Annex 1:
Technically feasible urban mitigation potential of buildings, transport, waste, and energy sectors

Method in brief

This analysis, conducted by the Stockholm Environment Institute (SEI), estimated global urban greenhouse gas (GHG) abatement potential using a bottom-up assessment of mitigation options. The approach quantified the emission reductions that can be achieved in urban areas across three sectors – buildings, transport, and waste – by comparing emissions under two sets of scenario assumptions running from 2015 to 2050: a "reference" scenario based on energy consumption and emissions projected in the 2017 *Energy Technology Perspectives*[1] from the International Energy Agency (IEA); and an "urban action" scenario informed by the IEA's "below 2 degrees" (B2DS) scenario and other sources, including the Global Buildings Performance Network,[2] the Institute for Transportation and Development Policy[3] and others.[4]

Globally, the analysis suggests that annual urban GHG emissions in buildings, transport, and waste could be reduced by 89% by 2050, using technically feasible abatement options. This constitutes nearly 45% of the abatement needed – beyond what countries have already pledged to do under the Paris Agreement[5] (see Box 1) – to keep energy-related CO_2 emissions in line with the IEA's global B2DS scenario.

Scope of analysis

This analysis assessed 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 were 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 SEI in 2014.[6] The 2014 study estimated the 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:

- It expressly focuses on mitigation outcomes in line with a "below 2°C" scenario (consistent with a 50% chance of limiting warming to no more than 1.75°C, as defined by the IEA in ETP 2017), rather than the 2°C scenario considered in the prior study. At the time that this analysis was conducted, the IEA had not yet published a 1.5°C scenario.
- 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.
- 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, such as 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 GHG reductions needed for the world to avoid more than 2°C of warming than the 2014 analysis.

Box 1. Defining an appropriate baseline for assessing mitigation potential

SEI's analysis assesses urban greenhouse gas mitigation potential against a specific *baseline scenario* (the "reference case"), which indicates a likely trajectory for GHG emissions in the absence of any *additional* mitigation actions by countries and subnational governments. This baseline was chosen because the purpose of the analysis is to answer the question, "What level of GHG abatement could be achieved in urban areas *beyond* what countries have already pledged?"

This is different from the questions posed (explicitly or implicitly) in other analyses, such as "What abatement could be achieved relative to a scenario where there is *no* future action to reduce emissions?" or even "…relative to a scenario where there is no change in technologies or practices?" It is also different from assessing potential GHG reductions against a *base year* (such as 2015 emissions).

In some countries, absolute emissions might decline only slightly by 2050 relative to current levels, but this decline could be the result of major efforts to avoid *what would have been much higher* future emissions. These differences should be kept in mind when comparing the results of SEI's analysis with those found in other studies. Transparency around the questions being asked – and the baselines being used – is critical to properly understand abatement potential estimates and how they compare.[7]

Some important qualifications are needed to put SEI's abatement estimates in proper context. First, as noted above, the analysis looked exclusively at **GHG emissions arising from activity and energy use in the urban buildings, transportation and waste sectors.** This consists of all energy-related CO_2 emissions – including those from cement and aluminium production – as well as CH_4 emissions from landfills. This is only a subset of the total emissions that could be attributed to urban areas. In particular, it excludes a large portion of emissions from industry (energy and process-related) located in urban areas.[8] It also excludes urban-area agriculture or land-use change and forestry emissions. This means the analysis does not address all GHG emissions that might typically be included in a city GHG inventory, such as black carbon, SOx, and NOx[9] (e.g., following the *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories*[10]). However, **these sectors were chosen because they are directly related to urban form and function**, rather than being only incidentally urban (e.g. industry). Addressing emissions in these sectors will require coordinated actions with local governments to pursue low-carbon models of urban development.[11]

Although the focus is on urban buildings, transportation, and waste, life-cycle emissions from fossil fuel combustion are included in the analysis (including extraction, transportation, and combustion of fuels), as well as upstream emissions from production of materials consumed in urban areas (specifically: cement, steel and aluminium used in urban infrastructure, as well as goods subject to waste prevention and recycling measures). This means the analysis addresses key sources of “Scope 3” emissions for these sectors. Table A1.1 summarises the scope of GHG emissions included in the analysis.

Second, **the analysis used a variety of assumptions to allocate national activity data, energy use and fuel use to urban areas**. These assumptions are summarised in Table A1.1, with more detailed descriptions of the methods used provided below in Tables A1.5–8. Although these assumptions were informed by data from a variety of studies, they may not always accurately reflect country-specific circumstances or coincide with definitions of “urban” areas found in other cross-national studies. In particular, national activity data for buildings, waste and infrastructure materials were allocated to urban areas in proportion to each country’s ratio of urban population to total population; see the next qualification, below.

Table A1.1. Scope of urban GHG emissions included in the abatement analysis

Sector	GHG emissions included	How data were assigned to urban areas
Buildings	Lifecycle CO_2 emissions from fossil fuels used directly in buildings CO_2 emissions from electricity consumption in buildings	Square metres of *national* floor space per capita derived from ETP 2017 Urban residential floor space per capita assumed to be the same as national; total urban floor space calculated from UN urban population estimates 90% of national commercial floor space assumed to be in urban areas In OECD countries, energy intensities and fuel use for both residential and commercial buildings in urban areas follow national averages In non-OECD countries, IEA's national averages adjusted based on data for the rural/urban splits of electricity access and traditional biomass use
Transportation	Lifecycle CO_2 emissions from fossil fuels used in vehicles CO_2 emissions from electricity used by electric vehicles	National motorised travel activity – passenger-km (pkm) for passenger transport and tonne-km (tkm) for freight – was derived from ETP 2017. Urban-specific activity was calculated using estimates of the ratio of urban to national travel by mode, derived from projections in IEA, 2013,[12] and IEA, 2016.[13]
Waste	CH_4 emissions from landfills subject to gas capture and utilisation CO_2 emissions from electricity displaced by landfill gas use Lifecycle CO_2 emissions from fossil fuels used in production of goods and materials subject to waste prevention and recycling measures	Urban waste generation per capita is assumed equal to national per capita waste generation, derived from IPCC Waste Model[14]
Materials	Lifecycle CO_2 emissions from fossil fuels used in production of cement, steel and aluminium for urban infrastructure (buildings, road and rail networks and vehicles) CO_2 process emissions from cement and aluminium production used in urban infrastructure	National production levels for cement, steel and aluminium used in buildings, vehicles, and road and rail construction derived from Pales et al., 2019.[15] National production allocated to urban areas based on population (applying the ratio of urban to total population in each country), as well as relative rates of urban infrastructure stock accumulation found in Müller et al., 2013.[16]

Finally, urban areas – and associated urban populations – were defined according to the classifications used in the UN *World Urbanization Prospects*.[17] These classifications are self-determined by national statistical offices in each country, which leads to some inconsistency in how urban areas are defined among different countries. In particular, the urban share of emissions may appear smaller in countries that use narrower definitions of "urban" (e.g. by excluding informal settlements or peri-urban areas). While this makes strict comparisons *between* countries challenging, it aligns our analysis with how individual countries approach urban policymaking. Table A1.2 indicates the 2015 share of urban population in each of six countries examined in our analysis, as well as globally, according to the classifications used in our analysis.

Table A1.2. Share of urban population by country and globally

Country	**Share of population classified as urban in 2015**
Brazil	86%
China	56%
India	33%
Indonesia	53%
Mexico	79%
South Africa	65%
World	54%

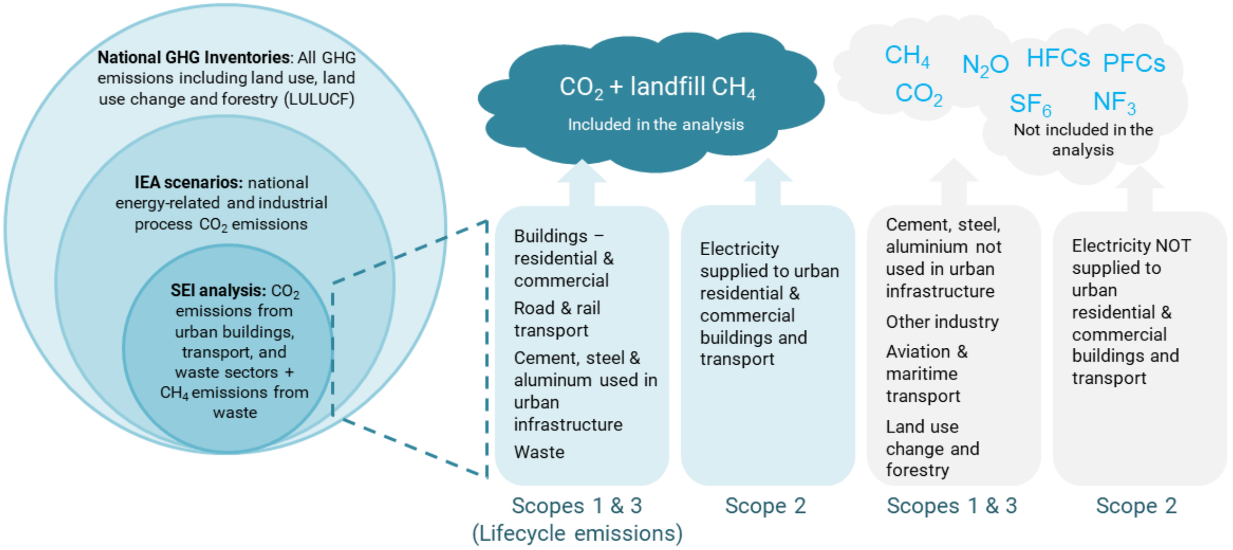
Because of the particular focus of SEI's analysis – on a subset of urban sectors and activities, using classifications of urban areas as found in UN World Urbanization Prospects data – estimates of "urban" emissions represent only a portion of emissions that may be attributed to urban areas in other analyses. According to the IPCC, for example, evidence suggests about 76% of CO_2 emissions from global final energy consumption can be attributed to urban areas.[18] The subset of emissions covered by SEI's analysis are equivalent to about 40% of 2015 global CO_2 emissions from final energy consumption, as reported in ETP 2017. Table A1.3 indicates how this subset of emissions compares to total national GHG emissions in 2015 for six countries and the world. Figure A1.1 visually breaks down SEI's analysis within the scope of urban related GHG emissions even further.

Note that for highly forested countries, such as Brazil and Indonesia, emissions from urban buildings, transportation and waste are a fairly small percentage of total national emissions, including emissions from land use, land use change and forestry (LULUCF). However, they are still a quite significant as a share of national energy-related emissions, and their significance will grow over time as these countries continue to urbanise. This highlights the importance of urban-focused policies for controlling emissions, even for major forested countries.

Table A1.3. Share of GHG emissions covered by SEI analysis of urban buildings, transportation and waste sectors

Baseline – 2015	**Total GHG emissions including land use, land use change and forestry (LULUCF)**[19]	**Total energy-related CO_2 emissions**	**GHG emissions (CO_2 and landfill CH_4) from urban buildings, transport and waste sectors**[20]	**Energy-related CO_2 emissions as share of total GHG emissions including LULUCF**	**Urban share of total energy-related CO_2 emissions**	**Urban share of total GHG emissions, including LULUCF**
Units	Mt CO_2	Mt CO_2	Mt CO_2	%	%	%
Brazil	1,410	528	221	37%	42%	16%
China	11,584	10,271	3,003	89%	29%	26%
India	3,177	2,280	565	72%	25%	18%
Indonesia	2,779	626	264	23%	42%	10%
Mexico	678	465	260	69%	56%	38%
South Africa	495	454	131	92%	29%	27%
World	49,855	34,372	13,749	69%	40%	28%
Data sources and calculation	CAIT in Climate Watch GHG Database[21]	IEA ETP 2017 in SEI modelling	SEI estimate based on ETP 2016 assumptions of urban share of energy emissions using ETP 2017 data for 2015	Total energy-related GHG emissions divided by total GHG emissions	GHG emissions from urban buildings, transport and waste sectors divided by total energy-related GHG emissions	GHG emissions from urban buildings, transport and waste sectors divided by total GHG emissions

Figure A1.1. Scope of urban GHG abatement analysis based on SEI assumptions



Note: ***Scope 1*** *covers emissions arising directly from an urban activity and/or source.* ***Scope 2*** *covers emissions that result from the generation of electricity, heat or steam consumed in urban areas.* ***Scope 3*** *covers emissions occurring as a result of an urban activity (other than electricity consumption), but not directly within urban boundaries. For a detailed explanation of the three scopes and the boundaries of urban GHG emissions used here, see Fong et al., 2014.*[22]

Methods and approach

SEI estimated global urban GHG abatement potential using a bottom-up assessment of mitigation options, a widely used approach in energy and climate modelling.[23] The approach quantified the emission reductions that can be achieved in urban areas across four sectors – buildings, transport, waste and material use in urban infrastructure – by comparing emissions at five-year intervals under two sets of scenario assumptions running from 2015 to 2050.

SEI's reference scenario was based on energy consumption and emissions projected in the 2017 Energy Technology Perspectives (ETP 2017) from the International Energy Agency (IEA),[24] specifically the Reference Technology Scenario (RTS).[25] This provides data for the major world regions listed in Table A1.4. The RTS assumes no further climate action in cities beyond current trends and commitments. However, current commitments include pledges reflected in countries' first round of Nationally Determined Contributions (NDCs) under the Paris Agreement. This means that the abatement potential modelled by SEI represents what could be achieved *above and beyond* the initial NDCs. But the baseline does *not* reflect more recent commitments, including increases in ambition in the second round of NDCs submitted in 2020–2021.

As explained above, SEI downscaled the IEA's projections 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,[26] the Institute for Transportation and Development Policy[27] and others.[28] For residential building floor space, waste generation activity, and cement, steel and aluminium production, downscaling to urban areas was done based on the ratio of urban population to total population; urban population data and projections were taken from the UN *World Urbanization Prospects*,[29] which follows the latest definition used in each country.

Table A1.4. Regions and Countries Modelled in ETP 2017

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

Following the reference scenario, SEI developed a mitigation scenario by applying a set of aggressive technology and practice assumptions to curb urban energy use and emissions in the buildings, transportation and waste sectors. Where possible, SEI used the IEA's Beyond 2°C Scenario (B2DS) as a guide,[30] so that the urban mitigation scenario is consistent with a future that limits global temperature change to well below 2°C. At the time of this analysis, the IEA had not yet modelled a 1.5ºC scenario, but the B2DS calls for an unprecedented policy effort to achieve energy sector carbon neutrality by 2060.[31] IEA defines the B2DS as follows:

> *In the B2DS, the energy sector reaches carbon neutrality by 2060 to limit future temperature increases to 1.75°C from pre-industrial levels by 2100, the midpoint of the Paris Agreement's ambition range. This pathway implies that all available policy levers are activated throughout the outlook period in every sector worldwide. This would require unprecedented policy action as well as effort and engagement from all stakeholders*.

SEI's 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, SEI 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 A1.5–8, we present the sector-specific data and assumptions used for each of these three drivers, for both the reference and mitigation scenarios.

Data and assumptions

Table A1.5 Buildings

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 UN *World Population Prospects*[32] and IEA estimates.[33] SEI assumed that residential floor space per capita is the same in both urban and rural areas, while for commercial floor space, SEI followed the assessment of the Global Buildings Performance Network that 90% of commercial floor space is in urban areas.[34]	In OECD countries, SEI 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, SEI adjusted IEA's national averages based on data concerning the rural/urban splits of electricity access and traditional biomass use.[35] For all urban areas, the energy intensity of heating and cooling demand was adjusted linearly[36] from population-weighted national averages[37] 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 ETP 2017. Emissions associated with the production of electricity in each region are calculated per kWh of consumption, from the Reference Technology Scenario (RTS) of the same source. SEI further adopt IEA's assumption that biomass, waste and commercial heat are assigned zero GHG emissions.[38]	Greater adoption of net-zero energy buildings, achieving "passive house" levels of energy use for heating and cooling;[39] deep energy retrofits of building shells on 1.4% of 2015 building stock per year in early years, 3% in later years.[40] Electrification of end uses, including space heating, water heating and cooking, following the IEA B2DS scenario. Electric 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 scenario.[41] GHG intensities of energy follow IEA B2DS scenario, including for electricity. Increased adoption of rooftop and building-integrated solar PV.[42]

Table A1.6 Transport (Passenger and Freight)

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 ETP 2017 with the urban component identified using data in IEA, 2013, and IEA, 2016.[43] 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 ETP 2017.	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 are estimated from the RTS of ETP 2017. GHG intensities of fuels and electricity are derived from the RTS of ETP 2017. For biofuels, SEI assumed a gradual transition to advanced net-zero emission fuel by 2050. Fossil fuel emission factors are based on well-to-wheel lifecycle estimates derived from multiple studies.[44]	The need for motorised travel (measured as pkm and tkm/capita) substantially reduced through logistics improvements for freight,[45] and a combination of national and local policies driving reduced passenger and freight travel demand, including rapid expansion of cycling.[46] Greater shift to mass transit, as reflected the B2DS of ETP 2017. 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 A1.7 Waste

Reference case activity levels	Reference case energy and GHG intensities	Mitigation actions
Urban waste generation over time followed trends projected in Kaza et al., 2018, through 2050.[47] Quantities of waste generation, in tonnes per capita, were based on IPCC Waste Model defaults for different world regions.[48]	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[49] 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 utilise 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 are assumed constant, including collection rates, degradable organic content (DOC) and the fraction of DOC that decomposes.[50] For recycling, emissions avoided represent a share of the emission intensities (tCO_2e/t product) of production for paper, steel, aluminium and plastics, derived from the RTS of the ETP 2017. 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 A1.8 Material use in urban infrastructure

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 "reference technology scenario" (RTS) in Pales et al., 2019.[51] Total production levels for buildings, vehicles, and road and rail construction are allocated to urban areas based on population (applying the ratio of urban to total population in each ETP 2017 region), as well as relative rates of urban infrastructure stock accumulation found in Müller et al., 2013.[52]	Energy intensities for the production of steel, cement and aluminium are derived from global energy use per tonne of production found in the RTS of ETP 2017.	GHG emissions intensities of coal, oil, natural gas and electricity used in the production of steel, cement and aluminium were all derived from the ETP 2017, with specific scaling factors (applied to direct CO_2 emissions and derived from life cycle studies for each fuel) to account for upstream emissions from fossil fuel extraction. Process emission rates for cement and aluminium were calculated from ETP 2017 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 material efficiency scenario (MEF) in Pales et al., 2019;[53] 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).[54] National-level policies drive reductions in the energy intensity of production for steel, cement and aluminium, following the IEA B2DS scenario. Reductions in process emissions derived from the B2DS scenario, using the same methods as applied in the reference case.[55]

Limitations

Projections for the reference and urban action 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 scenario. SEI applied results from a range of different studies to calibrate assumptions for the urban action scenario. Though SEI checked to ensure broad consistency with other low energy-demand scenario analyses,[56] the results are not the product of a single, consistent techno-economic scenario model. Finally, in various instances, SEI had to make assumptions about the data underlying IEA projections, including fuel mixes for different end uses. Uncertainties also arise from assumptions used to assign activity levels and associated energy consumption to urban areas. The results of this analysis – especially at the level of individual countries – should be considered indicative of the magnitude of potential abatement opportunities, not a definitive scenario.

Modelling results for individual countries

As noted above, SEI relied on scenarios developed in the IEA's 2017 *Energy Technology Perspectives* to inform its own reference and mitigation case analysis of GHG abatement potential in urban areas. The IEA provides scenario results for seven individual countries, two regional groupings (the European Union and ASEAN), and for all OECD and all non-OECD countries (Table A1.4). For five of the six countries explicitly examined in the analysis, therefore – Brazil, China, India, Mexico and South Africa – the results are country-specific, in that they reflect country-specific activity levels, energy intensities and GHG emissions intensities as derived from the IEA scenario results. (IEA's results, in turn, are derived from country-specific baseline data used in IEA's energy and emissions scenario models.)

The sixth country examined, Indonesia, is part of the Association of Southeast Asian Nations (ASEAN). To obtain results for Indonesia, SEI downscaled ASEAN-wide results in proportion to Indonesia's share of ASEAN's total urban population. (About 45% of the ASEAN region's total urban population is in Indonesia.) SEI then compared these results with readily available country-specific data. SEI concluded that the downscaled results are sufficiently representative to give a sense of the magnitude of urban abatement opportunities in Indonesia. One modification was made to the model, which was to use Indonesia-specific electricity emission factors, reflecting the higher carbon intensity of Indonesia's power sector compared with the ASEAN average. Changes in this emission factor over time were modelled to follow the same trajectory as IEA's power sector scenario results for ASEAN as a whole.

For all the countries examined, one question is whether the results accurately reflect energy usage and emissions in urban areas. The ETP 2017 scenario results are reported at a national or regional level, not broken out into urban versus non-urban areas.[57] Thus, SEI had to use various assumptions – detailed in Tables A1.5–8 – about what proportion of national energy use, motorised travel, waste production and materials consumption is associated with urban areas.

Another source of uncertainty is the specific mix of fuel types for each end use represented in the model. The ETP 2017 reports scenario results for total fuel consumption of each type across all end uses, and for total energy consumption (regardless of fuel) within each end use. It does not report the fuel mix assumed for each end use. SEI used various assumptions to approximate a reasonable fuel mix for different building energy uses and for transportation fuels by mode and vehicle class. However, the results may not correspond with the actual fuel mixes assumed within IEA's models, nor with country-specific data.

For the waste sector, SEI relied primarily on studies that reported results for different world regions, but not for specific countries. Thus, another source of uncertainty is how well these regional data correspond with actual circumstances in each country.

Table A1.9 summarises the most significant uncertainties within each urban sector in our model.

Table A1.9. Significant sources of uncertainty in SEI's model of urban GHG abatement

Source of uncertainty	**Buildings**	**Transport**	**Waste management**	**Infrastructure construction**
Representativeness of input data at the country level	(Indonesia)	(Indonesia)	X	(Indonesia)
Assignment of data to urban areas	X	X	X	X
Fuel mix within each end use	X	X		

X = possible source of uncertainty for all countries.

To investigate how significant these uncertainties are, SEI looked for country-specific data to cross-check our inputs and results. SEI found no major discrepancies in electricity emission factors, urban population estimates, or urban floor space estimates. SEI was unable to find readily available sources for urban-specific transport activity data (passenger-kilometres by mode or tonne-kilometres for freight). The most significant discrepancies were in the fuel mix estimates derived for certain end uses in three countries (Indonesia, China and Mexico).

Notwithstanding these uncertainties, the modelling results should be sufficient for their intended purpose, which is to provide an indication of the magnitude of potential abatement opportunities in urban areas in the countries examined.

Endnotes

[1] IEA, 2017, *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. For a glossary of definitions used in ETP 2017, see Annex C of the IEA report, or go to http://www.iea.org/etp/etp2017.

[2] Ürge-Vorsatz et al., 2012, "Best Practice Policies for Low Carbon & Energy Buildings: A Scenario Analysis."

[3] Mason, Fulton, and McDonald, 2015, "A Global High Shift Cycling Scenario: The Potential for Dramatically Increasing Bicycle and E-Bike Use in Cities Around the World, with Estimated Energy, CO2, and Cost Impacts"; Replogle and Fulton, 2014, "A Global High Shift Scenario: Impacts and Potential for More Public Transport, Walking, and Cycling with Lower Car Use."

[4] Creutzig et al., 2016, "Urban Infrastructure Choices Structure Climate Solutions," *Nature Climate Change;* Hickman and Banister, 2014, *Transport, Climate Change and the City*; Müller et al., 2013, "Carbon Emissions of Infrastructure Development," *Environmental Science & Technology*; Grubler and Fisk, 2012, *Energizing Sustainable Cities: Assessing Urban Energy.*

[5] SEI's reference scenario was based on IEA's ETP 2017 Reference Technology Scenario (RTS), which takes into account today's commitments by countries to limit emissions and improve energy efficiency, including in NDCs submitted under the Paris Agreement. By factoring in these commitments and recent trends, the RTS already represents a major shift from a historical "business as usual" approach with no meaningful climate policy response. The abatement estimates presented here therefore represent additional potential beyond what countries have already pledged, especially because the NDCs to date have included very few urban actions.

[6] Erickson and Tempest, 2014, "Advancing Climate Ambition: How City-Scale Actions Can Contribute to Global Climate Goals."

[7] Erickson and Broekhoff, 2017, "Baselines for Assessing Urban GHG Abatement Need to Be Transparent," *Stockholm Environment Institute* (blog).

[8] The analysis includes abatement from avoiding industrial GHG emissions associated with the production of materials for urban infrastructure (cement, steel and aluminium), but does not distinguish between urban and non-urban production capacity.

[9] Blanco et al., 2014, "Drivers, Trends and Mitigation," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

[10] Fong et al., 2014, "Global Protocol for Community-Scale Greenhouse Gas Emission Inventories: An Accounting and Reporting Standard for Cities."

[11] Broekhoff, Piggot, and Erickson, 2018, "Building Thriving, Low-Carbon Cities: An Overview of Policy Options for National Governments."

[12] IEA, 2013, "A Tale of Renewed Cities: A Policy Guide on How to Transform Cities by Improving Energy Efficiency in Urban Transport Systems."

[13] IEA, 2016, "Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems."

[14] IPCC, 2006, *2006 IPCC Guidelines for National Greenhouse Gas Inventories.*

[15] Pales et al., 2019, "Material Efficiency in Clean Energy Transitions."

[16] Müller et al., 2013, "Carbon Emissions of Infrastructure Development," *Environmental Science & Technology*.

[17] UN DESA, 2018, "World Urbanization Prospects: The 2018 Revision."

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[18] Seto et al., 2014, "Human Settlements, Infrastructure and Spatial Planning," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

[19] The unit of analysis is urban areas, as defined by national statistics reported to UN DESA, and does not include further distinction of degrees of urbanisation such as metro, non-metro, towns, and the like.

[20] Note that materials produced for urban infrastructure in the buildings and transportation sectors are also considered in the total for GHG emissions.

[21] Climate Watch GHG Database. All GHG emissions rounded to nearest whole number. Accessed November 10, 2020: https://www.climatewatchdata.org/ghg-emissions?end_year=2016&regions=WORLD%2CBRA%2CCHN%2CIND%2CIDN%2CMEX%2CZAF&sectors=total-including-lucf&start_year=1990

[22] Fong et al., 2014, "Global Protocol for Community-Scale Greenhouse Gas Emission Inventories: An Accounting and Reporting Standard for Cities."

[23] IEA, 2018, "World Energy Outlook 2018"; IPCC, 2014, "Summary for Policymakers," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; GEA, 2012, *Global Energy Assessment – Toward a Sustainable Future*.

[24] IEA, 2017*, Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*.

[25] In addition to energy-related CO_2 emission totals, IEA included CO_2 process emissions from cement and aluminium production as well.

26 Ürge-Vorsatz et al., 2012, "Best Practice Policies for Low Carbon & Energy Buildings: A Scenario Analysis."

[27] Mason, Fulton, and McDonald, 2015, "A Global High Shift Cycling Scenario: The Potential for Dramatically Increasing Bicycle and E-Bike Use in Cities Around the World, with Estimated Energy, CO2, and Cost Impacts"; Replogle and Fulton, 2014, "A Global High Shift Scenario: Impacts and Potential for More Public Transport, Walking, and Cycling with Lower Car Use."

[28] Creutzig et al., 2016, "Urban Infrastructure Choices Structure Climate Solutions," Nature Climate Change; Hickman and Banister, 2014, *Transport, Climate Change and the City*; Müller et al., 2013, "Carbon Emissions of Infrastructure Development," *Environmental Science & Technology*.

[29] UN DESA, 2018, "World Urbanization Prospects: The 2018 Revision."

[30] The B2DS was first presented in ETP 2017

[31] IEA, 2017*, Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*.

[32] UN DESA, 2019, "World Population Prospects 2019."

[33] IEA, 2017, *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. John Dulac, SEI Metrics Data, (March 27, 2019), distributed by SEI.

[34] Ürge-Vorsatz et al., 2012, "Best Practice Policies for Low Carbon & Energy Buildings: A Scenario Analysis."

[35] IEA, 2010, "World Energy Outlook 2010"; 2018, "World Energy Outlook 2018."

[36] Kennedy et al., 2009, "Greenhouse Gas Emissions from Global Cities," Environmental Science & Technology.

[37] Atalla, Gualdi, and Lanza, 2018, "A Global Degree Days Database for Energy-Related Applications," Energy.

[38] Note that the assumption that biomass has net zero emissions is only valid under specific conditions; in practice, biomass combustion may contribute to net emissions. See, e.g., Haberl et al., 2012, "Correcting a Fundamental Error in Greenhouse Gas Accounting Related to Bioenergy," *Energy Policy*; Searchinger et al., 2009, "Fixing a Critical Climate Accounting Error," *Science*. In our analysis, biomass constitutes around 5.7% of global final urban energy consumption in 2050 in the reference case, and

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around 6.3% in the mitigation scenario. The percentages vary by country and region, however, with larger percentages in developing countries.

[39] IEA, 2017, *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. Figure 3.8 in ETP 2017 shows approximately 30 billion m^2 in 2040 and 90 billion m2 in 2060 of nZEB floor space for the B2DS scenario. SEI assumes 60 billion m^2 in 2050 and expresses that as a fraction of all new floor space expected by 2050. This fraction is then divided equally in all years from 2025 to 2050 (an assumption) to yield the average share of newly added floorspace during that period that is nZEB-qualified.

[40] Ürge-Vorsatz et al., 2012, "Best Practice Policies for Low Carbon & Energy Buildings: A Scenario Analysis."

[41] IEA, 2017*, Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*.

42 Grubler and Fisk, 2012, *Energizing Sustainable Cities: Assessing Urban Energy.* SEI assumed that half of the solar PV in IEA's B2DS scenario (IEA 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, SEI limited 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.

[43] IEA, 2013, "A Tale of Renewed Cities: A Policy Guide on How to Transform Cities by Improving Energy Efficiency in Urban Transport Systems"; 2016, "Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems." Urban light-duty vehicle (LDV) travel activity is estimated by determining the ratio of urban LDV pkm for each region to total (urban and non-urban) LDV pkm in the ETP 2014 "4DS" scenario (from which the results in IEA 2013 were derived), and applying this ratio to the total LDV pkm levels found in the RTS scenario of ETP 2017; urban bus and rail travel pkm are calculated based on ratios of urban pkm for these modes to urban LDV pkm, derived from the 4DS scenario of ETP 2016. *Urban* freight activity is estimated by applying ratios of urban to non-urban freight travel found in ETP 2016 for OECD and non-OECD countries (4DS scenario) to the total freight travel reported in ETP 2017 (RTS scenario).

[44] IHS CERA, 2012, "Oil Sands, Greenhouse Gases, and US Oil Supply—2012 Update."; see also Oil Climate Index 2016: http://oci.carnegieendowment.org/#total-emissions.

[45] Façanha, Blumberg, and Miller, 2012, "Global Transportation Energy and Climate Roadmap: The Impact of Transportation Policies and Their Potential to Reduce Oil Consumption and Greenhouse Gas Emissions."

[46] Mason, Fulton, and McDonald, 2015, "A Global High Shift Cycling Scenario: The Potential for Dramatically Increasing Bicycle and E-Bike Use in Cities Around the World, with Estimated Energy, CO2, and Cost Impacts." These are examples of policies that would reduce PKM and TKM/capita, but some of these may induce mode shift as well. This is the "avoid" component of "avoid, shift, improve, and fuel-switch" (ASIF). Representative policies include fuel, carbon, and vehicle taxes; urban planning promoting compact development; incentives for and investments in non-motorised modes; multiple local travel demand management policies.

[47] Kaza et al., 2018, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*.

[48] IPCC, 2006, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

[49] Kaza et al., 2018, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*.

[50] IPCC, 2006, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

[51] Pales et al., 2019, "Material Efficiency in Clean Energy Transitions." These data are reported at the global level. To allocate global production to the regions/countries found in ETP 2017, SEI: (1) allocated production to OECD and non-OECD countries following the ratios reported in ETP 2017 for total production of relevant materials (steel, aluminium and cement) for the OECD and non-OECD regions; and (2) within OECD and non-OECD regions, determined shares of production for each ETP 2017 country/sub-region for each year based on a forward extrapolation of infrastructure material stock accumulation rates

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calculated from Müller et al., 2013, “Carbon Emissions of Infrastructure Development,” *Environmental Science & Technology*.

[52] *Müller et al., 2013, “Carbon Emissions of Infrastructure Development,” Environmental Science & Technology*.

[53] 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.

[54] Pales et al., 2019, “Material Efficiency in Clean Energy Transitions.” Note that the analysis presents global results, which SEI applied in equal proportion across all countries and world regions. Thus, although reference case urban infrastructure demand and associated emissions vary by country and region, the percentage abatement potential related to infrastructure materials in our model is the same in all areas. “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 scenario (road and rail construction), or the CTS scenario 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.

[55] These include, in later years, the effects of carbon capture and storage (CCS) applied to cement production.

[56] Grubler et al., 2018, “A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies,” *Nature Energy*; Knobloch et al., 2019, “Simulating the Deep Decarbonisation of Residential Heating for Limiting Global Warming to 1.5 °C,” Energy Efficiency.

[57] The ETP 2016 did report separate results for urban and non-urban areas within the OECD and non-OECD country groupings. SEI chose to base its model on the ETP 2017 results, however, given their explicit inclusion of a “below 2 degrees” scenario, which was lacking from prior ETP scenario analyses. Where possible – e.g. for the transportation sector – SEI relied on the ETP 2016 to inform estimates of urban-specific activity levels.

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