How to reach the 1.5°C target in urban areas

Contributions to the 1.5°C target in the Paris Agreement through electrifying transportation and ensuring energy efficient buildings and transitioning into green energy through sector coupling

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EXECUTIVE SUMMARY – THE URBAN QUEST FOR 1.5°C

Urban areas: Cities can take the lead

While world cities occupy just 3% of the Earth's land today,[1] they account for two-thirds of the world´s energy demand and 70% of global greenhouse gas (GHG) emissions.

As urbanization increases and the world's population expands, cities are also expanding rapidly. Urban areas are hubs of economic and cultural activity and continue to attract people looking to leverage the opportunities cities provide. Today, 55% of the global population live in urban areas; the urban population is expected to increase to an almost 70% share by 2050.[2]

Cities have large carbon footprints that impact their air quality and health. More than 91% of the global population is being exposed to air pollution beyond the limits set by the World Health Organization. The sources of air pollution vary but heating and cooling of buildings and transport based on fossil fuels are main contributors.

> Urban areas pose both threats and opportunities when it comes to reaching the Paris Agreement, which means that opportunities for cities to make a difference is enormous.

Cities need to curb emissions to increase liveability and create an environment for sustainable growth. Because cities' potential impact on climate and health is enormous, so too are their opportunities to make a difference. The good news is that the technologies needed are already here, or are in the pipeline, to future-proof our cities, meet the Paris Agreement, and safeguard air quality for the growing urban population.

Urbanization has changed the relationship between cities and their immediate surroundings, with cities increasingly impacting pollution and emissions. When sustainable solutions are developed in cities, positive spillover can occur.

Cities can act as ambitious, inspirational regional front-runners that showcase new technology and create attractive places to live and work.

Cities are essential to achieving 1.5°C

Buildings, transport, and sector coupling are key elements of the urban energy system.[3] This report shows what is needed for urban areas in Europe, the US, and China to reach the 1.5°C target in the Paris Agreement.

> Enabled by sector coupling, energy efficient buildings and electrified transport can bridge half of the gap in greenhouse gas emissions reductions needed for 1.5°C.

Cities and urban areas can reduce GHG emissions and air pollution significantly by investing in existing technology. This would improve health, well-being, and productivity in cities. To reach the

[1] The Earth Institute Columbia University, 2005
[2] United Nations, 2018
[3] IEA, 2017

Paris Agreement, cities also need to prioritize investments in energy efficient buildings and the electrification of transport.

Implementation of existing technology for buildings, transport, and sector coupling can bridge about half of the gap in the urban GHG emissions reductions needed for a 1.5°C pathway

By 2050, the implementation of existing technology solutions for energy efficient heating and cooling of buildings and electrified transport (both enabled by sector coupling) can bridge about half of the gap[4] in urban GHG emissions reductions needed for a 1.5°C pathway in cities and urban areas. Both sectors have high shares in total needed reductions, although we assume that transport will not reach zero emissions by 2050[5]. Figure 1 shows the necessary emissions reductions if cities are to reach the 1.5°C target in 2050. The figure indicates a 28% contribution from electrifying transport and a 20% contribution from ensuring energy efficient buildings[6].

However, contributions vary regionally and by city[7]. For European cities to achieve a 1.5°C pathway, the overall contribution from transport, buildings and sector coupling must total 42%. Navigant determined for US and Chinese cities to achieve the emissions reductions needed for a 1.5°C pathway, the contributions must total 47% and 52%, respectively.

The remaining half of the accumulated urban emission reductions needed for a 1.5°C pathway will come from other sectors, mainly industry, electricity for appliances, and construction.

[4] The methodology is laid out in Annex 9 and follows a sectoral approach. For each sector we scale the national/regional pathways under a 1.5C scenario to the city level effectively translating the global pathways to city level. This means that the near total decarbonization at the global level is also required at the city level.

[5] Electrification of cars is expected to reach levels ranging from 8% (Europe) to 21% (China) by 2030, increasing to 60%-68% (Europe and China, respectively) by 2050. (and include US)

[6] 'Contribution' reflects the projected necessary reductions for a city/urban mitigation to be aligned with a 1.5°C pathway.

[7] The base data at city level was primarily sourced from the C40 database and augmented with population numbers at city level from the UN. The data in the C40 database is self-reported by the cities according to the Global Protocol for Community-scale GHG Emission Inventories (GPC). The protocol clearly distinguishes between emissions within and outside the city boundary, but the definition of the city boundary is up to the city and could represent *“Any geographic boundary may be used for the GHG inventory. Depending on the purpose of the inventory, the boundary can align with the administrative boundary of a local government, a ward or borough within a city, a combination of administrative divisions, a metropolitan area, or another geographically identifiable entity.”* Typically, cities will strive to use the administrative/geographic boundary of the city for the emissions inventory, but they may need to deviate from this principle depending on the scope of available data sources.

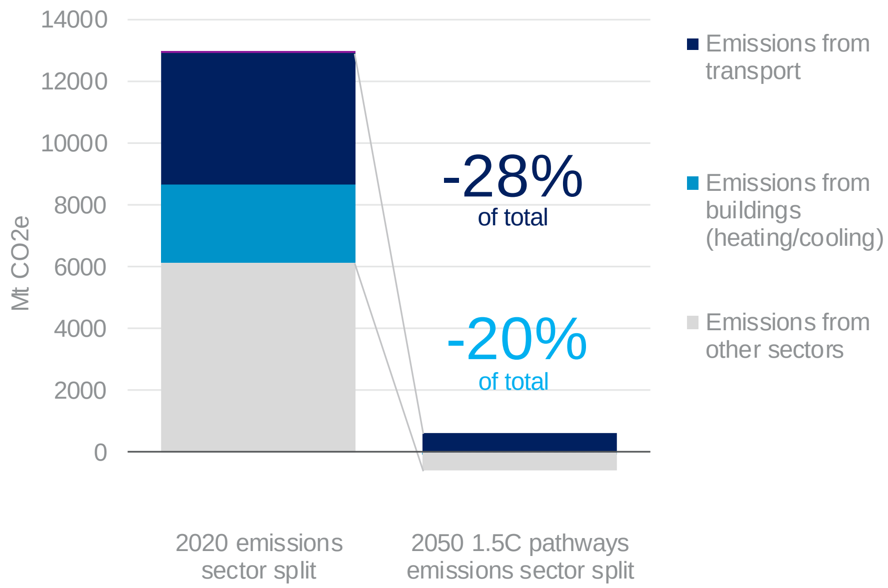

Figure 1. Towards 1.5°C in European, US, and Chinese urban areas[8]

The building sector can seize quick wins,[9] mainly stemming from optimization of technical building systems[10] for cooling and heating of buildings. However, between 2025 and 2030, transport can gain traction and make up for the currently low ambition in the nationally determined contributions (NDCs): Urban GHG emission reductions from electrification appear to be moderate at the beginning, but the study shows a rapid increase after 2025.[11] Electrification will be crucial for urban abatement strategies. These findings apply to European, US, and Chinese urban areas, while the relative contribution from heating and cooling of buildings in both Europe and US is larger than in China.

Electrifying transport will be the greatest lever to leap from business-as-usual to 1.5°C

If all urban areas in Europe, the US, and China electrified their private and public transport, they would contribute to the 1.5°C target of the Paris Agreement with 28%. However, the contribution from transport varies by region and by city. To meet the 1.5°C target, the contribution to needed reductions from electrifying transport in cities totals 17% in Europe, 24% in the US, and 37% in China.

Overall, transport requires the most drastic acceleration of technology uptake to transition to the 1.5°C level. Required technologies already exist or are in the pipeline and are starting to see good traction in the market. To give some examples, technology for the full electrification of cars, buses, and trucks, as well as city boats, work boats, and ferries, already exists. Further, big vessels like cruise ships can already be powered from sustainable energy through shore-side supply while at berth. However, regulation, incentives, and coordinated

[8] GABC Global Status Report 2018 arrives at similar shares for global emissions; note: Figure 1 does not include emissions from operating appliances in buildings. Please also see figure 19 in the Appendix.

[9] Emissions reductions as reported in IEA's pathway reflecting countries' Nationally Determined Contributions (NDC).

[10] as for a definition of technical building systems, see footnote 15.

[11] For more details on the pathway, see Appendix A.

planning are required to ensure a steep uptake and to tap the full potential of electrifying transport.

Decarbonizing transport cuts GHG emissions and local air pollution. For example, if London is to reach the 1.5°C level, two-thirds of London's passenger cars must be battery electric by 2050, meaning about 1.8 million EVs instead of combustion vehicles in the city. In addition, all buses across London will need to be electric zero-emission by 2037. This would relieve Londoners from annual emissions of 1,664 tons NO_X. This equals about 5,000 million diesel car kilometers.

Energy efficient heating and cooling of buildings will be the second greatest lever to leap to 1.5°C

Like transport, technologies for energy efficient heating and cooling of buildings will need a steep uptake. To reach the 1.5°C level, the renovation rate of buildings in cities would need to increase to 2%-3% yearly. This means that several cities would need to triple their current renovation activities, even then, the transformation of existing building stocks might take about 30 years. If all urban areas and cities in Europe, the US, and China invested in energy efficient heating and cooling of buildings, they would contribute to the 1.5°C target of the Paris Agreement with 20%.

However, the contribution from energy efficient cooling and heating of buildings varies by region and by city. To meet the 1.5°C level, the overall contribution to needed reductions from energy efficient heating and cooling of buildings in cities adds up to 24% in Europe, 23% in the US, and 15% in China.

Optimized technical building systems and more efficient, decarbonized district energy systems often can be implemented quickly and cost-effectively. This gradually needs to be complemented by effective building insulation to sufficiently reduce overall energy use and emissions. Cities need to act early, lead by example, and set up and implement ambitious and actionable plans to ensure the needed steep uptake.

As with transport, the needed solutions are already available and waiting for use. If Shanghai retrofits 10 million m^2 according to low energy standards, this would relieve its citizens from annual emissions of 250 tons particulate matter. This equals about 80 billion diesel car kilometers.

Thus, energy efficient heating and cooling of buildings cuts GHG emissions and local air pollution.

Sector coupling will enable the untapped potential

Sector coupling is an enabler of energy efficient buildings and electrification of transport. Sector coupling is about optimizing the use of renewable energy, stabilizing the grid, and cost-effectively using energy through interconnection of urban energy systems' elements like industry, buildings, and transport.

Cities with their high density of buildings, transport, industry, infrastructure, and economic activity can drive innovation and enable the efficient use and exploitation of synergies between sectors to create a highly efficient energy system. The world is transforming from a centralized, conventional energy-based system toward a smart, more efficient, decentralized and consumer-focused energy system, largely based on renewable energy sources. For this journey to be successful, cities need to invest in sector coupling.

Sector coupling is about optimizing the use of renewable energy and stabilizing the grid, as this is a precondition for a cost-effective transition to a decarbonized energy system. This can be reached through energy storage, peak-shaving, the conversion and storage of one energy carrier into another, and integrating and matching the energy consuming sectors (buildings for heating and cooling, transport, and industry) with the energy-producing sectors. The analysis shows that the 1.5°C pathway requires a consistent implementation of all measures—energy efficiency, renewable energy, and sector coupling. The most cost-effective way to reach the 1.5°C target is through investments in energy efficiency and sector coupling, as this will ensure that substantial investments in energy generation and energy infrastructure can be avoided.

For example, if New York City is to reach the 1.5°C level, it needs to provide system flexibility through flexible loads of 300 MW installed capacity of small individual heat pumps connected with thermal storage and 1.2 million EVs. In addition, battery storage will grow from less than 1 GW to approximately 110 GW in the US.

Action in urban areas and cities has great spillover effect on national emission reductions

By 2050, urban and city emission reduction from energy efficient heating and cooling of buildings and electrification of transport (both enabled by sector coupling) will contribute with more than one-third of total needed national emissions reductions in Europe, the US, and China:[12]

- Contributions vary regionally. Of needed reductions to meet the 1.5°C level, the overall contributions add up to 31% of national emissions in Europe, 34% of national emissions in the US, and 34% of national emissions in China.

- Urban and city emission reductions from the electrification of transport will contribute more than 20% of total needed national emissions reductions in Europe, the US, and China by 2050.[13] Overall, the contribution to needed reductions to meet the 1.5°C level adds up to 13% of national emissions in Europe, 17% of national emissions in the US, and 24% of the national emissions in China.

- Urban and city emission reduction from energy efficient heating and cooling will contribute with more than 15% of total needed national emissions reductions in Europe, US, and China by 2050.[14] Overall, the contribution to needed reductions to meet the 1.5°C level adds up to 18% of national emissions in Europe, 17% of national emissions in the US, and 10% of the national emissions in China.

[12] The baseline already considers today's policies and pledges including NDCs (Nationally Determined Contributions), i.e., stronger ambitions for buildings than for transport. As for details on the methodology see Appendix A.

[13] Ibid

[14] Ibid

Recommendations for urban policymakers

Urban areas and cities can lead the way to getting the world on track to 1.5°C, but it requires a steep uptake of technology. A core set of principles should be considered by urban policymakers around the world, as 1.5°C leaves limited space for variation in target setting and decision-making:

A core set of principles should be considered by urban policymakers across the world, as 1.5°C leaves limited space for variation.

- **Act now.** Lack of leadership, policy commitment, actionable plans, and regulation fails to stimulate the needed investment. Planning the journey toward the 1.5°C objective must happen now.
- **Align with all levels of government:** go for a clear engagement strategy with higher levels of governments to help address policy divergences, as well as leveraging financial and human resources.
- **Set ambitious and actionable short-, mid-, and long-term targets** and a suitable regulatory framework to incentivize investments.
- **Link energy use and air pollution**. A 1.5°C pathway offers an opportunity for urban areas and cities to drastically and cost-effectively mitigate air pollution along with GHG through an integrated clean air strategy.
- **Take leadership** and invest in the needed technology now. Move early and set examples by investing in own assets (e.g., lower the energy use of individual public buildings by 60%-90% till 2040 while decarbonizing supply, electrify the full public transport fleet by 2030, and use excess energy through sector coupling and energy storage by 2040).
- **Remove barriers for and implement pilot projects** – to innovate, test, and showcase new technology, ensuring your city shines as an ambitious and inspirational regional front-runner, and creating attractive places to live and work while also creating spillover effects in suburban and rural areas.
- **Coordinate initiatives with other cities** to learn from each other and ensure common pressure on a national and regional policy level. Decision makers in urban areas and cities can only influence about half of the needed decisions.
- **Collaborate with local business and manufacturers** to ensure a common goal.
- **Prioritize energy efficient heating and cooling of buildings, electrification of transportation, and sector coupling.** A strategy in line with 1.5°C can be achieved cost-effectively only with a strong focus on energy efficiency and sector coupling, as this will ensure that expensive overinvestments in energy generation and energy infrastructure can be avoided.

- **Energy efficient buildings:**
    - Start with consistent optimization of technical building systems[15] for the heating and cooling of own public building stock now.
    - Design and enforce mandatory building codes for new and existing buildings with a view to net zero and net plus energy buildings[16]. This means ambitious minimum performance requirements for the whole building, building envelope, and optimized technical building systems.
    - Ensure that the real-life energy performance of new or upgraded technical building systems is assessed, documented, and passed on to the building owner.
    - Set up long-term renovation strategies, including suitable regulation and incentives for sufficiently deep renovation, either one-off or staged, to use renewable energy and to boost renovation rates of existing buildings from currently often less than 1% to at least 2%-3% per year.
    - Take an integrated approach for energy planning on district level in order to find cost-effective synergies from combining measures to improve the energy efficiency of buildings and to decarbonize supply.
    - Ensure or facilitate access to funding for implementation, e.g., by using or asking for innovative financial business models, like ESCOs.
    - Closely monitor implementation of plans and immediately act when needed to keep on track.
    - Expand and decarbonize district heating and cooling, including large-scale heat pumps running on renewable power, and lead the way by connecting public buildings.
- **Electrified transport sector:**
    - Start with electrifying the public fleet now (vehicles, buses, city boats, ferries), including investing in the needed charging stations.
    - Introduce low environmental/emission zones.
    - Incentivize and regulate on electrification of all transport modes. Take the lifetimes of transport into account (vehicles of approximately 10-15 years).
    - Invest in and prepare for charging infrastructure for private transport modes (EV charging for vehicles, buses, and trucks and shore supply for boats, ferries, and cruise ships) and regulate and incentivize accordingly to ensure investments.

[15] Technical building systems in this report are to be understood as in the European Energy Performance of Buildings Directive's (EPBD) definition: "technical building system" means technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, onsite electricity generation, or a combination, including those systems using energy from renewable sources, of a building or building unit.

[16] A "plus energy buildings" means that annual on-site, nearby or off-site energy generation from renewable sources exceed the annual energy need of a building.

- Mandate the installation of charging stations in new builds and when renovation takes place (office buildings, residential, industry, hotels, supermarkets). Incentivise or finance pre-cabling for chargers.

- Introduce regulation and financial or other incentives for building owners to invest in charging stations.

- Introduce parking incentives, tax rebates on charging infrastructure, and other fiscal incentives for moving toward electrification of transport.

- Mandate the installation of shore supply in harbors and present a plan for how to address that all vessels use electric shore supply when at berth.

* **Sector coupling:**

  - Rethink energy planning to consider and support sector integration.

  - Prepare local plans on how to decarbonize the energy system, based on data on infrastructure, as well as sound assessments of the potential of utilizing synergies between sectors, to ensure a cost-efficient decarbonization and avoid ineffective investments or lock-in effects.

  - Leverage synergies, such as utilizing the waste heat from a datacenter for heating of buildings instead of investing in additional heat supply. Or reuse excess energy from a wastewater utility to power another sector.

  - Allow urban regulatory free test zones to innovate and develop new energy efficient technology, through removing technical, regulatory and financial barriers for reusing energy between sectors.

  - Ensure that power price signals incentivise/reward energy storage and other flexibility services.

  - Map sector coupling potential through energy storage, peak-shaving, the conversion of one energy carrier into another and coupling of energy sources.

  - Set a supportive policy framework by incentivizing or regulating the creation of decentralized integrated energy systems.

  - Increase the share of renewables in the power sector considerably.

1. INTRODUCTION

The world is already experiencing the alarming consequences of the global temperature increase, with the trend approaching 1°C. Exceeding the Paris target of 1.5°C will lead to a highly uncertain world, pushing human and natural systems beyond their limits of adaptation and leading to “exacerbated urban heat islands, amplification of heat waves, extreme weather volatility, floods, droughts, coastal inundation, and an increase in vector-borne diseases like malaria and dengue fever.”[17]

Leading scientists highlighted this fact to urban policymakers in the Intergovernmental Panel on Climate Change’s (IPCC’s) recent report on global warming of 1.5°C.[18] However, current global pledges, targets, and policies would result in about a 3°C increase.[19] Urban areas and cities are vital to[20] reaching the 1.5°C target. They can and must lead the way to getting the world on track with the Paris Agreement but almost all of them need to step up their aspirations.

Some cities have already started showing leadership, such as the C40 cities that joined the Net Zero Carbon Buildings and Green and Healthy Streets Declaration.[21] They show that drastic action is needed.

[17] Bazaz, 2018
[18] IPCC, 2018
[19] Climate Action Tracker, 2019
[20] Bazaz, 2018
[21] C40 Cities Climate Leadership Group, 2019

2. WHY THIS STUDY?

This report assesses how urban areas can get on a 1.5°C pathway while also reducing air pollution. The world's urban areas currently emit 70% of total global greenhouse gas (GHG) emissions, and the share is growing. The analysis shows that urban areas in Europe, the US, and China are responsible for half of these emissions. This report focuses on those three regions.

This study illustrates the technological transformation that needs to happen when cities and urban areas move to a 1.5°C pathway.

The most advanced urban action plans aim at a 2°C pathway, the high temperature end of the Paris Agreement, even though IPCC states that this is not enough and will include monumental risks. While 2°C is already recognized to be very ambitious, the 1.5°C pathway "… would require an immediate ramp-up of all low carbon options at a rate of deployment sustained over the next 25 years..."[22]

This study illustrates the necessary technological transformation when cities and urban areas move to a 1.5°C pathway. We explain the necessary technological changes and provide quantifications for selected technology uptake.

Based on suitable International Energy Agency (IEA) and IPCC scenarios for different world regions, we have quantified technology uptake on a 1.5°C pathway for a selection of cities in Europe, the US, and China: London (UK), Rotterdam (The Netherlands), New York (US), and Shanghai (China).

The full city examples are provided as fact sheets in an appendix to this report.[23] These fact sheets should be read along with this report and can help stakeholders in similar urban areas determine concrete targets, actions, and peer stakeholders on regional and national levels. The selected cities encompass significant shipping activities within the transport sectors. This highlights the additional challenge with locally restricted air pollution that cities with heavily used harbors or other waterways face.

[22] IEA, 2016a

[23] cf. chapter 8.2.4Appendix B

3. FOCUS AREAS OF THE STUDY

The urban energy system consists of the buildings, transport, heat and power, industry, agriculture, waste treatment, and water/wastewater treatment sectors.

Energy efficient heating and cooling of buildings, electrification of transport, and sector coupling are key elements of the urban transformation.

This report focuses on the following elements in urban areas:

- **Energy efficient buildings** (energy efficient heating and cooling of buildings including efficiency measures at the envelope).
- **Electrification of transport** (cars, buses, trucks, and examples of vessels, ferries, and boats plus required charging infrastructure).
- **Sector coupling** as an enabler of energy efficient buildings and electrification of transport. Sector coupling is about optimizing the use of renewable energy, stabilizing the grid, and cost-effectively using energy through interconnection of urban energy systems' elements like industry, buildings, and transport.[24]

Figure 2. Focus sectors for cities to reduce emissions

Ultimately energy efficiency in buildings and sector coupling can free electricity for transport and save cities from huge investments in renewable energy, grid, and storage capacity. These savings allow the city to spend elsewhere, such as on the quality of life for citizens.

Cities have an opportunity to reduce GHG emissions and air pollution by using synergies between the different sectors of the urban energy system.

[24] For more cf. chapter 7

4. CITIES MUST TAKE THE LEAD

The world has urbanized rapidly since the 1950s, with 55% of the world's population now living in urban areas; a number that is expected to increase to almost 70% by 2050.[25]

However, the global urbanization trend is not without its challenges. While urban areas occupy just 3% of the Earth's land,[26] they account for 70% of GHG emissions.

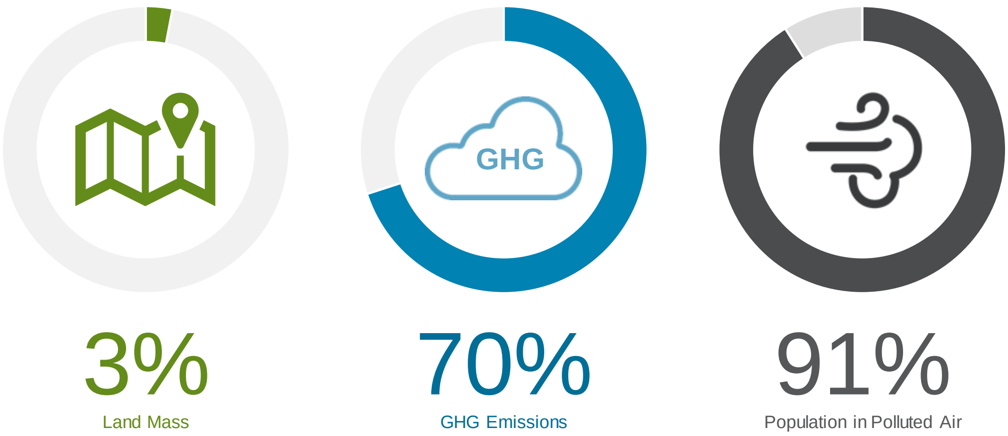

Figure 3. Cities are responsible for a hugely disproportional share in GHG emissions and air pollutants

Air pollution is also a real and growing concern; around 91% of the world's population live in places where air quality levels exceed the World Health Organization's (WHO's) limits.[27] The sources of air pollution vary, but individual heating and transport based on fossil fuels are main contributors.

Whereas GHG emissions are a global issue, air pollutants are above all a local issue linked to lung cancer, heart diseases, asthma, and lung diseases.[28] In China, the IEA attributed more than 150 premature deaths per 100,000 people to air pollution in 2012. In highly developed western countries like Denmark, Germany, and the US, numbers are significantly lower, but still range between 10 and 40 deaths per 100,000 people. In Europe, around 40 million people in the 115 largest cities have been exposed to air exceeding WHO air quality guideline values, which caused 4.2 million deaths in 2016.

Most urban areas around the world fail to meet the WHO's air quality guidelines for particulate matter (PM) and NO_X. Related welfare costs of premature deaths are huge, with estimated values being about $2,000 billion for China and $200 billion for the US. While buildings' operation through burning of oil and biomass contributes to emissions of PM, transportation by the burning of oil largely contributes to NO_X. PM emissions from

> Urban areas in Europe, the US, and China are currently responsible for more than one-third of those regions' total CO_2 emissions. Most urban areas also fail to meet air quality guidelines.
>
> A 1.5°C pathway can be used to efficiently eliminate urban air pollution.

[25] United Nations, 2018
[26] The Earth Institute Columbia University, 2005
[27] WHO World Health Organization, 2019
[28] IEA, 2016b

burning diesel or heavy fuel oil may be a major issue locally (like in port areas or along waterways), too.

Due to the close link between energy use and air pollution, a 1.5°C pathway offers urban areas an opportunity to drastically and cost-effectively mitigate air pollution in one go with GHG by an integrated clean air strategy including energy efficient buildings, electrification of transport and sector coupling.

Cities have a sizeable footprint and need to curb emissions to increase liveability and create an environment for sustainable growth. In other words, because cities' potential impact on climate and health is enormous, they also have enormous opportunities to make a difference.

Fortunately, the needed technologies already exist or are in the pipeline to future-proof our cities, meet the Paris Agreement, and safeguard air quality for the growing urban population. Cities' high density of facilities and infrastructure can drive innovation and enable the efficient use and exploitation of synergies between sectors to create a highly efficient energy system. It is now about rolling out existing technology at a much faster pace, while innovating new solutions in real-life city test zones.

Further, by 2050, 84% of total global GDP will be generated in urban areas and cities.[29] Urban areas and cities will be the future hotspots of economic activity and growth and may lead the way on the climate agenda. The increasing convergence of economic activity to cities will also bring about a shift of political and administrative power toward city mayors. Organizations like C40 or the Covenant of Mayors already bear witness to such development.

Cities can act as ambitious and inspirational regional front-runners that showcase technology and create attractive places to live and work, while creating spillover effects in suburban and rural areas.

[29] IEA, 2016c

5. WHY URBAN AREAS AND CITIES SHOULD FOCUS ON ENERGY EFFICIENT HEATING AND COOLING OF BUILDINGS

A highly energy efficient building stock is vital for reaching the 1.5°C target in cities and urban areas

Buildings alone account for one-third of the GHG emissions and final energy use, and 40% of urban primary energy use.[30] Inefficient heating and cooling of buildings is a major cause for emissions and air pollution globally.

The effects of pollution from buildings is an increasingly prominent policy priority. Shanghai's plans for energy renovation of 10 million m^2 of buildings will save its citizens an 250 tons of PM annually, equalling annual PM emissions of 80 billion diesel car kilometers.

The most cost-effective way to reach the 1.5°C target is to invest in energy efficiency first, meaning absolute reductions in final energy consumption. Therefore, technologies for energy efficient heating and cooling of buildings will need a steep uptake.

The analysis shows that from 2020 onward, there are quick GHG wins in the building sector. A large share of these quick wins can be achieved by cost-effective, easy-to-implement measures. Optimized technical building systems or more efficient, decarbonized heat generation in district systems based on renewable sources often belong to this category. As they also do not hamper subsequent deep renovations, they should be considered first for large-scale implementation.

If cities in Europe, the US, and China invested in energy efficient heating and cooling of buildings, they would contribute to the 1.5°C target of the Paris Agreement with 20%. However, depending on a city's structure, the contribution varies:

- Rotterdam: 10%
- Shanghai: 25%
- London and New York: 40%

Shanghai's GHG emissions from the heating and cooling of buildings will need to fall from 63 Mt today to -3 Mt in 2050. This requires net zero buildings and almost 100% of renewable energy supply in 2050, for example, achieved by a steep uptake to 2.4 million heat pumps in buildings, and decarbonized district heating and cooling powered by approximately 46 MW_{el} of large heat pumps running on renewable electricity.[31] It also entails a significant electrification of heat supply from 11% to 24%.[32]

Main conclusions

Navigant's conclusions on the potential of energy efficient heating and cooling of buildings in urban areas are as follows:

- If all urban areas and cities in Europe, the US, and China invested in energy efficient heating and cooling of buildings, they would contribute to the 1.5°C target of the Paris Agreement with 20%.

[30] IEA, 2016c.

[31] In a 1.5°C world it is expected that the power sector's net GHG emissions are "negative," i.e., the power sector is responsible to remove GHG from the atmosphere, e.g., by carbon capture and storage (CCS). As power sector's emissions are caused by energy services e.g., in transport, industry, and buildings sectors, in this report power sector's (so-called indirect) emissions are re-distributed and added to the direct emissions within these responsible sectors. As in the example of Shanghai's building sector, this consequently may lead to nominal negative emissions in a sector, too.

[32] Equivalent numbers for London, Rotterdam and New York: see from page 12 on and city factsheets.

- This would equal curbing 2,500 Mt of annual GHG emissions in 2020 down to 0 Mt by 2050, which alone is 10% of today's annual emissions of urban areas worldwide. This will require the steep uptake of existing technology for energy efficient heating and cooling of buildings in cities.

- The contribution from energy efficient cooling and heating of buildings varies by region and by city. Overall, the contribution to needed reductions to meet the 1.5°C level from energy efficient heating and cooling of buildings in cities adds up to 18% in Europe, 17% in the US, and 10% in China.

- Optimized technical building systems and more efficient, decarbonized district energy systems based on renewable sources often can be implemented quickly and cost-effectively; this needs to be gradually complemented by effective building insulation to sufficiently reduce overall energy use and emissions.

- Energy efficient heating and cooling of buildings cut GHG emissions and local air pollution.

- The renovation rate of buildings, often being below 1%, needs to increase to approximately 2%-3% for cities to reach the 1.5°C target. This means that several cities would need to triple their current renovation activities, even then, the transformation of the existing building stocks might take 30 years or more.

- Besides ensuring a cost-efficient way to reach the 1.5°C target, energy efficient heating and cooling of buildings save lives. This is because they provide a better indoor climate and cause less local outdoor air pollution.

Policy recommendations: What city mayors should do on buildings

1.5°C means going to the limit of what is imaginable with the technology available today and in the pipeline. Brave, decisive leadership will make energy efficient buildings deliver their indispensable contribution to a sustainable urban energy system, making the city a place where people want to live and work.

Act early

- Plan the whole journey now by means of a holistic 1.5°C strategy.
- Link energy use and air pollution. A 1.5°C pathway offers an opportunity for urban areas and cities to drastically, cost-effectively mitigate air pollution in one go with GHG emissions from buildings by an integrated clean air strategy.
- Urban areas cannot afford to leave any savings potential unused:
  - Seize the quick wins first, that do not compromise next steps. Start with tapping the potential from ensuring energy efficient heating and cooling of buildings.
  - Design and enforce mandatory building codes for new and existing buildings with a view to net zero and net plus energy buildings. This means ambitious minimum performance requirements for the whole building, building envelope, and optimized technical building systems.
  - Set up long-term renovation strategies, including suitable regulation and incentives to renovate as deeply as possible, to use renewable energy and to boost renovation rates of existing buildings from currently often less than 1% to at least 2%-3% per year.
- Ensure or facilitate access to funding for implementation, for example, by using or asking for innovative financial business models like ESCOs.

Lead by example

- Start with your own public building stock now, easy opportunities first, like optimization of technical building systems.
- Remove barriers for and implement city pilot projects.
- Expand and decarbonize district heating and cooling where possible, including large-scale heat pumps running on renewable power, and lead the way by connecting public buildings.
- Collect data and ensure transparency and accessibility of energy performance and CO_2 emissions data from implementing energy efficiency technology in buildings to facilitate research and timely regulatory or monitoring actions.
- Communicate and showcase your city examples (public and private case stories), show what existing and new technology can contribute with on the journey toward the 1.5°C target.
- Collaborate and set common targets with other city administrations, local industries/manufacturers, regional, and national governments to standardize and industrialize solutions that will drive cost down.
- Be a national, regional, and global front-runner.

Set up and implement ambitious and actionable plans

- Set ambitious and actionable short-, mid-, and long-term targets and plans and a suitable regulatory framework to incentivize investments.
- Closely monitor implementation of plans and immediately act when needed to keep on track.
- Ensure that real-life energy performance of new or upgraded technical building systems is assessed, documented, and passed on to the building owner.
- Use synergies and economies of scale of districtwide solutions by applying detailed mapping of heat, cold, power profiles, and renewable energy potentials of all urban energy system components—residential and service buildings, heat and power, industry, transport, water and waste treatment, and agriculture—also considering densification and extensions.
- Incentivize phasing out of technical building systems running on fossil fuels for space heating, domestic hot water, and cooling and replacement by those using renewable energy, such as heat pumps, solar heat, and photovoltaics or district networks.

The most cost-effective way to reach the 1.5°C target is to invest in energy efficiency first

Energy efficiency in buildings is a precondition for an affordable, fully renewable, and secure integrated urban energy system.

On a European scale, by 2050 high efficient buildings will save peak power generation capacity of almost 60 GW. This equals today's joint electricity generation capacity of Austria and the Netherlands or the estimated total power capacity of batteries in the European grid (70 GW) by 2050.

These benefits equal a total of €89-€153 billion of CAPEX reduction in 2050.[33] A major share of this CAPEX will be saved in urban energy systems, as approximately one-third is related to avoided expansion of low voltage distribution grids, which will largely be located in urban

[33] ECOFYS, 2015

areas. The remaining part is from avoided generation capacity, which—depending on the individual urban energy system—will also be located within the urban area.

It is estimated that electric power of large heat pumps for district heating from today's close to 0 MW will boom till 2050:

- Rotterdam: 2 MW
- New York: 2 MW
- London: 25 MW
- Shanghai: 46 MW

Electrification is key for all urban areas on a 1.5°C pathway, similar results will follow both in urban areas with rather stagnating building stocks like in the US, but also with high shares of new builds like in China or India.

At the same time, saving energy in buildings will free capacity and CAPEX for urgently needed electrification of transport—another reason for the energy efficiency first principle for buildings.

In proceeding toward the 1.5°C target, the right balance between investing in negawatt (not using a unit of energy thanks to higher energy efficiency) or investing in renewable megawatt (supplying that unit of energy from renewable sources instead) needs to be found.

Major studies on abatement cost have demonstrated huge potentials for negawatt solutions that come at much lower cost or much better cost-benefit ratios than renewable megawatt solutions. For this reason, the principle of "energy efficiency first" is a precondition to keep a fully renewable energy supply affordable. Energy efficiency measures like efficient water heating or air conditioning may even be highly profitable investments, yielding net financial gains or negative abatement costs of up to €150/ton CO_{2e}.[34]

Energy efficient buildings save lives

In a 1.5°C world, high efficiency, electrification, and renewable energy supply of buildings will drastically decrease buildings' contributions to air pollution.

Human health in urban areas is largely affected by air pollution. More than 80% of the world's population lives in urban areas, and close to 100% of the population in Southeast Asia, China, and India is exposed to air quality that does not meet WHO's Air Quality Guidelines.[35,36] In China's urban areas, this leads to 770,000 additional deaths each year.[37]

Indoor air quality and thermal comfort are features of high efficient buildings that support well-being, health, and productivity. One out of six Europeans report to live in unhealthy buildings. Assuming an even distribution between rural and urban areas and considering a 75% share of Europeans living in urban areas, this equals the population of France and leads to annual costs of some €60 billion per

Shanghai's current plans of energy efficiency retrofit of 10 million m^2 floor area could unburden its citizens from annual emissions of about 250 tons of particulate matter (PM). This equals about 80 billion diesel car kilometers.

[34] Enkvist et al., 2007. An energy efficient investment will save energy cost and GHG emissions in the future. If the investment pays back it means a financial benefit, i.e., the net present value of the investment is positive. Investment in efficient heating and cooling spoken of here pays back, i.e., means a financial benefit. As cost per se mean a financial loss, a financial benefit – being the opposite - can be regarded as „negative cost". If these "negative costs" are distributed over the tons GHG saved, "negative abatement cost" occur. This is contrary to often heard arguments that GHG abatement cannot be a beneficial financial investment.

[35] IEA, 2016b

[36] OECD, 2019

[37] OECD, 2019

year due to asthma and chronic obstructive pulmonary disease—half of these costs stem from productivity loss because of illness.[38]

Especially for office workers, high productivity is strongly related to good indoor comfort.[39] The more prominent the service sector is in urban areas the more relevant this gets.

Much improved energy efficiency will significantly mitigate the projected steep increase in cities' cooling demands,[40] and thus break the vicious circle of global warming and subsequent higher cooling need that contributes to more GHG emissions. People in urban areas will benefit most from such development due to the reduced urban heat island effect, which otherwise would expose them to 3°C-4°C hotter temperatures than surrounding areas.

Excess heat from air conditioning accelerates the heat island effect. Consciously designed and retrofitted high efficient buildings need no or much less cooling, or will be supplied by smart district cooling using excess heat (e.g., from industry) and thus contribute to heat island mitigation.

Urban areas and cities need to increase renovation rates

The renovation rate is often below 1% in cities today. As there are 30 years left to achieve zero GHG emissions, an annual 3.3% linear decrease of GHG emissions from heating, cooling, and other energy uses in buildings is needed.

If energy needs decrease and contribute 60% of the needed decarbonization (while the remaining 40% gap is bridged by onsite, nearby, and offsite renewable energy), having 30 years left till 2050 equals an annual ≥2.0% decrease of building stocks energy needs.[41]

There are different strategies to reach this, depending on a city's actual building stock. A simplified example can illustrate this challenge. The worst 60% (in terms of floor area) of an urban area's building stock would equal 80% of the stock's energy needs. If all the worst 60% would be renovated till 2050, *2% of the total building stock's floor area would be renovated each year*. If this resulted in (on average) 75% reductions of those worst buildings' energy needs, the 60% reduction will be met without touching the remaining 40% of the building stock.[42]

In general, we strongly encourage urban areas and cities to monitor the energy needs of their buildings. Setting up a pathway that leads to an annual ≥2% decrease of energy needs is a sound approach for achieving a fully decarbonized building stock by 2050.

[38] Velux et al., 2017 and own estimation.

[39] ECOFYS et al., 2018

[40] IEA, 2018

[41] This is to be understood as an illustrative example for a stagnating or slowly growing building stock, like in Germany, where a 60% decrease of energy needs is considered to be the feasible limit in the long-term renovation strategy.

[42] 80% - 80% *(-75%) = 80% - 60% = 20%

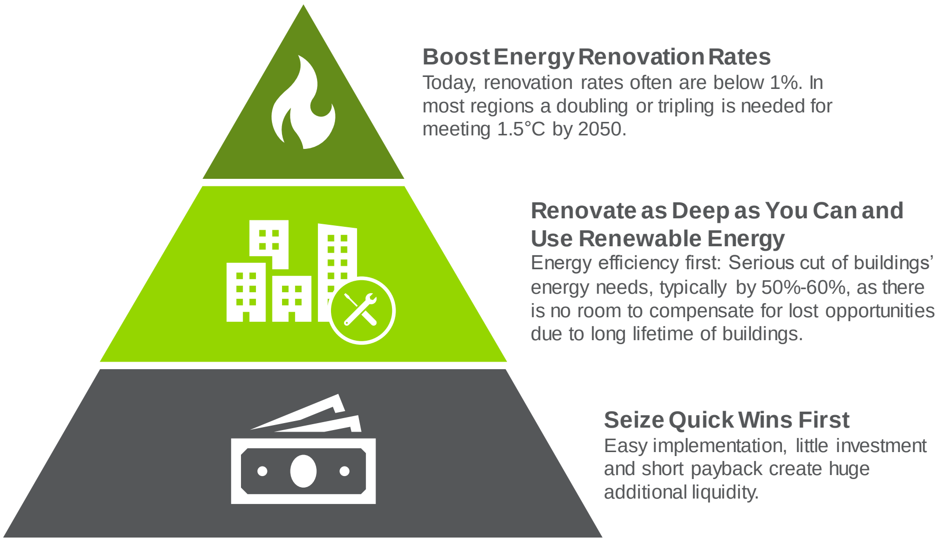

Figure 4. Pyramid of actions to get on track to 1.5°C

The pyramid of action as shown in Figure 4 highlights three main aspects of energy renovation:

- **Boost energy renovation rates:** A 1.5°C pathway will typically need 50%-60% reductions of urban buildings' energy use till 2050 to achieve the precondition for an affordable, 100% renewable energy supply. There are many ideas about what is meant by a renovation rate like 1%. From a 1.5°C perspective, the definition of such a rate should relate to actual reductions of GHG.

- **Renovate as deep as you can and use renewable energy:** Urban areas cannot afford to leave any savings potential unused. 1.5°C means going to technical limits in an unprecedented way, i.e., very deep renovation to (nearly) zero energy building levels.[43] This can be achieved step-by-step, which allows for seizing quick wins first. Each building and each efficiency measure (technical building systems [TBS], envelope, renewable energy) must contribute its maximum share to 1.5°C, as there is no room to compensate for lost opportunities.

- **Seize quick wins that do not compromise next steps:** Far-reaching optimization of TBS (heating, cooling, ventilation) is the priority to decrease up to 30% of emissions and energy costs.[44] Due to a city's high density, the relative potential of renewable energy generation within its boundaries is considerably limited. The bulk of renewable energy needs to be imported. Unlike energy efficiency, importing renewable energy does not save energy costs or create additional liquidity. By contrast, easy implementation, little investment, and short payback of optimization of TBS create huge additional liquidity that can be reinvested to boost energy renovation of buildings, creating a circle of further liquidity from energy savings.

[43] Schimschar et al., 2013
[44] Grözinger et al., 2017

Needed technological transformation in buildings to reach the 1.5°C pathway

To reach the 1.5 C pathway, buildings must have a technology transformation. Building managers, owners or operators can ensure a technology transformation in the following ways:

- Ensure energy efficiency first. Energy efficiency renovation of buildings must be a priority as it can lead to a 50%-60% reduction of energy needs in the building stock.
- When reducing the energy use of buildings, building envelopes must be improved and the heating and cooling of the building must be optimized—neither is optional. Each have an equal share in needed reductions.
- The most cost-effective way for urban areas and cities to tap the full potential of buildings in closing the gap for the 1.5°C target is through investments in:
    - Optimized, well-controlled, and maintained TBS for heating and cooling.
    - Flexible automation and control rather than traditional on-off operation,[45] thermostatic valves, use-dependent indoor air temperature and ventilation, or irradiation-controlled automatic exterior shading. In the energy renovation of existing buildings, this allows for a short payback of 2-5 years and short-term savings that help gather emissions.[46]
    - Improved building envelope to avoid heat losses in winter or heat gains in summer.

In energy efficiency renovation, advanced optimization of technical building systems alone may yield quick savings of 30% at short payback times of 2-5 years. This helps avoid cumulation of GHG emissions.

- Decarbonization of district heating/cooling systems or electrification of space heating and domestic hot water. Both require area-wide availability of highly energy efficient buildings and massive take up of:
    - Small and medium heat pumps and energy controls in single buildings, including implementing retrofit requirements for the installation of building automation and control systems in large, non-residential buildings and rolling out electronic performance monitoring and effective control functionalities in residential buildings.[47]
    - Large heat pumps and energy controls in district heating and cooling systems to ensure energy efficient power use and large-scale exploitation of significant low temperature and waste heat sources. The latter should be systematically addressed in urban heat maps and planning.

[45] For example using heat pumps with variable speed/power so called “inverter” technology.

[46] Grözinger et al., 2017

[47] Such requirements already have been introduced by the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) and needs to be implemented by all European Union Member States where technically and economically feasible.

This development goes hand-in-hand with a massive electrification of space heating:

- Shanghai: From 11% today to 24% by 2050
- Rotterdam: From 3% today to 30% by 2050
- New York: From 8% today to 15% by 2050
- London: from 7% today to 30% by 2050

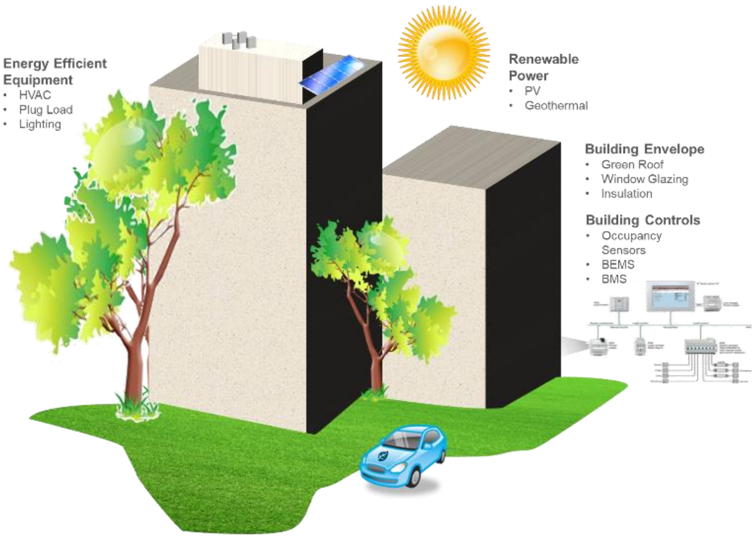

Figure 5. Main components for reaching the 1.5°C target: Increase efficiency and complement by fully shifting to renewable energy

Renewable energy

In the 2050 energy system, there must be a fully renewable, zero carbon energy supply for highly efficient buildings. Renewable supply is typically split into three categories of solutions:

- **Onsite:** Rooftop photovoltaics or solar thermal panels and individual heat pumps fall under this category. Due to restrictions in availability and storage capacity, alone they typically cannot guarantee a secure, fully renewable supply. While heat pumps for heating have a negligible share in the building stock today, we expect a massive uptake to 300,000 units in London, 370,000 in New York, and 2.4 million in Shanghai by 2050.

In the 2050 energy system, there must be a fully renewable, zero carbon energy supply for high efficient buildings. Renewable supply is typically split into three categories of solutions:

- Onsite
- Nearby
- Offsite

- **Nearby:** Typically, these are district energy solutions for heat or cold supply that can integrate significant storage capacity and exploit a wealth of different local renewable sources. This is a widely untapped source and we expect a massive uptake for large-scale heat pumps in district energy systems. Rotterdam and New York are both expected to have an electric capacity of 2 MW, London to have a capacity of 25 MW, and Shanghai to have a capacity of 46 MW.

- **Offsite:** Offsite indicates that, from a system's perspective, while sources cannot reasonably be linked to a single city, they still will supply the renewable electrification of cities. A prominent example of an offsite system is offshore wind power, which may feed both small individual heat pumps or large heat pumps for district heating systems. In regard to solar and wind power, in Europe a fivefold expansion is estimated between today and 2050, while in the US and China this expansion is expected to be 12-fold or 23-fold, respectively.[48]

Cost-effective, large-scale use of low and zero carbon energy in district heating or cooling systems requires area-wide availability of highly energy efficient buildings

Smart district energy systems for heating or cooling are an efficient supply solution for buildings in urban areas. However, what ultimately elevates district energy systems to be a preferred solution for a fully decarbonized urban energy supply of buildings is the provision of an area-wide stock of efficient buildings that need small amounts of low temperature energy.[49]

District energy systems have the potential to be flexible energy hubs, which in a 1.5°C energy system need to be fully utilized. These systems can serve as an energy broker between load profiles of the demand side (buildings) and the supply side, being fed by distributed renewable energy sources including solar thermal, geothermal, biomass-driven combined heat and power, and waste heat from industry, wastewater, or cooling processes, and wind power used directly or (preferably) by large heat pumps.

By aggregating demand and supply and potentially including large thermal storage capacity, district energy systems can level out different load profiles and the fluctuating nature of renewable generation. They add flexibility to the urban energy system, but only due to the overall low energy demand of area-wide energy efficient buildings. This ultimately allows for a 100% share of renewable heating or cooling energy on a large scale.

District heating and cooling:

- Requires area-wide availability of highly energy efficient buildings
- Is a preferred and ideal solution for a fully decarbonized energy supply of urban buildings
- Have the potential of being flexible energy hubs
- Allow for aggregating demand and supply and large thermal storage capacity

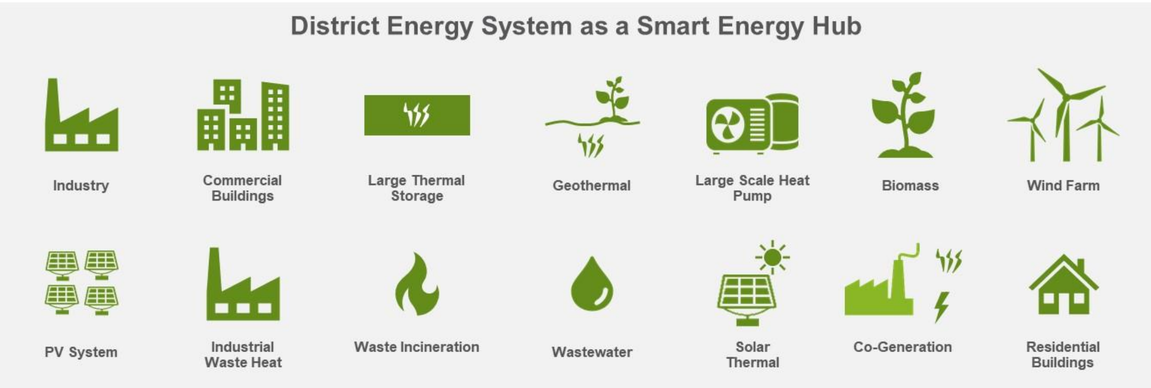

Figure 6. District energy systems are potentially flexible energy hubs

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[48] Estimated rise of power from wind and solar between today and 2050 in Europe: 400 MW => 1,900 MW; USA: 280 MW => 3,500 MW; China: 300 MW => 6,900 MW.

[49] Low-temperature generally means systems running below 60°C.

Electrification of space heating and domestic hot water is the most effective catalyst for fast decarbonization of energy supply

The following findings highlight the immense impact of energy efficiency in buildings for a sustainable urban energy system:

- Local fossil heat generation in buildings is the common solution for space heating and domestic hot water, whereas in most urban areas, electricity plays a minor role and mainly goes to direct heating rather than to heat pumps. This will significantly change on a 1.5°C pathway. Low energy buildings can run on low temperature heat, which predestines them for the highly efficient operation of heat pumps. Figure 7 illustrates the win-win situation by which heat pumps effectively catalyze the fast decarbonization of urban heat supply in combination with a low energy building stock.

- With little use of power, heat pumps mobilize multiple amounts of renewable energy for use in buildings. That little amount of power will gradually turn fully renewable on a 1.5°C pathway.

- The number of heat pumps needs to increase quickly. In the absence of district energy systems, small heat pumps will serve individual buildings while district heating systems will be fed with renewable energy to a large extent by large-scale heat pumps.

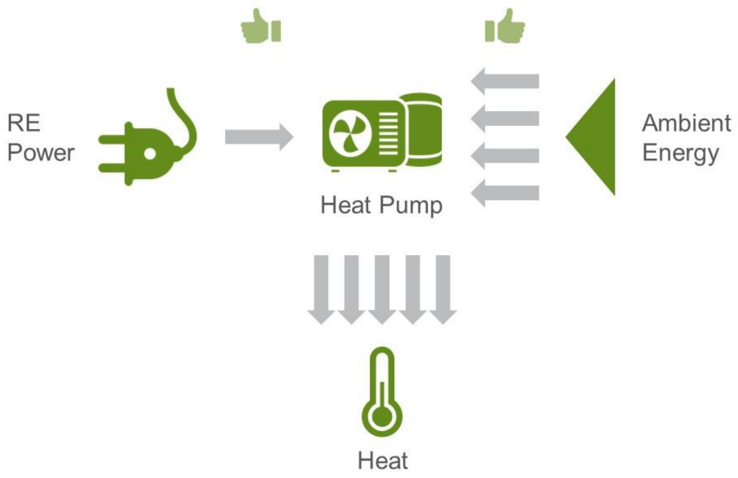

Figure 7. Win-win situation by using heat pumps

- The improvement of building envelopes and highly efficient TBS fed by renewable energy have approximately equal shares in these total savings.

> Large heat pumps that provide base load for district heating are projected to have an electric capacity of 17 MW in London by 2050.

Energy efficient buildings are crucial for an affordable and secure integrated urban energy system as they provide flexibility and allow significant downsizing

The affordability and security of the future urban energy system may depend on the massive electrification of heating and high shares of heat pumps. Both have a positive correlation with increasing energy efficiency of buildings. Highly efficient electrified buildings have four advantages over low efficient buildings:

- Efficient operation of heat pumps
- Significantly reduced electricity use and cost
- Significantly reduced peak load
- Significantly higher flexibility for demand response

Peak load determines investment in electricity grids and generation capacity. Both the reduced peak load of a high efficient building and its flexibility for when its peak load is needed allow for major downsizing of the power system (generation and grid) compared to buildings with poor efficiency.

In New York, heat pumps used for cooling of energy efficient buildings are estimated to provide 300 MW of flexibility to the grid by 2050. For Rotterdam, London, and Shanghai we estimate 10 MW, 150 MW or 1,200 MW, respectively.

Due to their high thermal inertia, high efficient buildings without comfort losses allow much longer switch-off times for heat pumps than low efficient buildings, enabling them to shift operation to off-peak times and reduce the risk of blackouts.

6. WHY CITIES SHOULD ELECTRIFY TRANSPORT

Electrifying transport is a key enabler for reaching the 1.5°C target in cities and urban areas; it reduces emissions, pollution, and costs

Transport accounted for 23% of global energy-related GHG emissions in 2015 and 26% of the final energy demand.[30] It accounts for 34% of the 2050 urban GHG abatement potential; the benefits from electrifying transport are large.

The electrification of transport reduces GHG emissions, air pollution (for example, from NO_X), and costs for transport owners and operators. It also ensures improved efficiency in the transport sector. Electrifying transport can occur on the following levels:

- At the global level, electrification of transport helps curb climate change by reducing GHG emission levels. As transport currently accounts for around 30% of global final energy demand and electrification, decarbonization potential is huge.
- At the urban level, electrification reduces NO_X and soot emissions. Transport is a major contributor to air pollution, accounting for around half of current global NO_X emissions. Currently available electrification technologies have the potential to reduce NO_X emission by 90% per passenger kilometer by 2050.[50] The effects of pollution from transport are especially important in cities, where large numbers of people and vehicles move within a small geographical space and, as a result, air pollution is an increasingly prominent policy priority. London and Rotterdam are both featured on the list of top 10 global cities where the chances of dying from transport pollution are high,[51] and have recently introduced (ultra) low emission zones.
- At the personal level, EVs provide a cost reduction compared to internal combustion engine cars. The reduced total cost of ownership stems largely from taxation regimes, fewer (moving) parts, and lower fuel costs, which results in reduced OPEX and increasingly lower CAPEX. Additional benefits from EVs exist including improved driving performance, reduced noise pollution, and the (monetizable) ability of EVs to provide services to the power system and buildings by using their batteries (and generation capacity in the case of fuel cell cars).

Electrifying the famous London double-decker bus fleet would relieve Londoners from annual emissions of 1,664 tons NO_X. This equals about 5,000 million diesel car kilometers.

Navigant's analysis shows significant contributions from electrifying transport in European, US, and Chinese urban areas for a 1.5°C pathway. These contributions are summarized in Figure 8, which shows the absolute reduction that is to be achieved, the percentage of the reduction total to be achieved, and the relative reduction in the city.

[50] Electrification of the Transport System - Studies and reports, European Commission, 2017

[51] A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015, International Council on Clean Transportation, 2019

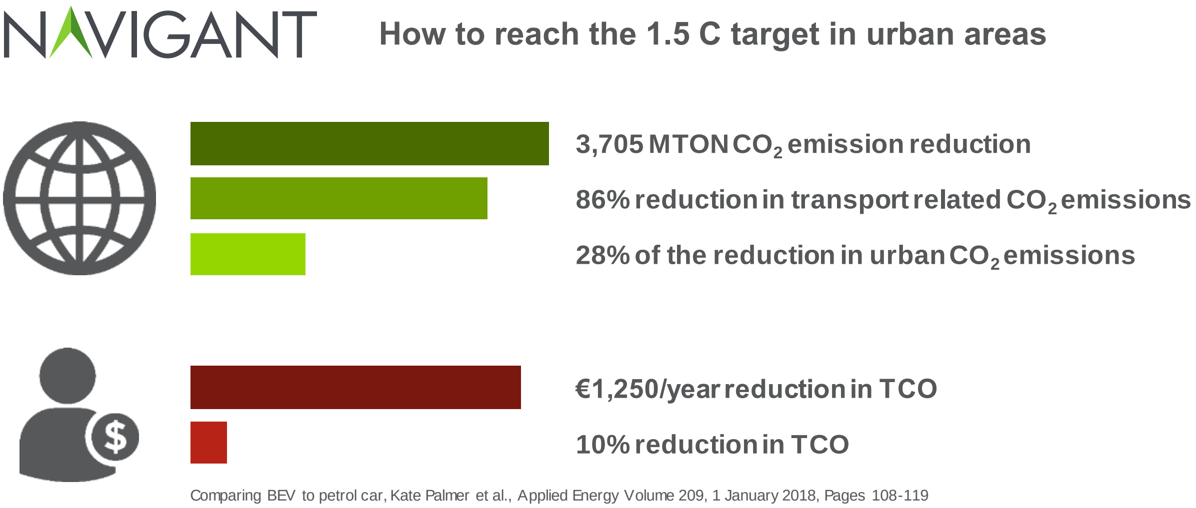

Figure 8. Benefits of the electrification of transport in a 1.5°C pathway scenario in European, US, and Chinese urban areas

Main conclusions

Navigant's conclusions on electrifying transport and its benefits are as follows:

- **Electrify transport to leap from business-as-usual to 1.5°C.** If all urban areas in Europe, the US, and China electrified their private and public transport, they would contribute to the 1.5°C target of the Paris Agreement with 28%. However, the contribution from transport varies by region and by city. Overall, the contribution to needed reductions from electrifying transport in cities to meet the 1.5°C level totals 17% in Europe, 24% in the US, and 37% in China.

- **Decarbonize transport to reduce GHG emissions and local air pollution.** Achieving a 1.5°C scenario requires rapid, large-scale electrification of land and sea transport and a huge modal shift and a fuel shift. Transport requires the most drastic acceleration of technology uptake to reach the 1.5°C level. Required technologies already exist or are in the pipeline and already are starting to see traction in the market.

- **Invest in electrifying vehicles** as they can contribute most significantly to the decarbonization of transport and reduction of air pollution in a 1.5°C scenario, as a result of their prevalence and suboptimal use in urban environments. However, policy instruments for cities are more limited here compared to buses, for which franchising and permitting options readily exist. Establishing low or zero emission zones for cars and trucks is often limited by national policy and disproportionally affects less affluent parts of the population.

- **Pursue the electrification of shipping needs** to fulfil the sector's potential for reducing carbon emissions (by electrifying power trains) and reducing air pollution (by using shore-side electricity).

- **Electrify transport to save lives**. As the guardian of health and comfort in urban areas cities can eliminate emissions and local air pollution.

- **Make substantial infrastructure investments** to enable electrification for charging infrastructure and the power distribution grid to accommodate the additional demand from passengers and light duty vehicles in urban areas by 2050. An estimated US$50 billion of investment is required for 42 million chargers alone until 2030 across Europe, the US, and China.

Policy recommendations: What city mayors should do on transport

Local authorities can create a context that amplifies positive effects from external autonomous technological developments and (inter)national laws and regulations. London demonstrated this with its congestion charge and environmental zones. Additionally, cities can bring together diverse actors in the urban environment that need to collectively make the mobility transition happen. Specifically, cities should:

Orchestrate

- Through information sharing, transparent planning, and active stakeholder management, cities should work with local energy companies, housing corporations, project developers, and fleet owners/operators on the timely co-creation of infrastructure that facilitates the electrification of the transport sector. An estimated US$50 billion of investment is required for 42 million chargers until 2030 across Europe, the US, and China.[52]

Act early

- Create clear, actionable plans to realize electrification's potential. These plans should link long-term climate goals to short-term air pollution and congestion management goals.
- Develop and implement a monitoring framework that enables tracking progress.
- Celebrate success early in the transformation to ensure stakeholder buy-in for reaching long-term, complex goals.
- Electrify the city's own fleet now (vehicles, buses, city boats, ferries).
- Invest in and promote public transport to facilitate a modal shift away from passenger cars.
- Use local regulation and permitting options to electrify last-mile inner city freight and goods delivery traffic.
- Using franchise agreements with public transport operators to enforce zero emission goals for buses, taxis, and more.
- Incentivize the installation of charging points at (semi-) public locations like office buildings, parking facilities, supermarkets, and tourist attractions.
- Introduce parking incentives and other fiscal incentives for moving toward electrifying transport.
- Incentivize the installation of shore supply in harbors and present a plan for how to address that all vessels use electric shore supply when at berth.

Enable an environment that promotes flexibility and adaptability in electrifying transport

- Cities should create platforms for collaboration and procurement on which other cities and stakeholders can drive innovation. Technology leaders can act as valuable knowledge partners and enablers for such platforms.

Achieving a 1.5°C scenario requires rapid, large-scale electrification of land and sea transport

To meet the ambitions of the Paris Agreement and improve air quality, electrifying public and private transport on land and at sea is inevitable. Successful decarbonization of the transport sector in line with a 1.5°C scenario requires a huge modal shift in addition to a fuel shift.

Navigant assessed the impact of electrification on the stock of vehicle categories in four cities based on expected national averages for 2050, IEA Mobility Model data for urban

[52] See footnote 55

areas, and historical city data. The analysis indicates a need for near-complete electrification of buses and for a high degree of electrification of passenger vehicles. Trucks see significantly lower uptake, which is understandable giving the current state of technology and the limited share in the urban transport sector.

The results for land transport are summarized in Figure 9, which also illustrates the range and need to accelerate electrification to meet 2050 targets. Of the researched cities, Rotterdam is projected to have the highest share (100%) of electric buses by 2030. This is the result of a Green Deal covenant in the Netherlands in which all public transport operators have committed to fully decarbonize by 2030. At only 18%, London is projected to have the lowest share of electric buses by 2030. By 2050, London, New York City, and Shanghai are expected to have reached electrification levels of at least 80%.

Electrification of cars is already gaining traction and is expected to reach levels ranging from 8% (Europe) to 21% (China) by 2030, increasing to 60%-68% (Europe and China, respectively) by 2050.

The amount of electrified trucks expected by 2030 is negligible. In 2050, electrification ranges from 34% (US) to 41% (Europe).

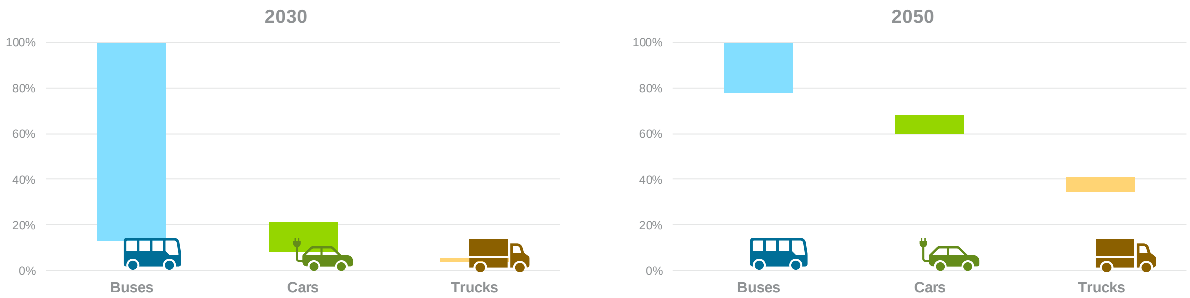

Figure 9. Range of target electrification levels for researched example cities for different transport modes to achieve a 1.5°C scenario

Cars can contribute significantly to the decarbonization of transport

Electrifying different forms of transport to achieve the 1.5°C pathway results in different contributions to GHG and air pollution reduction levels. This is because buses, cars, and trucks do not contribute equally to the final energy consumption and emissions due to their different usage patterns and use of fossil fuels.

Navigant analyzed the relative contributions of three categories of vehicles to help assess the potential and prioritize electrification. Figure 10 shows the results.

In Shanghai, the number of battery EVs is projected to rise from about 107,000 today to 6.7 million by 2050.

The analysis indicates that the largest contribution to emission reductions is from cars (see Figure 10). Cars will contribute with 35% (China) to 60% (UK), trucks with 36% (UK) to 48% (China), and buses with 3% (Europe and the US) to 17% (China). The relatively low contribution of buses is in part a reflection of the high level of electrification that has occurred to date.

Cities have moderate success but limited impact using policy instruments on transport like environmental zones to improve air quality,[53] whereas for other categories more direct influence can be exerted through franchising and permitting systems.

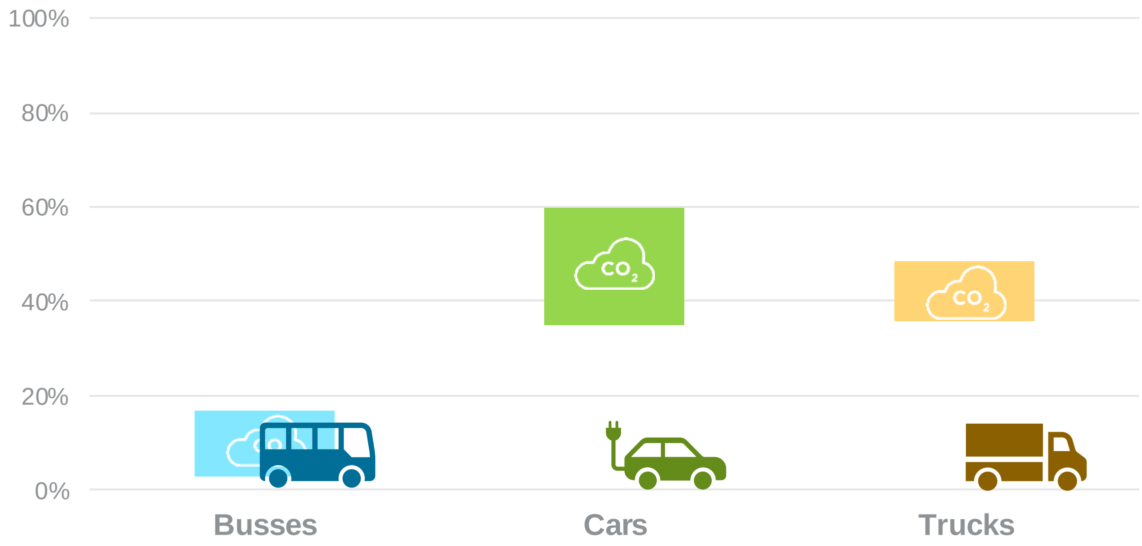

Figure 10. Estimated relative range of contribution to CO_2 reduction for different modes of urban transport in a 1.5°C pathway scenario

As for EVs cities should keep in mind the following:

- An EV's well-to-wheel energy efficiency is around 30% better than a comparable petrol car and the electricity will be increasingly generated from renewable sources.
- Most of the need for public charging will be in the cities and at the workplace. Therefore, cities should incentivize or invest in charging stations around office buildings, supermarkets, and city attractions.

Electrification of shipping needs to be pursued more rigorously

The electrification of buses, cars, and trucks is making serious inroads in the transport sector; however, the electrification of the shipping sector has not shown much progress. There are two application areas for electrification: powertrains and the shore-side electricity.

Navigant finds that powertrain electrification is suitable for domestic shipping due to short routes and small ships. International shipping requires globally available uniform fuelling, and in quantities to allow refuelling in every port.

Rotterdam is about to build the biggest shore power connection in the offshore industry. A shore power connection of 20 MW is required to electrify vessels in the Calandkanaal. The citizens of Rotterdam will be unburdened by 21.4 tons of PM emissions every year. This equals emissions from 6,800 million diesel car kilometers.

[53] Gemeente Rotterdam. As an example, Rotterdam claims a 4% reduction in NO_X and 13% in soot (EC) due to a set of policies between October 2015 and June 2017 whereas the autonomous reduction for these pollutants was 12% and 23% in that same period, respectively.

The potential is substantial. Battery electric ships are almost twice as efficient as ships with an internal combustion engine, and the higher efficiency will offset the higher price of electric ships considering a lifetime of 20-25 years. Electricity will be the most cost-optimal fuel to decarbonize domestic EU shipping; for international shipping, hydrogen, bio-LNG, or biodiesel are likely to dominate the fuel mix,[54] including hybrid solutions (e.g., hybrid, electric propulsion technology).

Ships at berth typically use auxiliary engines to generate electrical power for communications, lighting, ventilation, and other onboard equipment. Shore supply is an option for reducing the unwanted environmental impact of ships at berths—that is, GHG emissions, air quality emissions, and noise pollution. Port cities like Rotterdam are investing in clean shore power as part of a set of measures to meet European air quality norms.

Substantial infrastructure investments are required

EVs will be the single largest addition of energy demand to the power grid in many nations of the developed world. By 2050, Navigant estimates a more than a hundredfold increase from 2015 power demand from just passenger and light duty vehicles in urban areas. The total charging energy demand for EVs in Europe, the US, and China could reach 280 billion kWh by 2030, with AC charging at 20 kWh or below accounting for roughly 60% of that.[55]

Transport's large-scale electrification requires substantial investments in infrastructure. This concerns not only the build-out of an extensive (fast) charging network but also the distribution grid itself and data communication networks to support automated, connected, and clean transportation. The amount and nature of the investment is expected to vary significantly from city to city and is dependent on existing grid capacity, integration of local generation, the technology mix for clean transportation and space heating. This underlines the need for detailed energy master planning led by local authorities and energy companies.

Road infrastructure is also likely to see changes as public transport gains in importance and new forms of clean transport like speed pedelecs emerge as viable alternatives for commuting. It should also be noted that the need for new infrastructure strengthens the need for the electrification of currently diesel operated off-highway machinery (like excavators, wheel loaders, cranes) to mitigate their impact on air pollution.

There are substantial additional uncertainties related to the development of urban mobility; however, that have potentially huge impacts on infrastructure investment: an increase in carsharing, ridesharing, and autonomous vehicles reduces the number of vehicles in a city and, to a lesser extent, the number of kilometers driven. It changes the duty cycle of a car; which impacts a car's ability to participate in sector coupling services and increases the need for fast charging, pushing capacity requirements for charging infrastructure. Additionally, the development of smart charging solutions is critically important; a study for Germany shows that smart charging reduces the need for grid expansion to 2030 by 40% to 50%[56].

[54] Wouter Terlouw, Daan Peters, Kees van der Leun, 2019

[55] Charging ahead: Electric-vehicle infrastructure demand, McKinsey, 2018

[56] Agora Verkehrswende, Agora Energiewende, Regulatory Assistance Project (RAP) (2019): Verteilnetzausbau für die Energiewende – Elektromobilität im Fokus. Figure S-2, https://www.agora-verkehrswende.de/fileadmin/Projekte/2019/EV-Grid/Agora-Verkehrswende_Agora-Energiewende_EV-Grid_WEB.pdf

7. WHY CITIES SHOULD USE SECTOR COUPLING

Sector coupling is a key element for a 1.5°C pathway

Optimizing the use of renewable energy and stabilizing the grid is a precondition for a cost-effective transition to a decarbonized energy system. This can be reached through sector coupling, which is accomplished by:

1. Converting and storing one energy carrier into another.
2. Integrating and matching the energy consuming sectors (buildings for heating and cooling, transport, water, and industry) with the energy-producing sectors.

By coupling the biggest energy consumers, reducing their energy consumption, and storing energy, we will achieve the needed flexibility and resilience that an energy system primarily built on renewables requires.

Because renewable energy is fluctuating, the key issue is not how much renewable energy can be generated but how much can be integrated into our energy system. Sector coupling is a cost and energy efficient solution for linking the different sources of energy while increasing the penetration of renewable energy sources and affordably decarbonizing the economy.

If New York City is to reach the 1.5°C level it needs to provide system flexibility through flexible loads of 300 MW installed capacity of heat pumps connected with thermal storage and 1.2 million EVs. In addition, battery storage will grow from less than 1 GW to approximately 110 GW in the US. Energy storage can be used to store renewable and excess/waste energy when it is abundantly available, which can then be used at a more optimal time. Therefore, energy storage can increase the uptake of renewable energy and should be incorporated into the energy system.

If Shanghai is to reach the 1.5°C level it will require grid stabilization, which is about storing, reusing, and coupling excess energy to ensure grid stability and energy efficient use of energy to avoid expensive overinvestments in renewable energy and grid.

Main conclusions

The following findings support Navigant's recommendation for cities to use sector coupling:

- Cities' high density of buildings, transport, infrastructure, and economic activity drive innovation and enable the efficient use and exploitation of synergies between sectors to create a highly efficient energy systems.
- The analysis shows that the 1.5°C pathway requires a consistent implementation of all measures, including energy efficiency, renewable energy, and sector coupling. The most cost-effective way to reach the 1.5°C target is through investments in energy efficiency and sector coupling, as this will ensure that substantial investments in energy generation and energy infrastructure can be avoided.

Policy recommendations: What city mayors should do on sector coupling

Achieving 1.5°C means going to the limit of what is imaginable with the technology available today and in the pipeline. Decisive leadership will help sector coupling deliver an indispensable contribution to a cost-effective pathway to limit global warming to 1.5°C and will require an integrated energy system. Specifically, cities should:

Set up and implement ambitious and actionable plans

- Plan the whole journey by means of a holistic 1.5°C strategy now.
- Set ambitious and actionable short-, mid-, and long-term targets and regulate in order to incentivize investments.
- Keep track of targets and act accordingly.

Act early

- Seize quick wins that do not compromise next steps, such as investments in charging infrastructure.
- Adapt to the changing requirements of the energy transition and guarantee environmental compatibility, while simultaneously ensuring high security of supply and economic efficiency. The key ingredients for an integrated energy system are:
  - Renewable power sector
  - Energy efficient and electrified end-use sectors (transport and buildings)
  - Digitized (smart) appliances and equipment on both the supply and demand side
  - Smart infrastructure (e.g., power networks, district heating and cooling, telecommunication, charging infrastructure)
  - Demand response and storage
  - Connected energy system across sectors to ensure affordability

Lead by example

- Map potential and invest in the necessary zero emissions and networked infrastructure.
- Invest in and remove barriers for city pilot projects.
- Collaborate and set common targets with other city administrations, local industries/manufactures, and regional and national governments to standardize and industrialize solutions that will drive costs down.
- Collect data and ensure transparency and accessibility of energy performance and CO_2 emissions data to facilitate research and timely monitoring actions.
- Communicate and showcase your city's examples (public and private case stories), show what existing and new technology can contribute with on the journey toward the 1.5°C target.
- Be a national, regional, and global front-runner.

The most cost-effective way to reach the 1.5°C target is to invest in energy efficiency and sector coupling

In regions with growing shares of renewable power, situations with low spot market electricity prices occur more frequently and, despite ongoing grid extensions, increasing curtailment of renewable power is needed. Sector coupling reduces these situations and leads to the better use of renewable energy, fewer renewables installations, and reduced overall costs.

Cross-sector integration, or the connection between electricity, heat, and fuel, reduces investments in generation capacities and energy infrastructure. E.g. excess power can be used to heat water directly (power-to-heat) or more efficiently with heat pumps. The hot water can be stored cost-effectively in short- or long-term storage (e.g. water tanks or pits) and be used hours or even weeks later to heat buildings via the district heating network. If different modes are available to satisfy the demand (e.g., electricity via a heat pump and biogas via a boiler), the system is flexible and can avoid power peaks. In addition excess energy can be used to generate synthetic gases (power-to-gas), then these gases can be used when solar and wind energy are only partly available to generate relatively cheap electricity in power plants and avoid further investments in the renewable energy capacity for peak capacity. This flexibility can help reduce investments in the peak capacity and in grid-infrastructure. This also guarantees the security of the energy supply and resilience of the system to always balance generation and consumption. Combining this with energy efficiency measures to first reduce the demand can further optimize the economics.

The 1.5°C pathway can be achieved cost-effectively with only energy efficiency and smart shifting between power, heat, and fuels. Substantial investments in energy generation and energy infrastructure can be avoided.

Cities are well-suited for sector coupling solutions

Sector coupling will happen in cities with a high density of different energy demands, energy infrastructures, and potential for interconnections and shifts. To move toward a 1.5°C pathway, cities must electrify transport and buildings, creating additional and diverse loads combined with the benefits of reducing air pollution (as combustion engines and fossil are the main source for emissions in inner cities). In addition, district heating systems are often available in cities, which offer additional options for sector coupling solutions.

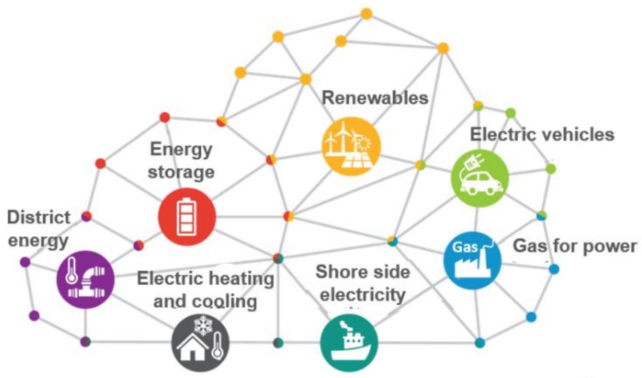

Figure 11. Interconnected urban energy system

The pathway to 1.5°C is about optimizing the overall urban energy system with a holistic systems approach rather than its individual elements. To meet the 1.5°C target, cities and urban areas need to entirely transform their energy systems. They have an opportunity to reduce GHG emissions and air pollution by using synergies between the different sectors of the urban energy system. These systems are currently in the middle of a major global transformation, changing from one-way power flow with centralized generation to a renewable, highly digitized and dynamic energy system with two-way energy and communication flows.

Sector coupling as an enabler for the decarbonization of transport and buildings

As the power sector is expected to be decarbonized by mid-century,[57] large-scale electrification enables the decarbonization of end-use sectors such as transport and buildings (end-use sector coupling). Electrifying end-use sectors helps increase renewables penetration as it offers new demand with different load profiles. It helps if the demand is flexible, meaning that it can be shifted in time (e.g., due to smart control systems).

[57] IPCC, 2018 chapter 2: p. 136

Large variety of sector coupling solutions

There are a variety of options for sector coupling solutions (e.g., storage, batteries, power-to-gas, flexible demand, integrated district energy networks, or reuse of excess heat from data centers or commercial buildings), which show that a digitized energy system, smart grids, and smart control systems are preconditions for sector coupling.

The options for sector coupling solutions differ between and within cities due to different starting points, urban structures, climatic conditions, political decisions, the state of the general energy market, market penetration levels, and the state of technological advancement. The following examples demonstrate the principles and the variety of sector coupling solutions.

Storage and system flexibility
Storage capacity and system flexibility are needed at different time scales. Depending on the requirements and characteristics of the technologies (e.g., investment costs, electricity costs, energy losses, frequency of storage cycles), different storage solutions are suitable for short-term variability of demand and renewable energy supply, daily fluctuations, or over and undersupply over days or weeks. While supercaps or batteries (connected to AC grids with grid converters) cover the need for short-term flexibility, power-to-heat, and thermal storage serve the medium-term and pumped hydro and power-to-gas provide long-term flexibility solutions.

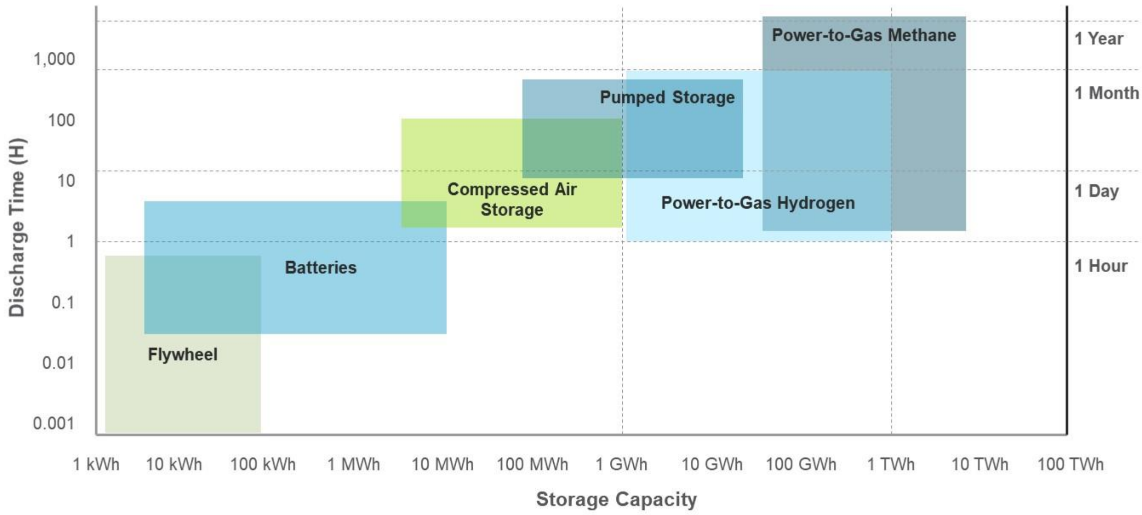

Figure 12. Timescale of different storage technologies[58]

Alone, the installed grid battery capacity is expected to rise from <1 GW to 70 GW[59] in Europe, 110 GW in the US,[60] and 350 GW[61] in China.

Flexible end user demand
Making electricity and heating loads more flexible helps synchronize demand and generation, avoid network bottlenecks, and ensure network stability and cost-efficiency. Short-term flexibility can be provided by heating (heat pumps, direct electric heating, and district heating), cooling (e.g., in supermarkets), smart charging EVs, and in electricity applications in industry and household appliances. A digitized energy system, smart grids,

[58] EC, 2018
[59] EC, 2018
[60] Wesley Cole, Trieu Mai, James Richards, Paritosh Das, and Paul Donohoo-Vallett, 2017
[61] China National Renewable Energy Centre, 2017

and smart control systems are preconditions for the effective management of flexible demands and can be considered the brain behind flexibility.

	Short-Term Flexibility	Medium-Term Flexibility	Large-Term Flexibility
Challenge	• Short-term variability of demand and RES • **Timescale:** Fractions of a second to minutes	• Daily fluctuation of demand and RES • **Timescale:** Hours	• Over or undersupply • **Timescale:** Days to weeks
Technology Solution	• Battery storage • Flywheels • Flexible demand from EVs and heat pumps	• Battery storage • Flexible demand from EVs and heat pumps • thermal storage	• Long-term storage (pumped-hydro, compressed-air) • Power-to-heat with thermal storage • Power-to-gas

Figure 13. Smart flexibility options[62]

Cross-sector integration
Power-to-X options (such as power-to-heat, power-to-gas, or power-to-liquid) use electricity to produce heat, synthetic gases (such as hydrogen), or liquid fuels. District heating systems, which are effective at bringing in sustainable heat to cities, offer great opportunities to connect different sectors. If different technologies are integrated in the district heating supply (such as cogeneration, heat pumps, thermal storage) the system can operate in different modes that are most beneficial for the overall energy system and are most cost-effective for the users. When wind and solar energy are not available, the cogeneration can be used to generate electricity and power simultaneously. If renewable energies are abundant, the heat pump can generate heat and the district heating network can be used as thermal storage.

[62] EC, 2018

8. CITY EXAMPLES

8.1 Why selected cities?

Cities were selected based on following criteria:

- Suitable representatives (regional metropolises) for upscaling
- C40 members
- Port cities
- Spread across Europe, US, and China
- Pilot city within EV 30@30 campaign
- Strategies for decarbonization

8.2 Overview of selected cities

IEA mentions several key drivers of urban energy systems that determine their potential for future development. For the selected cities, values are as follows:

Table 1. Key drivers of urban energy systems; numbers for selected cities

	London	Shanghai	Rotterdam	New York City
Affluence GDP per capita in €/(cap a)	53,300[63]	17,000[64]	42,800[65]	64,000[66]
Population in million	9.2[67]	23.3[68]	0.6[69]	8.6[70]
Area in km²	1,569[71]	6,340[72]	325[73]	784[74]
Density Population in 1/km²	5,860	4,150	3,080	10,990

[63] EC, 2019
[64] Statista, 2019
[65] Hindremäe
[66] NYC Data, 2018
[67] World Population Review, 2019a
[68] World Population Review, 2019d
[69] World Population Review, 2019c
[70] World Population Review, 2019b
[71] World Population Review, 2019a
[72] World Population Review, 2019d
[73] World Population Review, 2019c
[74] World Population Review, 2019b

	London	Shanghai	Rotterdam	New York City
Building Stock Residential in million m²	239[75]	630[76]	28[77]	309[78]
Building Stock Commercial in million m²	69[79]	574[80]	10[81]	90[82]
Land Availability (Land area to building area ratio)	Medium (0.2)	Low – Medium (0.24)	Medium – High (0.12)	Low (0.51)
Economic Structure	Service industry (financial and insurance), IT[83]	Business and trade-, financial and insurance services[84]	Business services and trade, Industry[85]	Financial, professional and technical services[86]
Climate[87]	Temperate oceanic, Cfb	Humid subtropical, Cfa	Marine West Coast, Cfb	Humid subtropical, Cfa
HDD[88] Set temperature 15.5°C	1,868 (320)	983.7 (165)	1,878.9 (295)	2,024 (212)
CDD[89] Set temperature 22°C	52.5 (19)	957 (185)	78.5 (30)	411 (128)

8.2.1 London

London is the capital of the UK and has more than 8 million inhabitants. It is the largest municipal population in the European Union. Although GHG emissions are decreasing, the city heavily relies on fossil fuels and suffers from poor air quality.[90] By 2050, the inhabitants of London will total around 12 million.

Currently, GHG emissions account for 34 $MtCO_{2e}$; around 6 $MtCO_{2e}$ can be accounted to the transport sector and approximately 15 $MtCO_{2e}$ to the building sector. Emissions of both

[75] Valuation Office Agency, 2012
[76] Shanghai Municipal Statistics Bureau, 2004
[77] Statline, 2019
[78] NYC Mayor's Office of Sustainability
[79] Valuation Office Agency, 2012
[80] Shanghai Municipal Statistics Bureau, 2004
[81] Statline, 2019
[82] NYC Mayor's Office of Sustainability
[83] Mayor of London, 2016
[84] Sun, 2016
[85] City of Rotterdam Regional Steering Committee, 2009
[86] U.S. Bureau of Labor Statistics, 2019
[87] Kottek et al., 2006
[88] BizEE Degree Days
[89] Ibid.
[90] Mayor of London, 2018a

sectors can be reduced to less than 1 $MtCO_{2e}$ until 2050, i.e. approximately 20% in the transport sector and around 40% in the buildings sector. To tackle challenges and impacts of climate change, London is one of the first cities to release a Paris Agreement-compatible plan and commits to be a zero-carbon city by 2050.[91]

The plan outlines what is needed to make London a GHG neutral city considering actions from the mayor, businesses, communities, boroughs, and national government. To achieve the zero carbon ambition, the city plans to have at least 50% of new car sales being ultra-low emission by 2030 and to have all new cars and vans be zero emissions with a London-wide zero emissions zone by 2050.[92] This will result in a massive uptake of electric cars, from 17,000 recently to 1.8 million electric cars by 2050. The city already hosts more than 1,700 electric taxis and 155 electric buses, with nearly 3% of new cars registered to be EVs.[93] By 2050 we expect around 10,000 buses will be electrified, representing a share of 79% of the bus fleet.

A total of 5,000 charging points have been installed throughout London, in which rapid charging points are expected to grow up to 300 points by this year[95] and to 6,000 by 2050 (based on our assumptions). With an additional 20,000 slow charging points, we expect that 26,000 public chargers will be operated in Greater London by 2050. GHG emissions can be reduced from around 6 $MtCO_{2e}$ to less than 1 $MtCO_{2e}$ in the transport sector based on the assumptions above and the outlined approach in Appendix A. In addition, low carbon vessels are core to the zero-carbon ambition that the city is exploring the potential of fully electric, zero-emission high speed vessels and the application of shore-side power throughout the port.[96]

London also aims for GHG reduction in the building sector by investing in various programs to incentivize energy efficiency and more efficient gas and renewable heating systems such as heat pumps.[97] Our results show that the share of electricity for heating has to increase from 7% to 30% by 2050, i.e., around 300,000 heat pumps have be to be installed, accompanied by a phase out of fossil gas boilers and electric radiators. For cooling, the share of electricity will decrease from 100% to 80% due to an expected boost of solar thermal cooling according to IEA's *Energy Technology Perspectives (ETP) 2017*. Large heat pumps with around 25 MW electric capacity running on renewable electricity and feeding thermal energy into district heating will be another essential pillar of decarbonized heat for

[91] Mayor of London, 2018b
[92] Mayor of London, 2019
[93] ibid.
[94] Calculations are based on input from GEMIS which is a life-cycle analysis model and database acknowledged as a tool by the World Bank for Climate-Smart Planning. The database provides energy flows, carbon footprints and air emissions of products/ processes such as Diesel-Busses, Diesel-Car, heating boilers and vessels.
[95] Ibid.
[96] Kehal, 2018
[97] Mayor of London, 2018a

Londoners. Energy efficient HVAC systems combined with nearly net zero energy buildings are a prerequisite toward sustainable heating and cooling; efforts in the building sector are assumed to result in an emission reduction from around 15 $MtCO_{2e}$ to less than 1 $MtCO_{2e}$.

The city is looking into decentralized energy systems to increase renewable generating capacity and flexible energy system pilot projects including Sharing Cities, Smart Bunhill, FlexLondon challenge, Smart Meter Rollout, and Electric Vehicle Trial of Commercial Logistics Vehicles. Until 2050, renewable electricity generation in Europe is expected to increase threefold from recently around 1,000 TWh (with 100 TWh for biomass, 400 TWh for hydro and 500 TWh for solar and wind). In 2050, the share of solar and wind will significantly increase to approximately 1,900 TWh. Electricity generation from hydro will account for about 400 TWh and generation from biomass will account for 700 TWh. To support increased solar and wind generation, battery storage needs to increase to 70 GW. Additional system flexibility can be provided through 150 MW installed capacity of heat pumps connected with thermal storage and 1.8 million EVs, which will respond to the needs of the power system.

8.2.2 Rotterdam

With a turnover of 469 million tons in 2018, Rotterdam has the largest port in Europe and the seventh largest in the world. It is strongly rooted in the fossil sector, importing huge amounts of oil and coal and featuring the most energy efficient refinery and chemical cluster in the world. Around 1.2 $MtCO_{2e}$ of emissions are produced in the transport sector and another 0.9 $MtCO_{2e}$ in the building sector. To align with a 1.5°C scenario, emissions in both sectors need to be cut down to nearly 0 $MtCO_{2e}$ (share of GHG reduction in the transport sector is around 15% and the buildings sector 10%). Overall GHG emissions account for 7 $MtCO_{2e}$ in the Greater Rotterdam Area today. The city has 645,000 inhabitants, by 2050, the population will be closer to 700,000. The city is one of the 23 constituting municipalities of the Metropole Region Rotterdam The Hague (MRDH), a collaboration of 23 municipalities with a total of 2.3 million inhabitants that have expressed the ambition of being an innovative, economic strong, sustainable, and accessible region.

The port is moving away from the city, and this impacts its drive toward sustainability (both physically[98] and mentally) as it has proven difficult to align on decarbonization pathways, support policies, and operationalizing them. While the port bets heavily on carbon capture and utilization, providing CO_2 to greenhouses in the region and providing excess heat to the city for space heating, it is unclear if the legacy industry delivering these resources can or should exist in the future. This raises questions about investing in city infrastructure that uses these commodities.

Targets were set for public transport and city logistics in the Green Deal 010,[101] which was signed in 2014 and strives for urban deliveries with the lowest possible emissions by 2025. To align with a 1.5°C scenario, Rotterdam's emissions in the transport sector have to be cut from currently approximately 1.2 $MtCO_{2e}$ down to zero. This is line with the ultimate aim of the Green Deal 010 to reduce harmful emissions (CO_2, NO_X, PM) due to urban logistics to zero, as stated in the national "Green Deal Zero Emissions City Logistics." Currently, 20% of city buses are already emission free, by far the largest percentage of all cities considered in this study,[102] as is the case for EVs' uptake. Until 2050, we expect that the number of electric cars increases from around 8,000 today to 120,000 (4% to 60%) and an uptake of electric

[99] Roadmap Next Economy
[100] Jeroen Overduin (CC EAF RC-NL BP)
[101] Logistiek 010
[102] Greendealzes

buses from 55 to around 320; the share of electric buses will accelerate to 100%. To fulfil demand, the number of charging stations will also increase, from 3,000 today to more than 7,000 with a minor share of fast charging stations (400) to reduce impact on the grid.

Similar to the other cities in our study, heat pumps will significantly increase to 20,000 for each space cooling and heating. The share of electricity will consequently increase from 3 to 30% for heating, whereas demand for electricity for cooling will decrease from 100% to 89% due to the uptake of solar thermal cooling in the EU. Furthermore, we expect that 2 MW of electric capacity will be available in the district heating system by 2050. For this purpose, large heat pumps running on renewable electricity will be crucial.

As described for the Greater London Area, annual renewable electricity generation has to increase threefold to 3,000 TWh in the EU, with 1,900 TWh from solar and wind, 400 from hydro, and 700 from biomass—around 60% will be generated by solar and wind. Recently, electricity generation from solar and wind is approximately 500 TWh, from 400 TWh of hydro and from 100 TWh of biomass. To support increased solar and wind generation in 2050, battery storage needs to increase to 70 GW. System flexibility will be provided through 10 MW installed capacity of heat pumps connected with thermal storage and 120,000 EVs, which will respond to the needs of the power system.

8.2.3 New York City

With nearly 9 million inhabitants, New York City is the largest, most densely populated city in the US. By 2050, the inhabitants of New York City will total 11 million. In September 2014, New York City committed to cutting 80% of its GHG emissions by 2050, with an interim target of 40% GHG reduction by 2030. Today GHG accounts for 50 $MtCO_{2e}$ in Greater New York Area. Around 15 $MtCO_{2e}$ of emissions are produced in the transport sector and 21 $MtCO_{2e}$ in the buildings sector. To align with a 1.5°C scenario, emissions in both sectors need to be cut down to nearly 2 $MtCO_{2e}$ (share of GHG reduction around 25%) in the transport and 1 $MtCO_{2e}$ in the buildings sector (share of GHG reduction around 40%).

The city aims to have 20% of new vehicle registrations for EVs by 2050.[103] It also plans to convert its entire public bus system to an electric fleet by 2040.[104] In 2019, New York State had more than 40,000 EVs on the road, including 18,000 battery EVs and 26,000 plug-in hybrid/extended range EVs,[105] representing a minimal share within the more than 2 million registered cars in New York City.[106] Until 2050, we expect that the share of battery EVs needs to increase to 60% and of electric buses to 80%, which makes a 170-fold increase of EVs. By 2050, more than 1.2 million electric cars and 16,000 buses will be operated in the city. At the same time, the number of public chargers will boost from less than 1,000 today to 20,000 in 2050 with a larger number of slow chargers (around 13,000) and around 7,000 fast chargers. New York City announced its plan to invest a $10 million to install fast charging stations in the short- to mid-term. [107]

A large share of New York City's emissions come from buildings. The city aims to reach the goal of One Million Buildings Clean and Efficient through a range of programs such as The NYC Retrofit Accelerator and the Voluntary Leadership of Carbon Challenge in addition to robust legislation frameworks including The Climate Mobilization Act 2019, Climate Action Executive Order, Greener Greater Buildings Plan.[108] A pillar of decarbonized heat is the massive uptake of electric heat pumps until 2050. We expect that around 370,000 heat pumps for space heating will be operated in Greater New York Area, which represents a share of around 15% for heating. For cooling, the share of electricity remains similar to today (87%), but heat pump installation will significantly accelerate to 1,000,000 devices. Additionally, we expect an increase of district heating; around 2 MW electric capacity will be provided though large heat pumps running on renewable electricity.

The New York City electric grid must become 70% to 80% renewable to achieve the ambitious target.[109] The Clean Energy Standard mandates New York City utilities to achieve 50% of electricity consumption from renewable energy by 2030.[110] Since 2014, the solar energy production has increased over sixfold. New York City endeavors to install 1 GW of solar capacity by 2030, this is accompanied by several city, state, and federal incentives programs for solar energy.[111] US annual renewable electricity generation will likely increase sevenfold from 640 TWh today to 4,600 TWh in 2050. The share of solar and wind increases to approximately 75% in total power, from 280 TWh today to 3,500 TWh in 2050. Electricity generation of biomass increases from recently 60 TWh to 800 TWh in 2050, whereas hydro remains on the same level as today (300 TWh). To support increased solar and wind generation, battery storage needs to increase to 110 GW in 2050. Additional system flexibility in 2050 can be provided through 300 MW installed capacity of heat pumps connected with thermal storage and 1.2 million EVs, which will respond to the needs of the power system.

8.2.4 Shanghai

With more than 23 million inhabitants, Shanghai is the largest city in China. By 2050, the city's inhabitants will total around 39 million. It also represents the financial innovation and technology hub of the country[112] and its port is the busiest container port in the world. Shanghai faces multiple challenges when it comes to fossil energy use, GHG emissions, and air quality. GHG emissions account for 260 $MtCO_{2e}$; around 32 $MtCO_{2e}$ are emitted in the transport sector and 63 $MtCO_{2e}$ in the building sector. Emissions in the transport sector can be reduced to approximately 10 $MtCO_{2e}$ until 2050, meaning the share of transport in total

[108] NYC Mayor's Office of Sustainability
[109] NYC Mayor's Office of Sustainability
[110] NYC Mayor's Office of Sustainability
[111] NYC Mayor's Office of Sustainability
[112] World Population Review, 2019d

GHG reduction would be around 10%. Building sector emissions can be reduced to approximately -3 $MtCO_{2e}$ and accounts for around 25% of total emission reductions.

Shanghai is one of the low carbon pilot provinces and cities selected by the National Development and Reform Commission in China, targeting to peak its city emissions and emissions per capita by 2025.[113,114] As mentioned, we expect that by 2050 22 $MtCO_{2e}$ can be reduced in the transport sector and 66 $MtCO_{2e}$ in the buildings sector. In its latest city development plan, Shanghai aims to increase the adoption of public transportation to account for 50% of all transportation in the inner city areas by 2035.[115] To this end, the share of battery electric cars needs to increase from recently 3% to 68% and of electric buses from less than 1% to 85% by 2050. Around 107,000 electric cars and 5,000 electric buses are currently operated in the Greater Shanghai Area and will increase to more than 6.7 million electric cars and 18,000 buses. This will result in an increased demand for public chargers, mainly slow chargers, complemented with fast chargers to limit impact on the grid. In total 98,000 charging stations, i.e. 20,000 fast and 78,000 slow chargers, will be required by 2050.

The city plans to have all new buildings reach the national green building standard by 100% and encourages the use of natural gas and district heating and cooling systems.[116,117] By 2050, we expect that 46 MW electric capacity will be available in the district heating system to ensure that decarbonized heat is available for Shanghai's population. For this purpose, large heat pumps running on renewable electricity will be crucial. Another key pillar for sustainable heating and cooling are heat pumps for cooling and heating; around 2.4 million heat pumps for space heating and 3.2 million for space cooling are required. This will increase the share of electricity for heating from 11% to 24%. For space cooling, the share of electricity will slightly decrease from 100% to 98%. Shanghai Municipal Government and Changning District Government are examples of low carbon city development and show that by retrofitting 10 million m^2 of buildings and aiming at an overall increased energy efficiency of 17% results in a reduction of:

- 249 tons PM equal to 79,320 million diesel car kilometers,
- 336 tons of NO_X, equal to 1,000 million diesel car kilometers and
- 242,000 tons GHG equal to 1,600 million diesel car kilometers.

In its 13th Five-Year Plan on energy efficiency and climate change, Shanghai foresees the development of shore-side electricity supply for ports and LNG vessel pilot and sets ambitions to increase the source of primary energy from renewable sources up to 14%.[118] Until 2050, we assume that annual electricity generation in China will increase sixfold from around 1,600 (300 TWh solar and wind, 1,200 TWh hydro, and 100 TWh biomass) to 8,800 TWh, with around 80% (6,900 TWh) generated from wind and solar and approximately 20% from hydro and biomass (1,700 TWh and 200 TWh, respectively). To optimize use of renewable energy, battery storage needs to increase to 350 GW. Additional system flexibility can be provided through 1,200 MW installed capacity of heat pumps connected with thermal storage and 6.7 million EVs, which will respond to the needs of the power system.

[113] NCSC, 2018
[114] Shanghai Municipal Government, 2018
[115] Ibid.
[116] Shanghai Municipal Government, 2018
[117] Shanghai Municipal People's Government, 2017
[118] Shanghai Municipal People's Government, 2017

APPENDIX A. METHODOLOGY

A.1 Overview

To estimate energy, emissions, and low carbon technology trends in cities in our focus regions (Europe, the US, and China), we developed decarbonization pathways referencing the future trends from the IPCC *Special Report on Global Warming of 1.5°C* (SR15)[119] and the Beyond 2°C Scenario in IEA's *Energy Technology Perspectives (ETP) 2017* report.[120]

We developed energy demand estimates for the sectors in the focus regions in line with the trends of 1.5°C compatible scenarios from ETP 2017 and IPCC SR15 to reflect the higher ambition of these scenarios in 5-year steps until 2050. We then combined these insights with historical data collected for representative C40 cities in these focus regions, including Rotterdam, London, New York City, and Shanghai, to derive estimates for low carbon developments in these cities until 2050. This city data included sectoral GHG emissions, population estimates, and technology-specific inputs such as vehicle stocks or the current number of heat pumps. Historical data and projections from the city authorities and literature were adopted where available and applicable. It is also assumed that the rate of decarbonization for these cities aligns with the national pathways.

For the transport sector, we derived the number and share of EVs, buses, and trucks in the respective total stock as well as the number of public charging points based on the projected electricity demand of the road transport sector in a 1.5°C compatible scenario on the national level. The national estimates are scaled down to the city level based on the current number of vehicles, buses, and trucks. The share and energy intensity of EVs in cities are assumed to align with the national level by 2050. This study only includes trucks up to 15 tonnes, given these represent most of the electrification potential in the next few decades.

For the buildings sector, we estimated the electricity demand for space heating and cooling in the focus regions. These estimates are based on the projected electricity demand of the buildings sector in line with the 1.5°C compatible scenario. To derive estimates on the city level in the focus regions, we took the differences in population, buildings floor area, and heating and cooling degree days from the national average into account. The number of heat pumps in 2050's building stock for each city was calculated by considering the projected population growth from UN Population Division,[121] and the share of residential and non-residential buildings to derive number of buildings that could be equipped with heat pumps. Finally, the electricity share of total space heating/space cooling on national level, consistent with the future trends indicated by ETP 2017, has been applied to determine the number of heat pumps installed in the building stock in 2050. Electric capacity needed for heat pumps in district heating has been calculated by considering the projected total heat demand, the expected share of commercial heat in line with the trends shown in ETP 2017 and a Coefficient of Performance of five.

For the power sector, we developed the projected generation of the different energy sources on the national level based on insights from ETP 2017 and IPCC SR15 on the national level.

[119] IPCC, 2018
[120] IEA, 2017
[121] United Nations, 2018

Storage capacity projections are based on these adjusted generation estimates, considering storage requirements of regional scenarios.[122, 123]

To estimate scaled-up emission impacts of comparable climate action efforts in all cities and towns in the focus regions and for 2030, 2040 and 2050 (see Figure 15, Table 2, Table 3, Table 4, Table 5), we combined population projections from UN[124] and recent estimates of urban/rural per capita emissions[125] with insights from the ETP 2017 and IPCC SR15. Sectoral emission splits for the urban areas in the focus regions were derived from the C40 Global Protocol for Community-scale GHG Emission Inventories (GPC) database[126] and other literature[127, 128]. In the absence of city-level data for Chinese cities, we used proxy cities from the ASEAN region from this database. To understand cities' contributions to the Paris Agreement through electrifying road transport and space heating and cooling in buildings, we developed a baseline pathway for the urban areas in the focus regions, reflecting the commitment stated in the NDCs. Similarly, the national baseline pathways are adjusted down to urban areas on a per capita basis. Both the 1.5°C pathways and the baseline pathways include negative emissions in the power sector in the later years which are reflected in negative indirect emissions from electricity use for buildings and transport. The amount of negative emissions is even higher in the 1.5°C pathways (see Figure 16).

It is also important to note that the future pathway (i.e., slope and shape of the curve) to achieve 1.5°C highly varies across cities and remains highly uncertain subject to future market, policy, and technology development. Some cities may have a higher ambition than the national pathway. Therefore, the results of this study shall not be used as the projection for individual cities but rather offer the possible direction of travel as the starting point for looking into measures and implementation plans to get there.

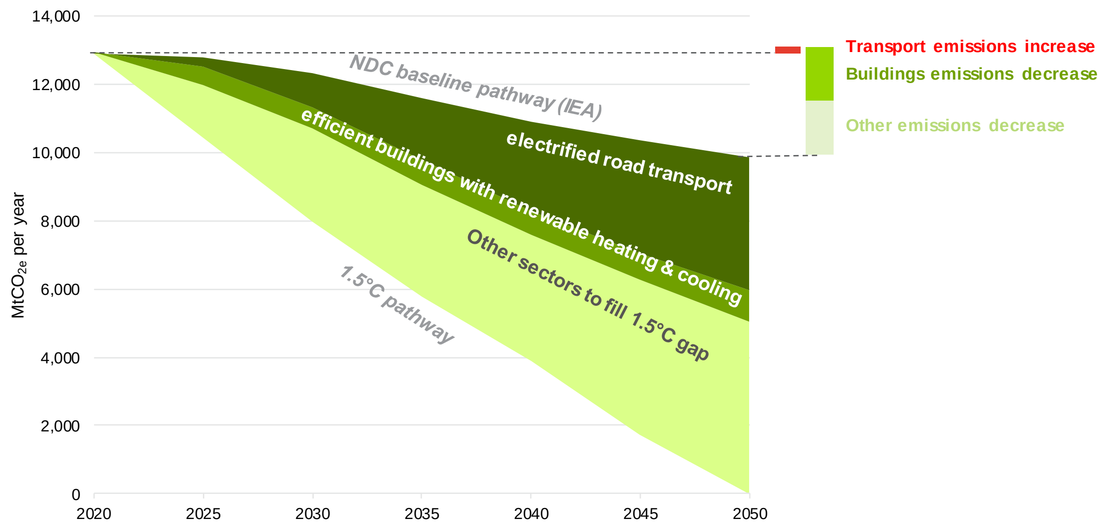

Figure 15. Emission pathways and sector contributions for urban areas in Europe, the US, and China

[122] China National Renewable Energy Centre, 2017
[123] Wesley Cole, Trieu Mai, James Richards, Paritosh Das, and Paul Donohoo-Vallett, 2017
[124] United Nations, 2018
[125] City carbon footprints
[126] C40 Cities Climate Leadership Group, 2018
[127] Ohshita et al., 2015
[128] Building Energy Research Center of Tsinghua University, 2018

A.2 Contributions of energy efficient heating and cooling of buildings and transport to a 1.5°C pathway by region in 2030, 2040 and 2050

Numbers must be interpreted as follows: As shown in Figure 16 the 1.5°C pathway starts with annual GHG emissions of approximately 13,000 Mt CO_{2eq} in 2020 and reaches 0 by 2050. Table 2, Table 3, Table 4 and Table 5 show contributions of energy efficient heating and cooling of buildings as well as transport to bridge the gap between 2020 GHG emissions of urban areas and the milestones 2030, 2040 and 2050 on the 1.5°C pathway. The presentation is shown for urban areas as a whole in Europe, the US and China, but also for urban areas' individual 1.5°C pathways in each of these regions.

Table 2. Europe, US, China

	2030	2040	2050
Buildings	19%	21%	20%
Transport	13%	25%	28%
Other	67%	54%	52%

Table 3. Europe

	2030	2040	2050
Buildings	33%	28%	24%
Transport	16%	18%	17%
Other	51%	54%	58%

Table 4. US

	2030	2040	2050
Buildings	29%	27%	23%
Transport	23%	26%	24%
Other	48%	47%	53%

Table 5. China

	2030	2040	2050
Buildings	6%	15%	15%
Transport	6%	26%	37%
Other	88%	59%	48%

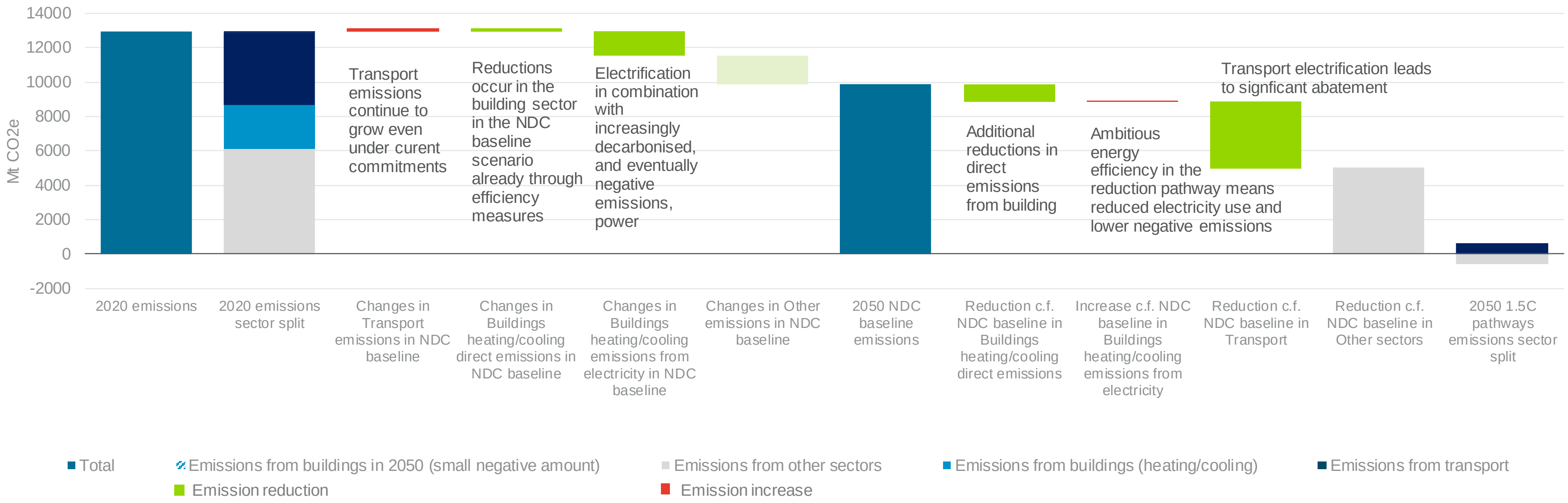

Figure 16. Evolution GHG emissions between 2020 and 2050 across sectors and scenarios

The second and last column of Figure 16 are equal to the columns as presented in Figure 1.

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