics 750 Global Cities database.[123] For consistency, population data are from the same source. The emissions data are for the identical land area and are from the CDP (formerly Carbon Disclosure Project) online database.[124]

London

Population, GVA and emissions per capita data are for the greater London area and are from the official website of the Greater London Authority (GLA).[125]

Approach

From the CDP database, we identified all cities that have published their emissions level annually for the past five years (63 cities). We then selected only the cities which were publishing their emissions for their metropolitan region, in order to match the Oxford Economics 750 Global Cities database, which contains population and GVA data at the metropolitan level. Matching those two datasets, only 29 cities remained. Among them, only one city was decoupling over the past five available years: Montreal.

Due to the small number of cities for which data are available for the three interest variables (population, emissions and GVA) at the metropolitan level, we also sought to find additional cities with data at the administrative boundary level. Data were available for all the three variables from the same source (i.e. exactly the same coverage for all three variables) for the greater London area, we found that incomes or GVA per capita were increasing while CO_2 emissions per capita were decreasing.

Limitations

Data for CO_2 emissions include only production-based emissions. The cities' consumption-based emissions may actually have risen over the period, which would mean that the emissions associated with goods and services consumed in the cities may have been "exported" or produced elsewhere. Reducing emissions from consumption will be increasingly important in cities in high-income countries such as London and Montreal.[126]

Moreover, as the text accompanying these findings in the *Urban Opportunity* report explains, many of the city-level changes in income or emissions may be due to factors beyond the city, such as policies or macroeconomic trends at the national or global level. We recognise that this decoupling is not currently a trend among cities more widely.

Annex 9: Linkages between National Urban Policies and Nationally Determined Contributions

Analysis conducted by Catlyne Haddaoui (Coalition for Urban Transitions), drawing on data provided by Steven Bland (UN-Habitat), Johannes Hamhaber (Technical University of Cologne), Tadashi Matsumoto (Organisation for Economic Co-operation and Development), Marcus Mayr (UN-Habitat) and Nicola Tollin (University of Southern Denmark)

Scope of analysis

This analysis is intended to indicatively quantify the number of countries that have integrated approaches to climate and urban policymaking, particularly with the goal of creating lower-carbon cities.

Nationally Determined Contributions (NDCs) and National Urban Policies (NUPs) have been used as proxies for climate and urban policies in this analysis. NDCs and NUPs are imperfect proxies. Many countries have coherent climate policies that are not fully recognised in their NDCs, while urban development is typically influenced by policies that fall outside the conventional purview of NUPs. However, NDCs and NUPs offer a useful indicator of the extent to which cities and climate change are considered in tandem, and they have two added advantages: (i) they can relatively straightforwardly be compared among countries; and (ii) comprehensive databases are already in place.

The results reflect: (i) the number of countries that identify low-carbon measures in cities as a means of reducing national greenhouse gas (GHG) emissions; (ii) the number of countries that identify decarbonisation of cities as part of their national urban agenda; and (iii) the number of countries that do both (i.e. that have integrated approaches to climate mitigation and urban policy).

Data

The methods and findings from the NDC analysis are documented in UN-Habitat's *Sustainable Urbanization in the Paris Agreement: Comparative review of nationally determined contributions for urban content*.[127] The detailed analysis covers 160 NDCs from 188 countries and regions (note that the European Union submitted a single NDC for its 28 members). The 160 NDCs were analysed by UN-Habitat and the University of Southern Denmark, who constructed a comprehensive database based on mentions of key economic, social and environmental issues. This database is not yet publicly available, but UN-Habitat and the University of Southern Denmark generously provided the Coalition for Urban Transitions with access to discrete sections pertinent to this report. Note that the UN-Habitat report also includes a more limited analysis of the NDCs for four additional countries (Cuba, South Africa, Timor-Leste and Uzbekistan), but detailed results for these countries were not included in the database. This explains why this report by the Coalition for Urban Transitions offers an assessment of 160 NDCs, while the UN-Habitat report offers an assessment of 164 NDCs.

The methods and findings from the NUP analysis are documented in UN-Habitat and OECD's *2018 Global State of National Urban Policy*.[128] This analysis covers 150 NUPs from individual countries. Of these, 42 NUPs are still in the feasibility and design phases, so they could not yet be assessed for their thematic scope. This analysis therefore focused on the 108 NUPs (or policies with many of the characteristics of a NUP) that were fully formulated at the time of publication. These 108 NUPs were analysed by the OECD team based on mentions of key economic, social and environmental issues.

Please note that the Coalition for Urban Transitions did not independently verify the contents of the databases.

Approach

The purpose of this analysis was to assess the extent to which NDCs and NUPs addressed climate mitigation.

Analysis of NDCs

The main variable used in the NDCs dataset is "reference to mitigation as a challenge". Values describing this variable answer the question: Is there any reference to *the challenge of* climate change mitigation? The answer can be No, Yes/Direct or Yes/Indirect.

The NDC dataset also had a variable, "Is there any reference to mitigation measures". This is a more stringent variable, requiring the NDCs to explicitly identify actions to reduce emissions from cities. In this analysis, the less stringent variable was used as a proxy.

Please note that, when urban adaptation and resilience are also taken into account as well as climate mitigation, 113 out of 164 NDCs show strong or moderate urban content.[129] Moreover, this analysis does not account for sectoral contributions to urban mitigation; for example, many more countries speak to climate mitigation in urban-relevant sectors such as buildings, transport and waste.

In the NUPs dataset

The main variable used in the NUPs dataset is the theme "environmental sustainability". The attention given to climate mitigation within each NUP is assessed using a three-point scoring system, where 3 is high, 2 is moderate, and 1 is low.

Please note that 12 countries gave extensive attention to climate resilience in their NUP, while 21 gave the issue moderate attention and 56 gave the issue low attention.[130] However, the number of countries giving attention to climate-related issues rises when the scope of the analysis includes resilience and adaptation ("climate resilience" in the dataset).

We then compared the results from the two databases to identify any countries that have both an NDC that makes a direct or indirect reference to climate change mitigation challenges in urban areas, and an NUP that pays high or moderate attention to climate change mitigation.

Limitations

This analysis is only looking at two specific national documents: NDCs and NUPs. These are imperfect proxies for the ambition or coherence of climate and urban policies, and most countries will have many additional policies and programmes in place that influence urban development and carbon intensity. However, these are useful proxies for three reasons:

1. NUPs and NDCs each serve a broadly similar purpose across regions, allowing international comparisons.
2. Comprehensive databases and reviews have already been conducted by reputable organisations in this space.
3. NUPs and NDCs usefully indicate national aspirations and commitments as much as concrete policy instruments and investments. This reveals the extent to which decision-makers are considering climate change and cities in tandem.

Further limitations to the methodologies are outlined in the reports that underpinned this analysis.[131]

Annex 10: Subsidies for fossil fuel consumption in urban areas

Analysis conducted by Ipek Gençsü and Sam Pickard (Overseas Development Institute)

Scope of analysis

This analysis provides a first-of-a-kind quantification of national and subnational subsidies that support unsustainable urban growth through fossil fuel consumption in urban areas in OECD[132] and BRIICS[133] countries. It covers the most recent data that were available at the time of analysis: 2015–2016.

Data

Raw data for fossil fuel support measures (subsidies) in 2015 and 2016 was extracted for all 36 OECD member countries[134] and the BRIICS countries (Brazil, India, Indonesia, China and South Africa) from the OECD Inventory of Support Measures for Fossil Fuel.[135] This was, as of January 2019, the most recent comprehensive dataset available. In using the OECD.Stat data, we adopt the World Trade Organization's definition of subsidies: "any financial contribution by a government, or agent of a government, that is recipient-specific and confers a benefit on its recipients in comparison to other market participants".[136] In this analysis, we equate support for consumption of fossil fuels in urban areas with support for unsustainable urban growth.

This analysis focuses on the largest quantified source of support from governments, which is fiscal support. Support is provided through direct spending by government agencies and tax breaks. Other sources of support, such as finance provided by public finance institutions and non-monetised support (such as political support), are not included, even though they are substantial.

Urban allocation

Data were rarely available in OECD.Stat to determine the proportion of each measure that specifically supported unsustainable growth in urban (as opposed to non-urban) areas. A considerable body of work is ongoing in an attempt to provide a universal definition of "urban", which currently varies between countries.

Following similar work estimating total urban greenhouse gas (GHG) emissions,[137] we used the European Commission's Global Human Settlement Layer (GHSL). This defines land as urban centres (cities or large urban areas), urban clusters (towns and suburbs or small urban areas) or rural.[138] The GHSL Urban Centres Database (GHS-UCDB)[139] provides CO_2 emissions from fossil fuel use in each urban centre from five sectors, including households, industry and transport.[140] This allowed us to account for different levels of consumption of fossil fuels in different sectors and contexts (using emissions as a proxy), rather than assuming uniform consumption of fossil fuels across the board.

Sectoral allocation

In many cases, there was insufficient information available in OECD.Stat to determine the exclusivity to a specific sector. Subsidies in OECD.Stat data are disaggregated by fuel type. Thus, exclusivity was approximated using the sector's proportional consumption of the fuel type to which the subsidy was attributed. In most cases, the consumption of the fuel by different sectors was sourced from the United Nations Statistics Division's Energy Statistics Database,[141] which provides data at a national level. This was used for all national and subnational subsidies, except in the few cases where subnational consumption data were available.

Approach

All the government support identified in this analysis was estimated using an inventory approach. This bottom-up method is highly detailed and reveals potentials for reform and policy change, because it focuses on individual policies and instruments.

Items extracted from OECD.Stat with a zero value in both years were excluded.[142] Using the database's metadata notes, each measure was assessed to identify whether it supported unsustainable urban growth through fossil fuel consumption in one or more of the five target sectors: transport; industry and commerce; households; public agencies and non-commercial entities; and fossil fuel-based power generation.

Subsidies with no obvious direct link to unsustainable urban growth (such as subsidies for consumption of fossil fuels in rural areas, for agricultural purposes, etc.) were excluded. In some cases, there was insufficient detail available to decide whether a subsidy related to unsustainable urban growth.[143] To overcome this, we followed a consistent methodology where we only included subsidies that had a plausible direct link to encouraging the consumption of fossil fuels in urban areas. This typically meant that we only included subsidies provided to consumers (including domestic, industrial and public sector) and to retailers. Table A.25 illustrates the range of measures and examples that were included in this analysis, and the specific sectors that they benefit. Table A.26 provides some examples of subsidies that were excluded from the analysis and the reasons for their exclusion. In some cases, although a direct link to consumption could be made for the subsidies, it was not possible to quantify how much of this would support consumption in urban areas, so those subsidies were excluded.

Table A.25. Examples of the subsidies to unsustainable urban growth in the assessed sectors through supporting fossil fuel consumption and fossil fuel-based electricity production

Type of subsidy	Examples
Consumption of fossil fuels in transport	Foregone tax revenue for the consumption of fossil fuels (including diesel, LPG and natural gas) for public and private transportation
	Foregone tax revenue from or direct support to petrol stations

Consumption of fossil fuels in business and industry	Foregone tax revenue energy-intensive or other specific processes
	Foregone tax revenue for electricity for commercial use
	Foregone tax revenue for the use of LPG and natural gas in industrial engines
	The free allocation of permits to industry under the European Union Emissions Trading Scheme
Consumption of fossil fuels by households	Free, discounted or tax-reduced energy (fossil fuels, heat and electricity)
	Direct spending on fossil-fuel-consuming infrastructure (e.g. boilers)
Consumption of fossil fuels by public entities	Programmes that promote the use of fossil fuels in public buildings (e.g. hospitals, emergency shelters)
	Free, discounted or tax-reduced energy for use in public sectors (fossil fuels, heat and electricity)
Production of fossil-fuel-powered electricity	R&D spending on themes that directly support fossil-fuelled power generation
	Grants and foregone tax revenue related to the construction of heat and power plants
	Relief on property taxes and normal business charges for land, water use and pollution for power plants
	Fiscal incentives and capacity markets[144] designed to promote the use of fossil fuels in power generation
	Compensation for providing subsidised fuels to end-users

Table A.26. Examples of subsidies to fossil fuel production and use that are not included in the analysis because no direct or quantifiable link could be made to urban consumption

Type of subsidy	**Examples**
Fuels consumed in rural sectors	Fuels consumed in agricultural, forestry, mining or marine sectors
Non-land-based fuels	Aviation and shipping (domestic and international)
Support for the production of fossil fuels	Royalty reductions, direct spending on decommissioning, exploration/production investment tax relief, upstream R&D, worker support packages, support for energy inputs to fossil fuel production
Support for the transmission, transport, distribution, quality assurance or security of supply of fossil fuels	Support for intermediate transport of fossil fuels (e.g. pipelines or transmission networks) or stockpiling of fossil fuels
Support for the consumption of fossil fuels in urban areas in other countries	Subsidies supporting coal-fired power plants overseas

General support for fossil fuels	Most R&D spending (the notable exception being support for fossil-fuelled electricity generation)

For subsidies with a direct link to unsustainable urban growth, relevant extracts of text from OECD.Stat were added to the data sheet to support the decision to include them.

The remaining subsidies were further interrogated to decide the proportion of each that was attributable to unsustainable urban growth ($S_{u,i}$). To estimate this proportion, the nominal value of each subsidy (S_{Total}) was multiplied by two factors:

- exclusivity (E_i; 0–100%); namely, how exclusively the subsidy supported the consumption of fossil fuels in each target sector(s); and
- the urban component of the subsidy (U_i; 0–100%); namely, how much of the subsidy is consumed by urban areas.

The values of E_i and U_i for each subsidy were determined in a cascade fashion. If the metadata included in OECD.Stat provided a clear indication of the sector to which a subsidy was targeted or its urban proportion, then this information was used. Otherwise secondary data (detailed below) was used.

Sectoral allocation (exclusivity)

As mentioned above, exclusivity was approximated using the sector's proportional consumption of the fuel type to which the subsidy was attributed. A sector's proportional consumption of the fuel was then determined in one of three ways (see below) depending on the information available in OECD.Stat and the fuel's consumption profile. Double-counting was avoided by attributing subsidies that could not be disaggregated between sectors to the dominant sector only, and by ensuring that the total value for the exclusivity of each subsidy across all duplicated lines (sectors) did not exceed 100%. Exclusivity to a sector was then calculated as the average of proportional consumption in 2015 and 2016 by the target sector.

Option 1: Metadata in OECD.Stat details that the subsidy was provided to specific sectors, but does not quantify the allocation between sectors.

- Exclusivity is calculated as the amount of fuel consumed by the target sector divided by the amount of fuel consumed by all sectors specified in the OECD.Stat metadata.

Option 2: Metadata in OECD.Stat does not detail the sectors to which the subsidy applies, and the fossil fuel is overwhelmingly consumed in the country as an energy-end product.

- Exclusivity is calculated as the amount of fuel consumed by the target sector divided by the "final energy consumption".

Option 3: Metadata in OECD.Stat does not detail the sectors to which the subsidy applies, and the fossil fuel is partially consumed in the country as an energy-end product and partially consumed as an intermediate input (e.g. as a feedstock for the production of industrial chemicals, the fuel used to generate heat or electricity, or fuel used for the energy industry's own use).

- Exclusivity is calculated as the amount of fuel consumed by the target sector divided by the "total energy supply".

Urban allocation

For households, industry and transport, the proportion attributed to urban centres was calculated by summing each sector's emissions from urban centres and dividing this by the national total of emissions from the sector. The fraction used for the households sector was also used to estimate the proportion of the national total of subsidies provided to public services in urban centres.

The GHS-UCDB database was not a good match for subsidies to fossil-fuelled electricity generation because most electricity consumed in urban centres is generated outside of them. Population data were therefore used as the proxy for electricity consumption in urban centres.

The GHS-UCDB database only provides data for urban centres, and not for urban clusters. Therefore, we used the above analysis to calculate the proportion of a subsidy flowing to cities. In addition, we also estimated the proportion of subsidies flowing to urban clusters or towns and suburban areas (i.e. all areas that are not "rural"). To do this, in absence of further data, we assumed *uniform* GHG emissions per capita for rural and suburban populations. We divided a sector's GHG emissions that were not emitted from urban centres equally among the non-urban-centre population. We then subtracted the urban-centre population from the nationally defined "urban" population to yield an estimate of the population in towns and suburbs. We then multiplied this fraction by the per capita value for a sector's GHG emissions to yield the GHG emissions for each sector from towns and suburbs. We added this to the emissions from urban centres and divided by the national total to yield a proxy for this broader interpretation of "urban".

Figure A.5 is a flowchart showing the calculation process, and Figure A.6 is a Venn diagram of the different terminologies used for different areas of population covered in this analysis.

Figure A.5. Flowchart showing the calculation process for quantifying allocation of subsidies to unsustainable urban development through fossil fuel lock-in

Note to designer: The first orange box here (last line) needs the quote marks removed

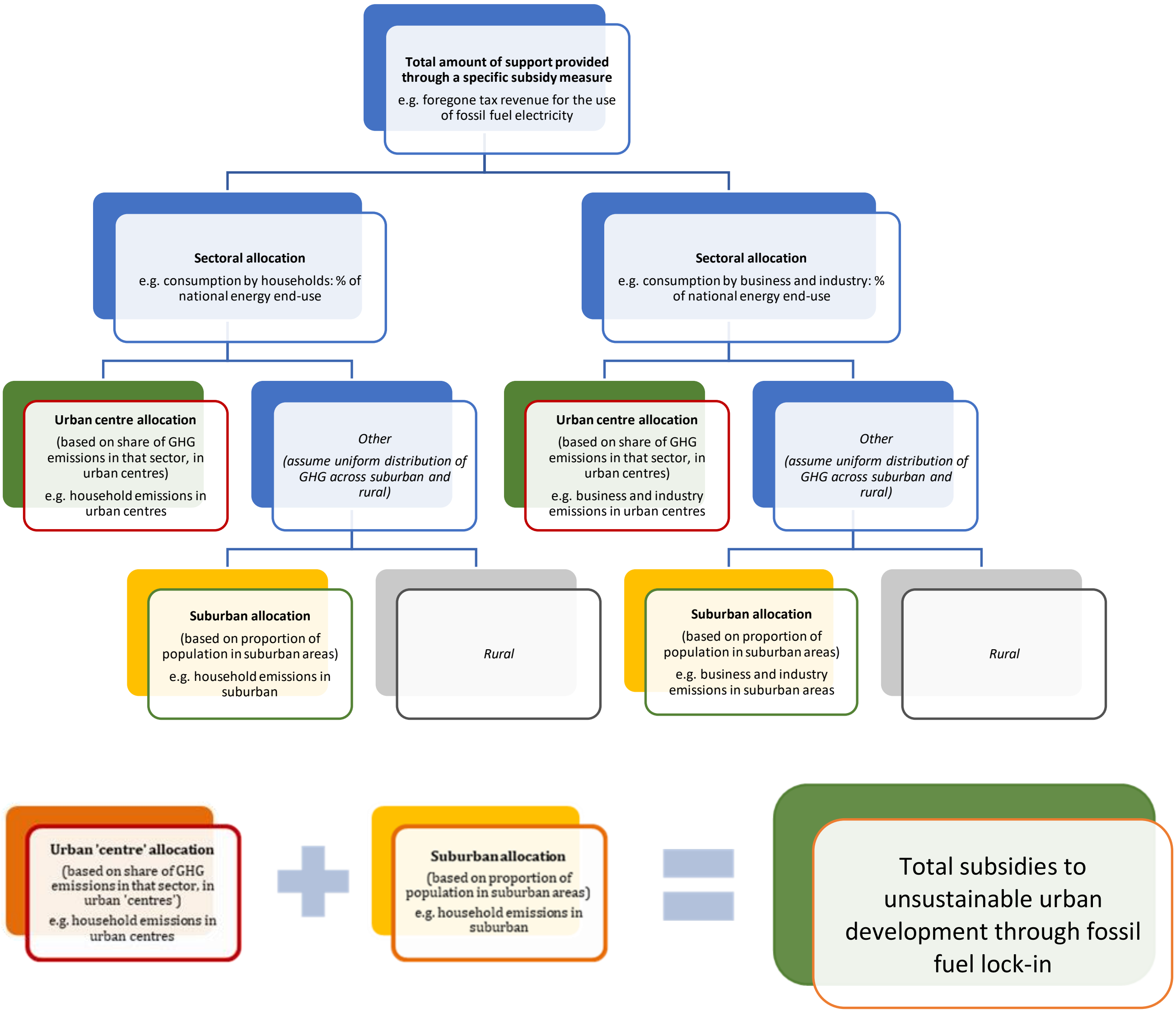
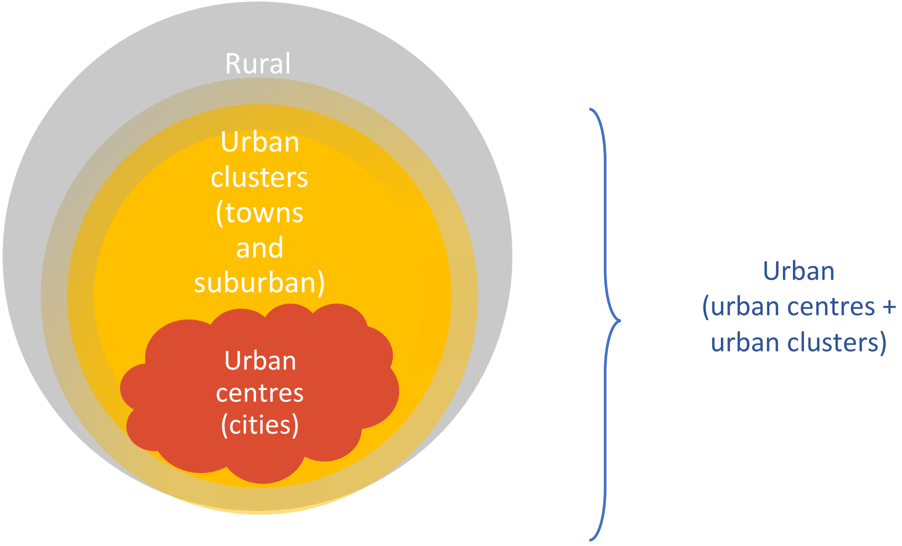


Figure A.6. Venn diagram showing the different scopes and terminologies for urban areas



Limitations

Our conservative approach to including subsidies in the analysis means that the values provided are likely an underestimate of government support for fossil fuel consumption in urban areas. The analysis is also limited by the availability of raw data. In the extreme cases, we found no subsidies supporting fossil fuel consumption in urban areas in two countries (Russia and New Zealand). As noted throughout the methodology, our analysis regarding the urban component of subsidies has been hampered by a lack of representative data.

Annex 11: Analysis of the climate-relevant powers of different tiers of government

Analysis conducted by Derik Broekhoff (Stockholm Environment Institute)

Scope of analysis

For this assessment, the Stockholm Environment Institute (SEI) investigated the relative ability of different levels of government to drive the adoption of low-carbon technologies and practices in urban areas, in different countries around the world. This assessment builds on an earlier analysis by SEI that examined how national and local governments could coordinate on policy actions needed to unlock urban greenhouse gas (GHG) abatement potential.[145] The previous analysis was global in scope and examined the potential for governmental "vertical integration" at a theoretical level. The current assessment refines this by examining the actual allocation of authority and governing capacity related to urban low-carbon interventions in a variety of countries with differing governing structures. It also assesses specific kinds of urban abatement technologies and practices in more detail.

The countries selected represent a range of governance structures, from federal (or quasi-federal) systems with a high degree of decentralisation, to unitary, more centralised systems (Table A.27).

Table A.27. Countries included in the analysis

Countries	Governmental structure
Mexico	*Federal or more decentralised*
USA	
South Africa	
France	↕
Canada	
India	
China	
UK	*More unitary and centralised*

The low-carbon measures included in this analysis were those identified for the other SEI analysis in this report (see Annex 1). These span energy supply, buildings, transportation, waste and urban infrastructure. By combining these assessments, SEI have estimated how much abatement can be achieved through nationally or locally led policy action, and how much may require improved vertical coordination among all levels of government.

Data

As noted, this analysis builds off prior work by SEI, including an assessment of the relative degree of local government influence over urban GHG abatement options,[146] using data from a survey of C40 cities and other sources.[147] It follows the methodological framework developed in Broekhoff et al. (2015),[148] which reviewed multiple sources related to multi-level governance applied to urban climate action.[149]

Primary source of data was a survey of experts familiar with the governance structures in the eight countries listed in Table A.27. Respondents were asked to evaluate which levels of government have the most influence over each of the identified low-carbon measures. Ratings were solicited on a five-point scale, ranging from primarily local government influence to primarily national or state-level influence (Table A.28). For the purpose of rating, no distinction was made between national and state influence.

Table A.28. Rating scale used for degree of influence

Survey question: Who has the most direct authority or ability to influence?	
1	Almost exclusively local/metro governments
2	Mostly local/metro governments
3	Equal ability/co-responsible
4	Mostly state/national governments
5	Almost exclusively state/national governments

A total of 10 survey responses were completed, covering the eight countries in Table A.27. Two responses each were received for both India and South Africa. For each country, the results of the two responses were averaged when analysing the final results.

Approach

Survey results were used to evaluate, for each country, whether local or higher-level governments have more ability to drive the adoption of different technologies and practices needed to reduce urban GHG emissions – or whether governing responsibilities related to these technologies and practices are shared. The eight countries were then ranked according to the sum of all survey ratings across all 27 technology/practice areas. Mexico had the lowest total score, indicating that – relative to other countries – local governments in Mexico have more power and authority to influence urban abatement outcomes. This accords with Mexico's more decentralised, federal system of government. The United Kingdom had the highest total score, reflecting its highly centralised system of government. Governmental systems for each country were characterised based on OECD and UCLG (2019)[150] and Rode et al. (2017).[151]

Survey results were averaged to generate a composite rating of governmental influence for each technology/practice area. Composite ratings were normalised to a nine-point scale, with the degree of local versus national influence assigned as in Table A.29.

Table A.29. Classification of composite survey scores related to governmental influence on urban abatement technologies and practices

Score range	Classification
1–3	Primarily local and metropolitan governments
4–6	Equal influence / co-responsibility
7–9	Primarily state and national governments

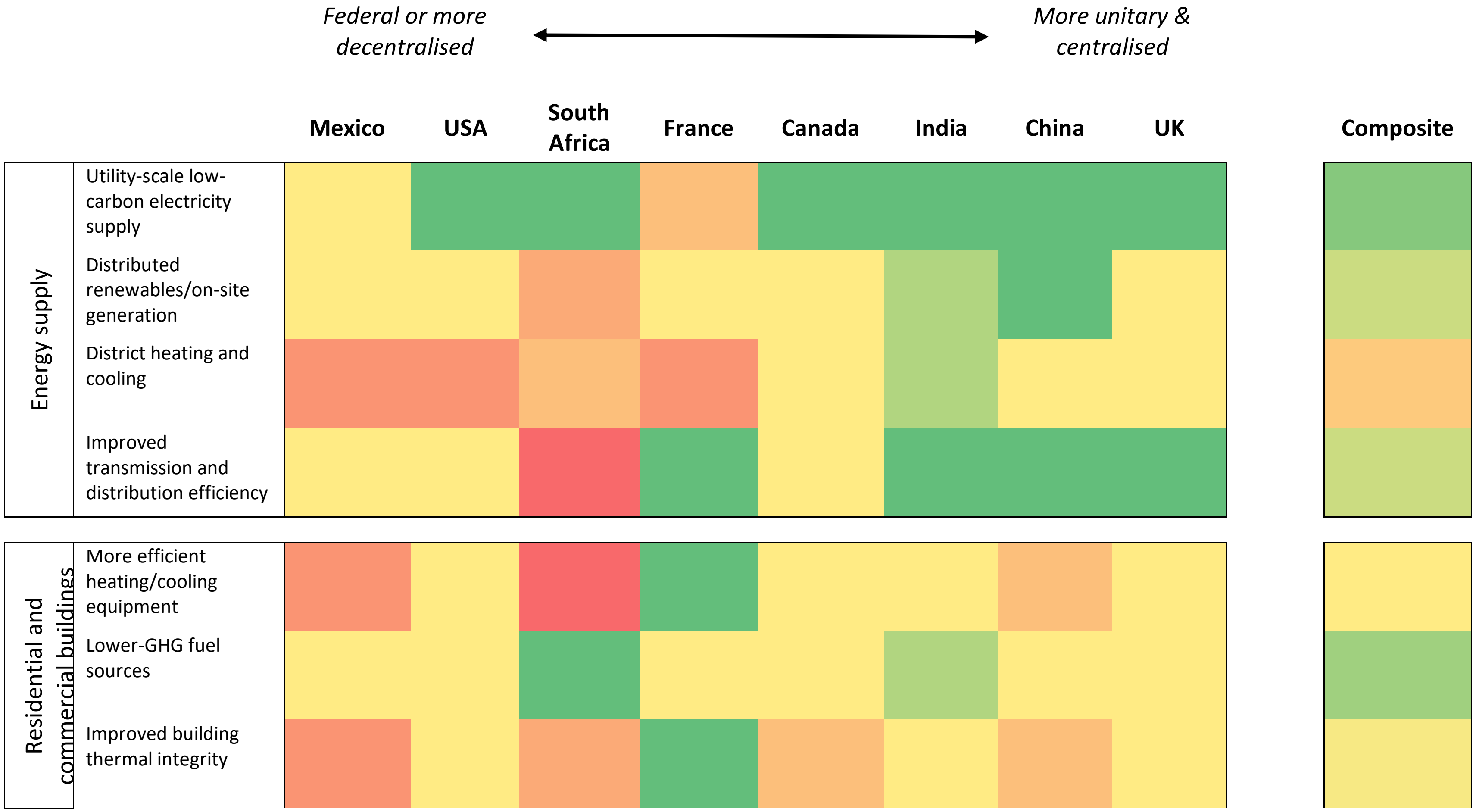
Each technology/practice area was assigned to one of the three classifications in Table A.29, based on its composite score. The global GHG abatement potential for each technology/practice area was determined from SEI's separate abatement potential analysis, for the years 2030 and 2050 (see Annex 1). This allowed an estimation of total GHG abatement potential associated with each category of governmental influence identified in Table A.29; specifically, abatement potential associated with policy action that (on average) would be: primarily locally led; primarily nationally led; or achieved through joint or coordinated efforts by local and higher-level governments.

Grouping state and national governments allowed us to distinguish between governmental bodies whose jurisdictions are exclusively or primarily urban from those with mixed urban & non-urban jurisdictions. Moreover, there are many different vertical configurations of government in different countries, we have therefore tried in this analysis to keep definitions fairly open.

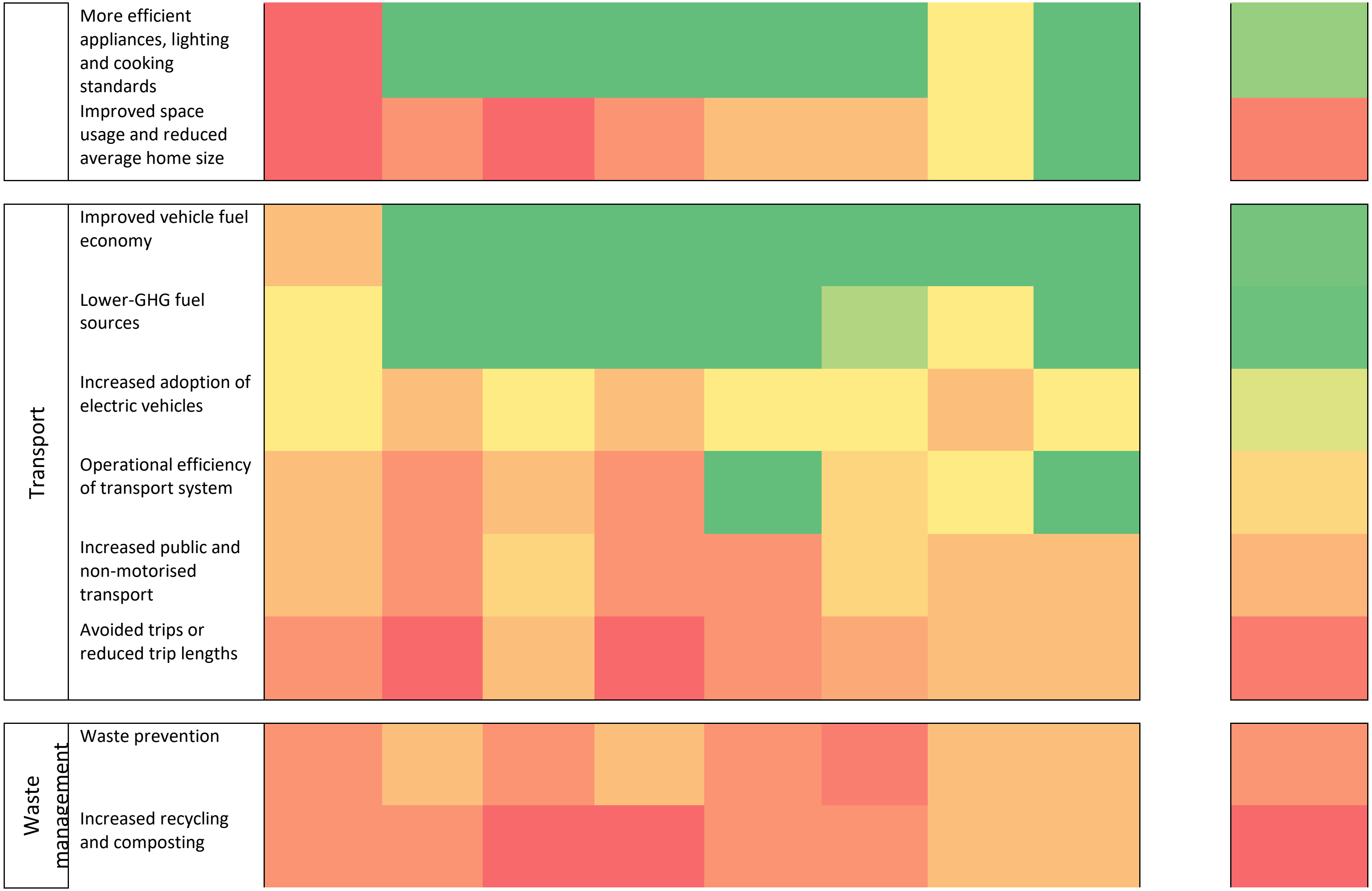
Selected results

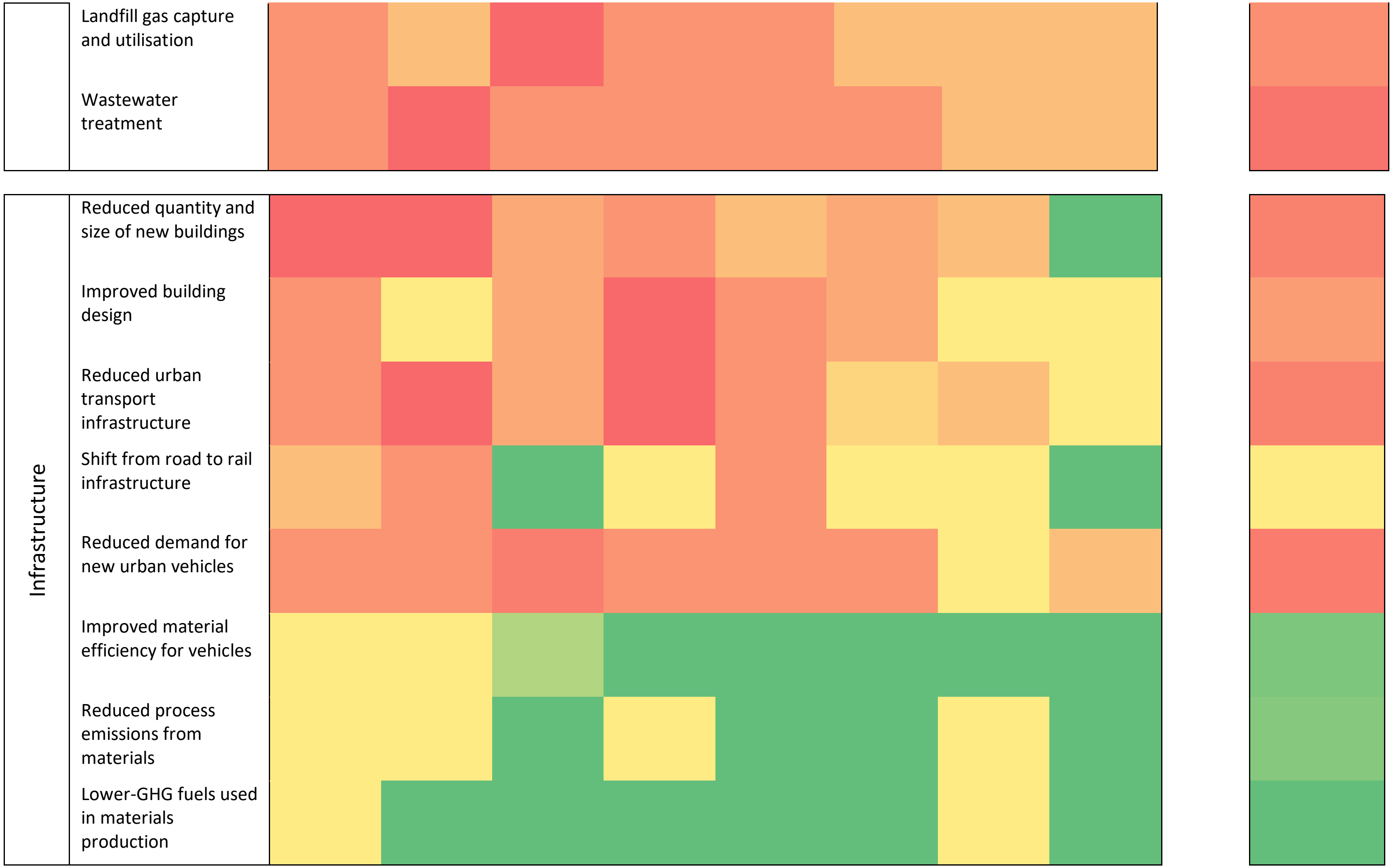
Table A.30 presents selected results for countries and regions of particular interest.

Table A.30. Relative ability of local vs. national governments to drive the adoption of low-carbon technologies and practices in urban areas



		Mexico	USA	South Africa	France	Canada	India	China	UK	Composite
Energy supply	Utility-scale low-carbon electricity supply	🟨	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩
	Distributed renewables/on-site generation	🟨	🟨	🟧	🟨	🟨	🟩	🟩	🟨	🟩
	District heating and cooling	🟧	🟧	🟧	🟧	🟨	🟩	🟨	🟨	🟧
	Improved transmission and distribution efficiency	🟨	🟨	🟥	🟩	🟨	🟩	🟩	🟩	🟩
Residential and commercial buildings	More efficient heating/cooling equipment	🟧	🟨	🟥	🟩	🟨	🟨	🟧	🟨	🟨
	Lower-GHG fuel sources	🟨	🟨	🟩	🟨	🟨	🟩	🟨	🟨	🟩
	Improved building thermal integrity	🟧	🟨	🟧	🟩	🟧	🟨	🟧	🟨	🟨


More efficient appliances, lighting and cooking standards
Improved space usage and reduced average home size
Transport
Improved vehicle fuel economy
Lower-GHG fuel sources
Increased adoption of electric vehicles
Operational efficiency of transport system
Increased public and non-motorised transport
Avoided trips or reduced trip lengths
Waste management
Waste prevention
Increased recycling and composting


Landfill gas capture and utilisation
Wastewater treatment
Infrastructure
Reduced quantity and size of new buildings
Improved building design
Reduced urban transport infrastructure
Shift from road to rail infrastructure
Reduced demand for new urban vehicles
Improved material efficiency for vehicles
Reduced process emissions from materials
Lower-GHG fuels used in materials production

Legend:

🟥 🟥 🟧	🟧 🟨 🟨	🟩 🟩 🟩
Primarily local & metro governments	Equal influence/ co-responsibility	Primarily state and national governments

Limitations

These initial results are based on a single survey of country experts familiar with governmental structures and policy arrangements in the eight countries that were targeted. The results should be considered indicative. Further analysis is needed to explore in more detail the kinds of policy coordination that is most needed to realise high-priority GHG abatement opportunities in different countries and within distinct categories of cities.

Acknowledgements

With warm thanks to the experts who completed the survey:

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- Manisha Gulati, formerly C40 Cities Climate Leadership Group
- Robin King, World Resources Institute
- Alice Mias, Energy Engineer
- Sue Parnell, African Centre for Cities / University of Bristol
- Stephanie Siehr, Lawrence Berkeley National Laboratory
- Andrew Sudmant, University of Leeds

Annex 12: The allocation of national inland transport budgets

Analysis conducted by Ipek Gençsü and Sam Pickard (Overseas Development Institute)

Scope of analysis

This analysis is looking at investments being made in roads versus railways in several socio-economically and geographically diverse countries. These levels of investment were used as an indication of the relative levels of support being provided for business-as-usual, road-based and individual motor use-based transport development, versus low-carbon and efficient modes which encourage public transport. This covers the most recent data available for 2014–2016.

Data and approach

The most comprehensive and recent data available were extracted from OECD.Stat for six out of the eight countries we reviewed (Australia, Canada, China, France, India and Mexico).[152] For those countries that were not included in the OECD database (Ethiopia and Tanzania), we used the data presented in the Global Infrastructure Hub's (GIH) Global Infrastructure Outlook.[153] The Outlook uses a range of sources to put together information on infrastructure investment in several key areas, including for roads and rail (as well as water, telecoms, energy, ports and airports). The main source of data used is the OECD database, and this is supplemented with information from government documents and other reliable national and international databases, where relevant. For more information on the range of sources used, please see the Global Infrastructure Outlook Full Report methodology notes.[154] Table A.31 below summarises the data sources for road and rail investments in each country.

Table A.31. Data sources for road and rail investments in the eight countries reviewed

	Road	**Rail**
Australia	OECD, 2014–2016, road infrastructure investment	OECD, 2014–2016, rail infrastructure investment
Canada		
China		
France		
India		
Mexico		
Ethiopia	International Road Federation 2000–2003, World Bank Ethiopia Public Expenditure Review, 2007–2013, road capital expenditure	World Bank Ethiopia Public Expenditure Review, 2005–2012, ERC capital spend
Tanzania	National Statistics, 2001–2013, gross fixed capital formation for roads and bridges	Econometric estimate*

**The only data point which does not have high level of reliability is the rail infrastructure investment for Tanzania, which was based on an econometric estimate of the GIH, as no other suitable data was available.*

Results

Table A.32 presents the results from the analysis.

Table A.32. Total budget for inland transport by country and investment type, 2014-2016 average

	Total transport budget (2014–16 average, US$ millions)	**Rail investments (2014–16 annual average, US$ millions)**	**Road investments (2014–16 annual average, US$ millions)**	**Motorway investment, as a sub-portion of road investments (2014–16 average, US$ millions)**	**Rail as percentage of total inland transport spending**	**Road as percentage of total inland transport spending**	***Motorway as percentage of total inland transport spending (a sub-component of road spending)***
Australia	16,269	3,792	12,477		23%	77%	
Canada	7,282	1,060	6,222		14%	86%	
China	532,001	128,110	249,466		23%	77%	
Ethiopia	2,521	139	2,382		6%	94%	
France	19,301	6,975	11,434	1,377	36%	59%	*7%*
India	25,994	11,708	14,286		45%	55%	
Mexico	6,110	1,312	4,797	1,476	22%	78%	*24%*
Tanzania	224	60	164		27%	73%	

Limitations

The most recent and comprehensive data sources available do not distinguish between public and private investments. According to the report of the Global Commission on the Economy and Climate,[155] in developing and emerging economies, about 60–65% of the cost of infrastructure projects is financed by public resources, while in advanced economies this figure is around 40%. However, the total infrastructure investment numbers still provide a strong indication of governments' priorities and key role when it comes to the type of development pathway followed. Government policy and regulation is key to determining where investments are made, whether through public budgets, through private–public partnerships, or through private entities.

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[3] IEA, 2017. *Energy Technology Perspectives 2017.* Organisation for Economic Co-operation and Development, Paris. Available at: http://www.oecd-ilibrary.org/content/book/energy_tech-2017-en. Hereafter referred to as ETP2017.

[4] Ürge-Vorsatz, D., Petrichenko, K., Antal, M., Staniec, M., Ozden, E. and Labzina, E., 2012. *Best Practice Policies for Low Carbon & Energy Buildings: A Scenario Analysis.* Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the Global Buildings Performance Network. Global Buildings Performance Network, Paris. Available at: http://www.gbpn.org/sites/default/files/08.CEU%20Technical%20Report%20copy_0.pdf.

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Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S. and Brattebø, H., 2013. *Carbon emissions of infrastructure development*. Environmental Science and Technology, 47(20). 11739–11746.

Grubler, A. and Fisk, D., 2012. *Energizing Sustainable Cities: Assessing Urban Energy*. Earthscan, London and New York.

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IEA, 2018. *World Energy Outlook 2018.* International Energy Agency, Paris. Available at: https://www.iea.org/weo2018/.

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Atalla, T., Gualdi, S. and Lanza, A., 2018. A global degree days database for energy-related applications. *Energy*, 143(C). 1048–1055.

[14] IEA, 2017. *Energy Technology Perspectives 2017*.

[15] Ürge-Vorsatz et al., 2012. *Best Practice Policies for Low Carbon & Energy Buildings*.

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[17] We assume that half of the solar PV in IEA's B2DS (IEA, 2017, *Energy Technology Perspectives 2017*) is distributed PV, and that the distributed PV is built in urban areas proportional to the share of urban population in each country analysed. For any given city, we limit generation capacity at the maximum level (0.5 W per m^2 of *land* area) identified by an assessment by the International Institute for Applied Systems Analysis (IIASA; Grubler and Fisk, 2012, *Energizing Sustainable Cities*).

[18] IEA, 2017. *Energy Technology Perspectives 2017*.

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Urban private vehicle travel activity is estimated by determining the ratio of urban private vehicle pkm for each region found in IEA (2013) to total private vehicle pkm in the ETP2014 "4DS" scenario, and applying this ratio to the total private vehicle pkm for each region in the RTS of ETP2017; urban bus and rail travel activity is determined by applying ratios of urban pkm for these modes to urban LDV pkm, based on the 4DS scenario found in ETP2016 (IEA 2016), for OECD and non-OECD countries.

Urban freight activity is estimated by applying ratios of urban to non-urban freight travel found in ETP2016 for OECD and non-OECD countries (4DS scenario) to the total freight travel reported in ETP2017 (RTS).

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[29] Eggleston et al., 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*.

[30] IEA, 2017. *Energy Technology Perspectives 2017*.

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[31] These data are reported at the global level. To allocate global production to the regions/countries found in ETP2017, we: (i) allocated production to OECD and non-OECD countries following the ratios reported in ETP2017 for total production of relevant materials (steel, aluminium and cement) for the OECD and non-OECD regions; and (ii) *within* OECD and non-OECD regions, determined shares of production for each ETP2017 country/subregion for each year based on a forward extrapolation of infrastructure material stock accumulation rates calculated from Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H., 2013. *Carbon emissions of infrastructure development*. Environmental Science & Technology, 47(20), 11739-11746.

Note that, due to data limitations, Pales et al. (2019) report only cumulative totals (2017–2060) for steel and cement use in road and rail networks. To convert these into annual amounts, we distributed the total change across individual years in proportion to the varying levels of global production for cement and steel projected in the ETP2017 RTS. These values should be considered indicative and subject to further revision based on future research.

Pales, A.F., Teter, J., Abergel, T. and Vass, T., 2019. *Material Efficiency in Clean Energy Transitions.* International Energy Agency. Paris, France. Available at: https://webstore.iea.org/material-efficiency-in-clean-energy-transitions.

[32] IEA, 2017. *Energy Technology Perspectives 2017*.

[33] IEA, 2017. *Energy Technology Perspectives 2017*.

[34] Pales et al., 2019. *Material Efficiency in Clean Energy Transitions*. "MEF" refers to the "materials efficiency" variant of the "Clean Technology Scenario" examined in this study.

[35] "CTS" refers to the Clean Technology Scenario examined by Pales et al (2019). For SEI's analysis, different scenarios are used either because results were only reported for the CTS (road and rail construction), or the CTS better reflects urban-focused policy measures (e.g. reduction of vehicle use due to urban policies). The MEF scenario applied to vehicles, for example, includes measures to improve design and reduce material use in vehicles, beyond simply reducing growth in vehicle demand. Such measures would be national in scope, and not primarily urban focused.

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[142] A zero value does not necessarily mean that these measures are no longer providing support to fossil fuel production and consumption. Instead, the measure may be dormant (for example, it may only be triggered when oil prices reach a certain level), or it might not have been possible to quantify the support during the years in focus. Even though these measures may have no monetary value in the years assessed, their existence confers a significant subsidy to fossil fuel consumption owing to their prospective value.

[143] For example, uncertainty can arise from the relationship between the subsidy and consumption, and its relationship with urban areas.

[144] A capacity mechanism is an administrative measure to ensure the desired level of security of supply by remunerating generators for the availability of resources (Erbach, G., 2017. *Capacity Mechanisms for Electricity*. European Union, European Parliamentary Research Service. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/603949/EPRS_BRI(2017)603949_EN.pdf). Support for capacity mechanisms is included in the data to the extent that it is covered by the OECD database. However, these measures are not captured in many of the country datasets.

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