



GREENHOUSE GASES: A PRIMER FOR URBAN PRACTITIONERS

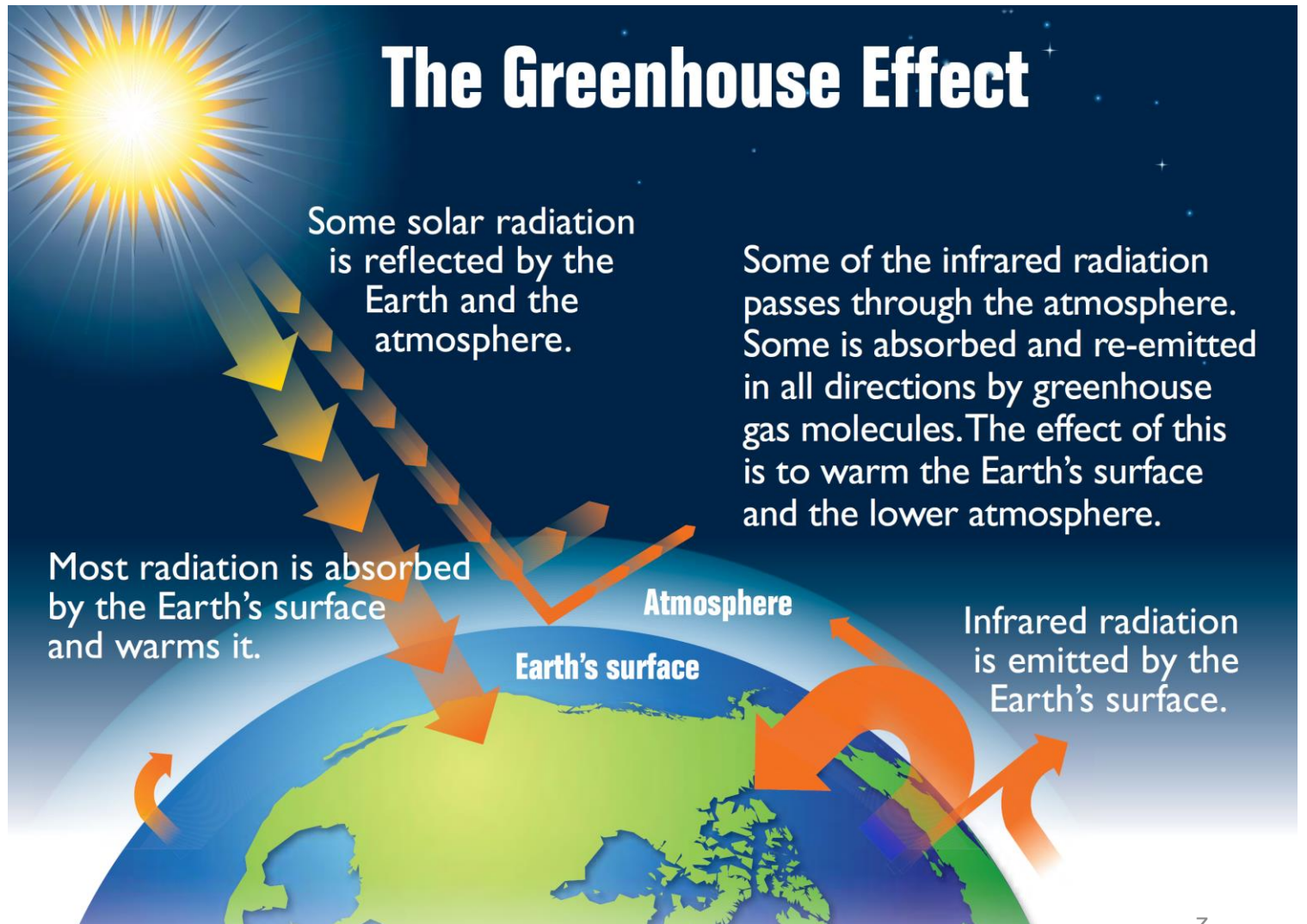


A multi-gas perspective on urban climate mitigation

- Cities contribute **70% of greenhouse gas (GHG)** emissions that are responsible for the majority of observed and anticipated global warming – Strong mitigation action is needed.
- Most of this warming is attributed to emission of **carbon dioxide or CO₂** associated with combustion of fossil fuels. As a result, most efforts have been directed at reducing this key and important gas.
- However, the **non-CO₂ GHGs** emitted directly by human activities include methane (CH₄) and nitrous oxide (N₂O), and a group of industrial gases including perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF₆). When taken together with the already banned chlorofluorocarbons (CFCs), their climate significance over the past century is **roughly equivalent to that of CO₂**.
- The objective of this note is to discuss the varying sources and impacts of CO₂ and non-CO₂ gases, place their emissions into context, and discuss ways in which cities can address their contributions to global warming.

Global warming via the greenhouse effect

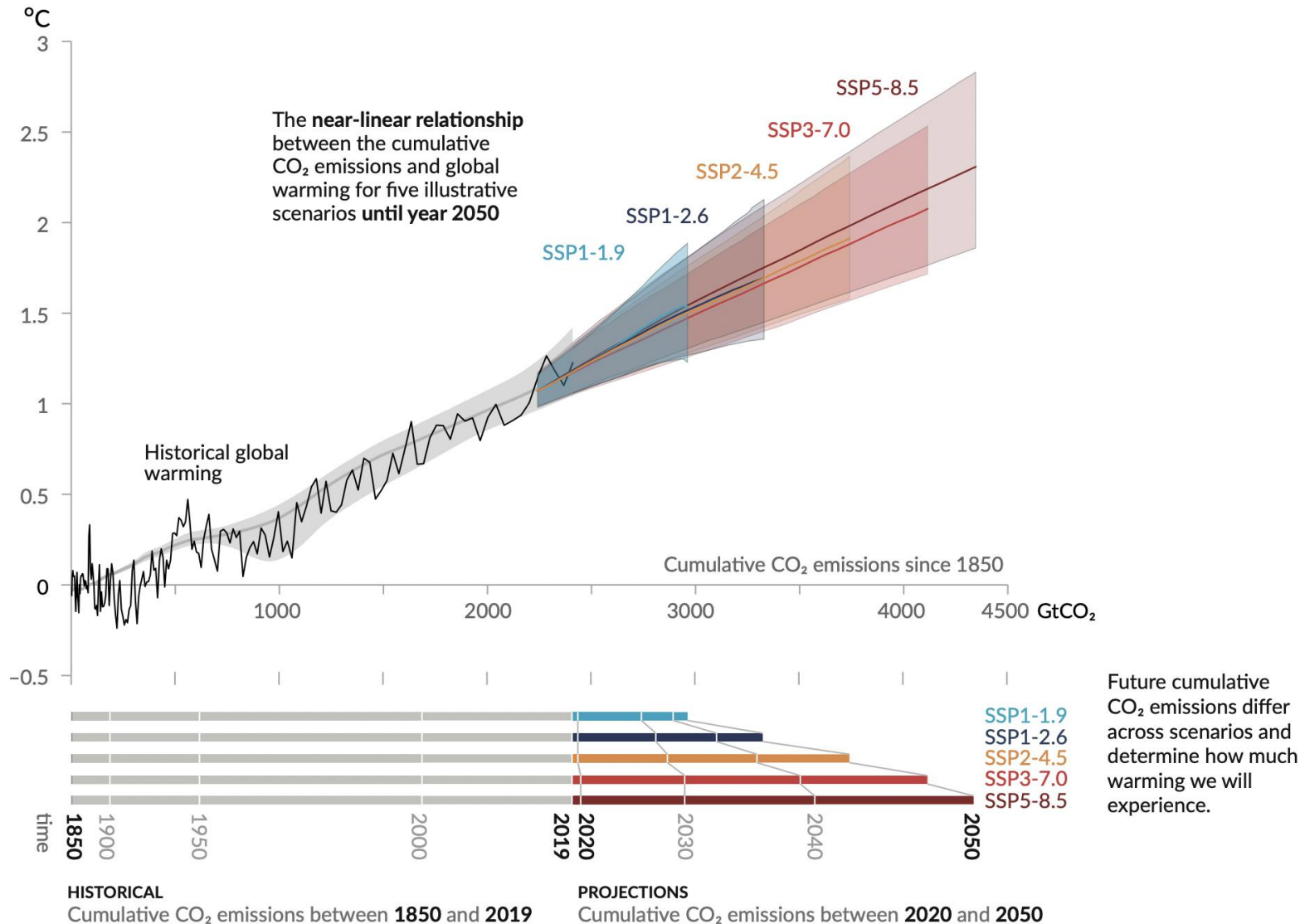
- Light from the sun heats the surface of the Earth.
- There is a natural balance of light that reflects to space or heats the atmosphere.
- Some heat from the surface of the earth is “captured” by the natural CO₂ and other gases in the atmosphere (water vapor, natural methane, etc.).
- The more we add CO₂, methane and other GHGs to the atmosphere, the more heat energy the atmosphere absorbs from the surface of the earth.
- Over time, the balance shifts to a warmer equilibrium.



Source: US EPA (2012)

Every tonne of CO₂ emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO₂ emissions (GtCO₂)



The problem is cumulative!

Warming won't stop until we cease all carbon emissions.

What is CO₂-equivalence?

- Increased CO₂ emissions are the primary driver of human-made climate change and global warming; however other emissions also contribute.
- The 6 primary gases that contribute (often called the 'Kyoto gases' because they were called out in the Kyoto Protocol) include: Carbon Dioxide (CO₂), Methane (CH₄), Nitrous Oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulfur Hexafluoride (SF₆).
- Each gas has a factor that allows you to convert 1 ton of emissions of other gases into the equivalent contribution of 1 ton of CO₂.
- When expressed as a ton of CO₂, the contribution of other gases are said to be expressed as "CO₂-equivalent" or "CO₂e."
- The factor for converting other gases to CO₂e is called the "global warming potential" or GWP and is usually expressed as the GWP₁₀₀ denoting that the accounting is done over a 100-year period.
- This accounting can be done for other time periods, such as 20 years, which is relevant for shorter-lived species, like methane.



Short-Lived Climate Pollutants (SLCPs)

- Some emissions are far more potent than CO_2 but may only last in the atmosphere for a few weeks or months. For these short-lived pollutants, a different GWP (like GWP_{20}) may provide better insight into their contribution to global warming over the near-term but can overestimate impact into the future.
- For example, kg for kg, **methane** warms much more than CO_2 . However, methane has a lifetime of only 12 years, compared to CO_2 's lifetime of more than 100 years. Thus, 1 ton of methane is 28 times more potent than CO_2 measured over 100 years ($\text{GWP}_{100} = 28$) because most of the methane will be gone after 10 or so years, but it is 86 times more potent than CO_2 when measured over a shorter period like 20 years ($\text{GWP}_{20} = 86$).

SLCPs (continued)

- **Black Carbon (BC)**, or soot, is a solid component of air pollution (fine particles) that results from inefficient combustion and lasts for only a few weeks in the air; however, 1 ton of BC emissions still warms the atmosphere hundreds of times more than 1 ton of CO₂ even when measured over 100 years and thousands of times more than CO₂ when measured over 20 years.
- BC is also a component of fine **particulate matter (PM_{2.5})**, the form of air pollution responsible for the greatest burden of air pollution-related disease, so reducing PM_{2.5} (especially from BC-rich sources) saves lives and cools the planet simultaneously and quickly!

Each pollutant has a unique potential to warm the planet and will also warm over a unique timescale.

While we need to reduce all climate pollution, reducing SLCPs immediately and avoiding lock-in to long-lived GHG infrastructure can provide immediate relief while we decarbonize the broader economy!

Ambient Air Pollution (AAP)

- Many sources of GHG emissions or SLCP emissions are also sources of more traditional air pollutants (i.e., fine particulate matter or $PM_{2.5}$, BC and organic carbon or OC, nitrogen dioxide or NO_2 , sulfur dioxide or SO_2 and toxic chemicals).
- Reductions of GHGs that have common sources with ambient air pollution can result in multiple development benefits including cooling the planet, protecting public health associated with reduced air pollution exposure, increased food and energy security, reduced traffic fatalities and congestion, enhanced economic activity through alternative patterns of investment and quality-of-life benefits.
- By including the multiple benefits of emission reduction in GHG planning assessments, you can improve cost-benefit assessments and engage a broader array of stakeholders to support climate action plans with multiple benefits.

Example conversion factors (GWPs) to estimate GHGs as CO₂e

Species	CO ₂	CH ₄	N ₂ O	HFCs (e.g., HFC ₂₃ , HFC _{134a})	PFCs (e.g., NF ₃ , PFC ₁₄)	SF ₆	Black carbon	Organic carbon
Lifetime (Years)	120	12	109	228/ 14	569/ 50,000	3,200	Days-weeks	Days-weeks
GWP ₁₀₀	1	28	273	14,600/1,530	17,400/7,380	25,200	460	-69
GWP ₂₀	1	81	273	12,400/4,140	13,400/5,300	18,300	1600	-240

Its true! Emitting one ton of SF₆ (sulfur hexafluoride, used in electrical switching equipment) will warm the planet over the next century as much as 25,000 tons of CO₂!

However, we emit far, far more CO₂ than SF₆, so it remains less of a problem.

CO₂ dominates warming on an annual average basis...

Global greenhouse gas emissions by gas

Greenhouse gas emissions are converted to carbon dioxide-equivalents (CO₂eq) by multiplying each gas by its 100-year 'global warming potential' value: the amount of warming one tonne of the gas would create relative to one tonne of CO₂ over a 100-year timescale. This breakdown is shown for 2016.

Our World
in Data



OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020).

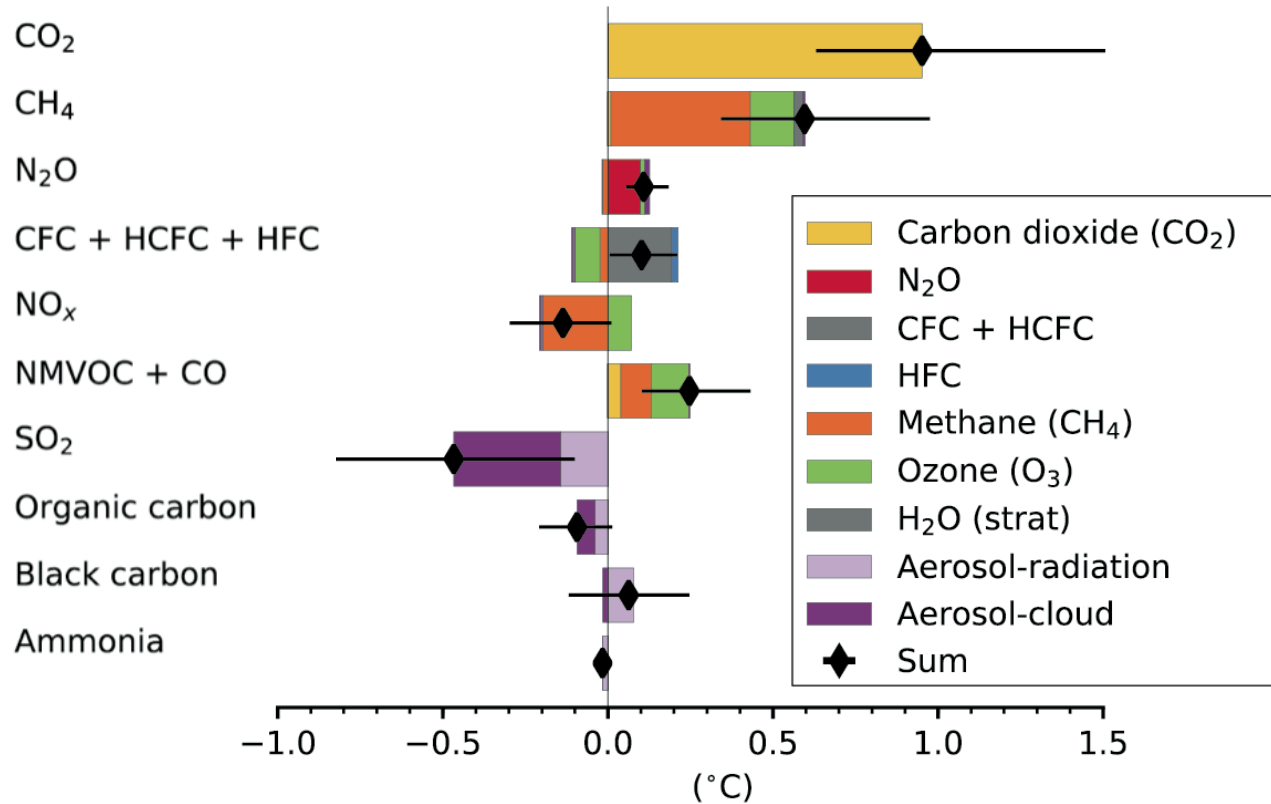
Licensed under CC-BY by the author Hannah Ritchie.

In the chart we see the breakdown of global emissions **in 2016**, measured on the basis of carbon dioxide-equivalents (CO₂e).

Carbon dioxide was the largest contributor, accounting for around three-quarters (74.4%) of total emissions. Methane contributed 17.3%; nitrous oxide, 6.2%; and other emissions (HFCs, CFCs, SF₆), 2.1%.

... but integrated over time, other gases add up.

Change in Global Mean Surface Air Temperature, 1750 to 2019



Integrated over the historical record, and accounting for shifts in key economic sectors and their contributing emissions, we see that CO₂ is still the largest contributor to overall temperature increase, but when accounting for the indirect, knock-on effects of the emission of some gases – like CH₄ – which leads to formation of other climate pollutants – like ozone (O₃) – the combined contribution of other GHGs is about equal to that of CO₂.

This is especially true for some non-GHG pollution like SO₂ and organic carbon that form aerosols (purple) which cool the planet. As air pollution is reduced, we stop masking the warming of GHGs.

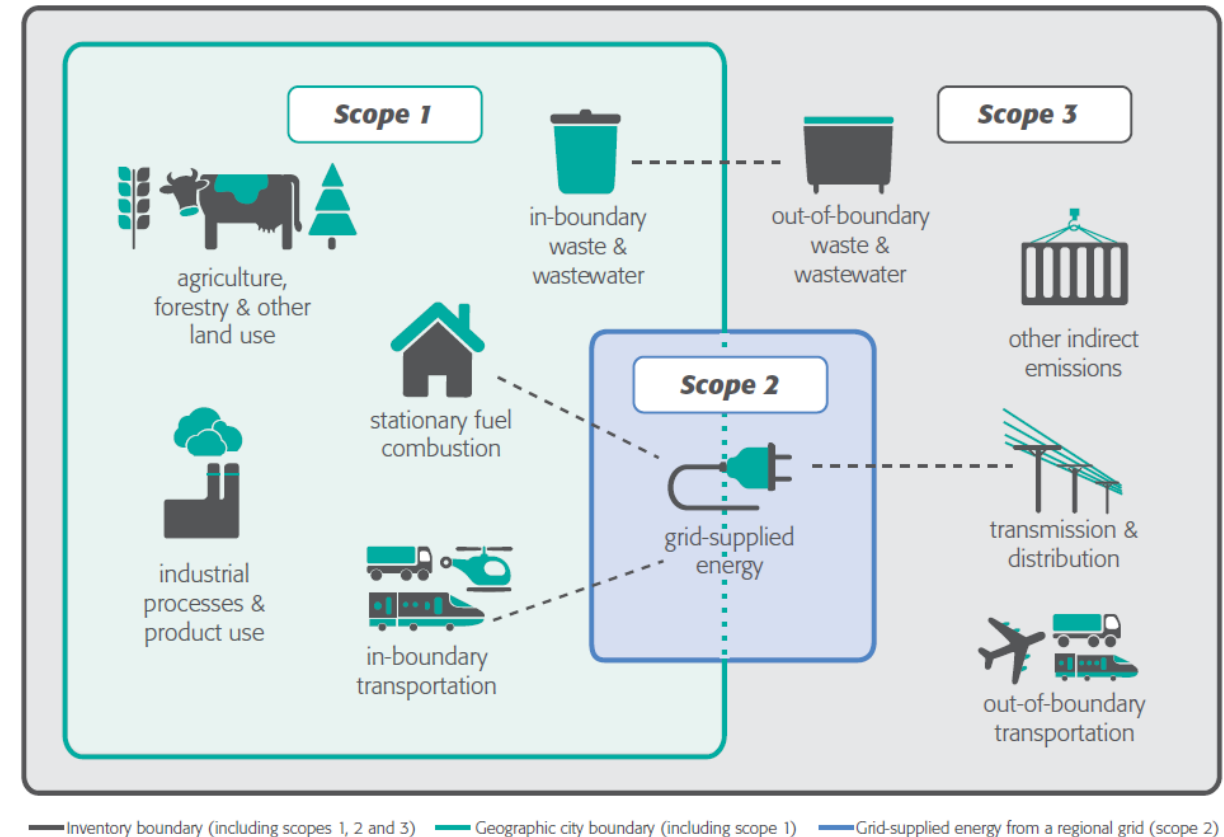
Contribution to global mean air temperature between 1750 and 2019

A city's emissions include different scopes.

"Scope" refers to where emissions physically occur:

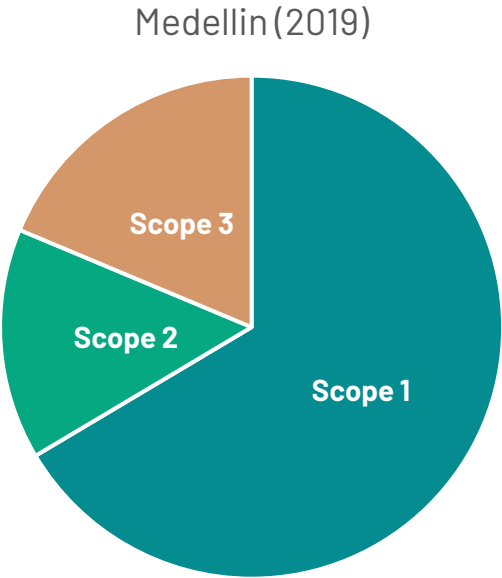
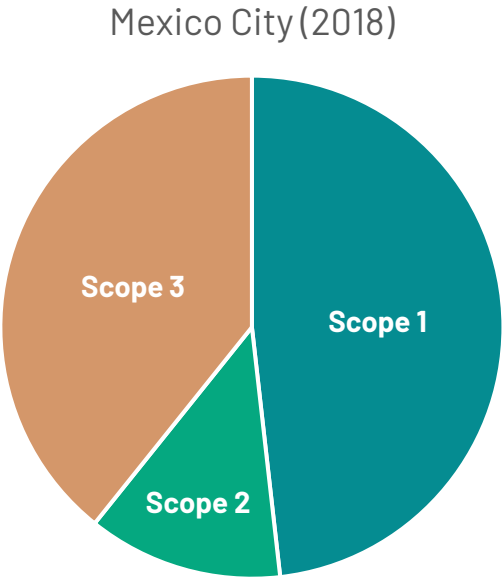
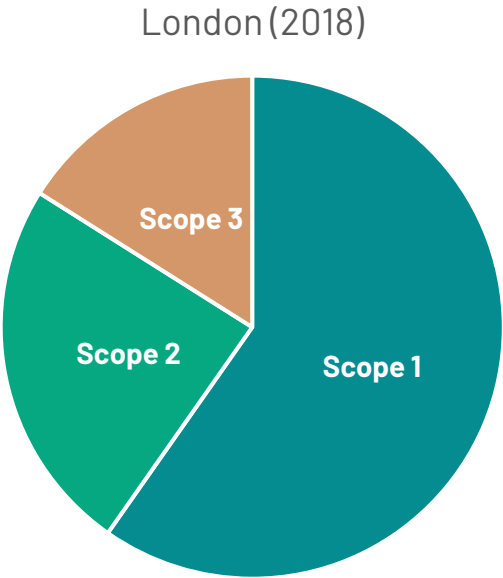
- Scope 1 - emissions within administrative boundaries
- Scope 2 - emissions associated with imported electricity
- Scope 3 - transboundary life-cycle supply-chain emissions

These designations lead to so-called "production"-based accounting (scope 1 emissions) or "consumption"-based accounting that includes the community-wide life-cycle (global) footprint of residents and businesses of a city (scope 1+2+3).



Source: WRI et al (2019) - Global Protocol for Community-Scale Greenhouse Gas Inventories

Examples of emissions categorized by scope:



Carbon Dioxide



Lifetime
~120 years

GWP₁₀₀
1

GWP₂₀
1

GWP for CO₂ is 1 for both 20 and 100 years, by definition, since GWP is defined relative to CO₂.

Key facts

- CO₂ results from combustion of carbon-containing fossil (and biogenic) fuels which are oxidized in the atmosphere through chemical processes that break combustion products up into this very stable and ubiquitous molecule.
- Some CO₂ is taken up by plants, but not nearly as much as we produce.

Key urban sources of CO₂

(Figures in parentheses are CO₂ emissions from Paris in Mt CO₂/yr)

Scope 1:

- Residential buildings (2.1)
- Commercial buildings (2.0)
- Transportation (1.3)
- Solid waste (0.4)
- Industry (0.1)

Scope 2: Upstream energy (1.3)

Scope 3:

- Air transport (8.7)
- Food consumption (4.8)
- Road transport (supply-chain)(3.4)
- Materials/construction (1.5)

Key urban solutions – Paris Climate Action Plan, 2018

The lifetime of CO₂ is hundreds of years, so eliminating the use of carbon fuels now will only correct the imbalance sometime later this century, so it is critical to decarbonize quickly, avoid long-term infrastructure CO₂ lock-in and reduce SLCPs:

- Renewable Energy
- Circular economy/energy & waste recovery
- Shared, active and clean transportation*
- Low-emission zones/Smart transit
- Thermal improvement to buildings
- Financing energy renovation and energy management
- Flexible/reversible construction
- Local/low-carbon food production

*Mixed use, compact growth can also reduce distances traveled and enable low-carbon transport.

Methane



Lifetime
10-12 years

GWP₁₀₀
28

28x more warming than CO₂ over 100 years

GWP₂₀
81

81x more warming than CO₂ over 20 years

Key facts

- CH₄ results from oil/gas extraction and distribution leakage as well as from bacterial decay of organic material in absence of oxygen (i.e., in a landfill or under water).
- Methane is considered both a GHG and an SLCP.
- When methane does break down, it contributes to the formation of ground-level ozone, another SLCP that is also a threat to health.
- Some of the biggest sources of methane globally take place outside of cities but remain attributable to cities (i.e., scope 3 emissions).

Key urban sources of CH₄

- Scope 1: Municipal solid waste decay
- Scope 1: Wastewater decay
- Scope 2: fossil fuel extraction
- Scope 2: fossil fuel distribution
- Scope 3: Livestock Agriculture

Key urban solutions

- Expand integrated solid waste management
- Circular economy/energy & waste recovery
- Expand/improve wastewater treatment or fecal sludge management
- Source local food
- Reduce fossil-fuel use
- Reduce meat consumption

Nitrous Oxide



Lifetime
109 years

GWP₁₀₀
273

273x more warming than CO₂ over 100 years

GWP₂₀
273

273x more warming than CO₂ over 20 years

Key facts

- N₂O is produced as a by-product during the remineralization of organic matter via the primary processes of nitrification and denitrification.
- N₂O is also released in combustion of fuels.
- Nitrous oxide emissions have been increasing due to increased use of synthetic fertilizer and manure (adding nitrogen to the soils). Land-based agriculture and fossil fuel burning have been the largest driver of the observed increase through 2019.
- Since N₂O has a very similar lifetime to CO₂, the GWP₁₀₀ is very close to the GWP₂₀, 273x more warming over both 100 and 20 years.

Key urban sources of N₂O

- Scope 1: Wastewater processing
- Scope 1: Industrial chemical processing (nitric and adipic acid production)
- Scope 1: Combustion of fossil fuels
- Scope 1: Residential solid biofuels
- Scope 3: Synthetic fertilizers/manure
- Scope 3: aquaculture
- Scope 3: manure management

Key urban solutions

- Certify food stocks as fertilizer friendly/organic
- Practice regenerative/sustainable agriculture
- Expand/improve tertiary wastewater treatment
- Regulate chemical industry
- Reduce fossil-fuel and biofuel use
- Enhance modern energy access

Hydrofluorocarbons

HFCs

Lifetime
10s-100s of years

GWP₁₀₀
1000s

GWP₂₀
1000s

1000s of times more warming than CO₂ over varied lifetimes

Key facts

- HFCs were introduced as replacements for ozone-depleting CFCs.
- While they break down more readily than CFCs, it is not before they warm the planet significantly with very high GWPs.
- Emissions of HFCs are growing at a rate of 10-15% per year. The global stock of air conditioners in buildings are projected to grow to 5.6 billion by 2050, or 10 new units sold every second for the next 30 years.

Key urban sources of HFCs (All scope 1)

- A/C, refrigeration
- Foam agents
- Aerosols
- Fire retardants

Key urban solutions

- Adopt/enforce Kigali Amendment to the Montreal Protocol
- Substitute low- or zero-GWP alternatives, combined with improvements in lifecycle energy efficiency
- Improved insulation/building designs to reduce A/C

Perfluorocarbons

PFCs

Lifetime
100s-1000s of years

GWPs
1,000s-10,000s

1000x-10,000x more warming than CO₂ over varied lifetimes

Key facts

- PFC gases do not exist naturally in the atmosphere but are produced synthetically.
- PFCs - like HFCs - replace chlorofluorocarbons (CFCs) but are used in the manufacture of semiconductors and have several other uses.
- Not technically a perfluorocarbon, nitrogen tri-fluoride, or NF₃, is a greenhouse gas, with a global warming potential (GWP₁₀₀) 18,500 times greater than that of CO₂. Its GWP places it second only to SF₆ in the Kyoto gases.

Key urban sources of PFCs

- Scope 1: By-product during aluminum production
- Scope 1: Solvent in electronics industry
- Scope 1: Specialized refrigeration
- Scope 1: (NF₃) Manufacture of flat panel displays, photovoltaics, LEDs and other electronics
- Scope 3: imported products using PFCs in their manufacture

Key urban solutions

- Strict inventory reporting for PFCs and NF₃
- Materials efficiency, circular material flows and emerging primary processes
- Fluorine gas (F₂, diatomic fluorine) is a climate neutral - but highly toxic - replacement for nitrogen trifluoride in some manufacturing applications; however, it requires more stringent handling and safety precautions, especially to protect manufacturing personnel.

Sulfur Hexafluoride



Lifetime
3,200 years

GWP₁₀₀
25,200

25,200x more warming than CO₂ over 100 years

GWP₂₀
18,300

18,300x more warming than CO₂ over 20 years

Key facts

- SF₆ is an inorganic compound that is a colorless, odorless, non-flammable, and non-toxic gas.
- Its observed increase over the last 40 years was driven in large part by the expanding electric power sector, including fugitive emissions from banks of SF₆ gas contained in medium- and high-voltage switchgear.

Key urban sources of SF₆ (All scope 1)

- Electrical switches
- Etchant in semiconductor industry
- Casting for magnesium (mostly in China, Canada, Russia and USA)

Key urban solutions

- Strict inventory reporting for SF₆ to ID local sources
- Regulate semiconductor etchants
- Alternative melt-protection for magnesium manufacture (e.g., fluorinated ketone with N₂/CO₂)

Emission Inventory Comparison

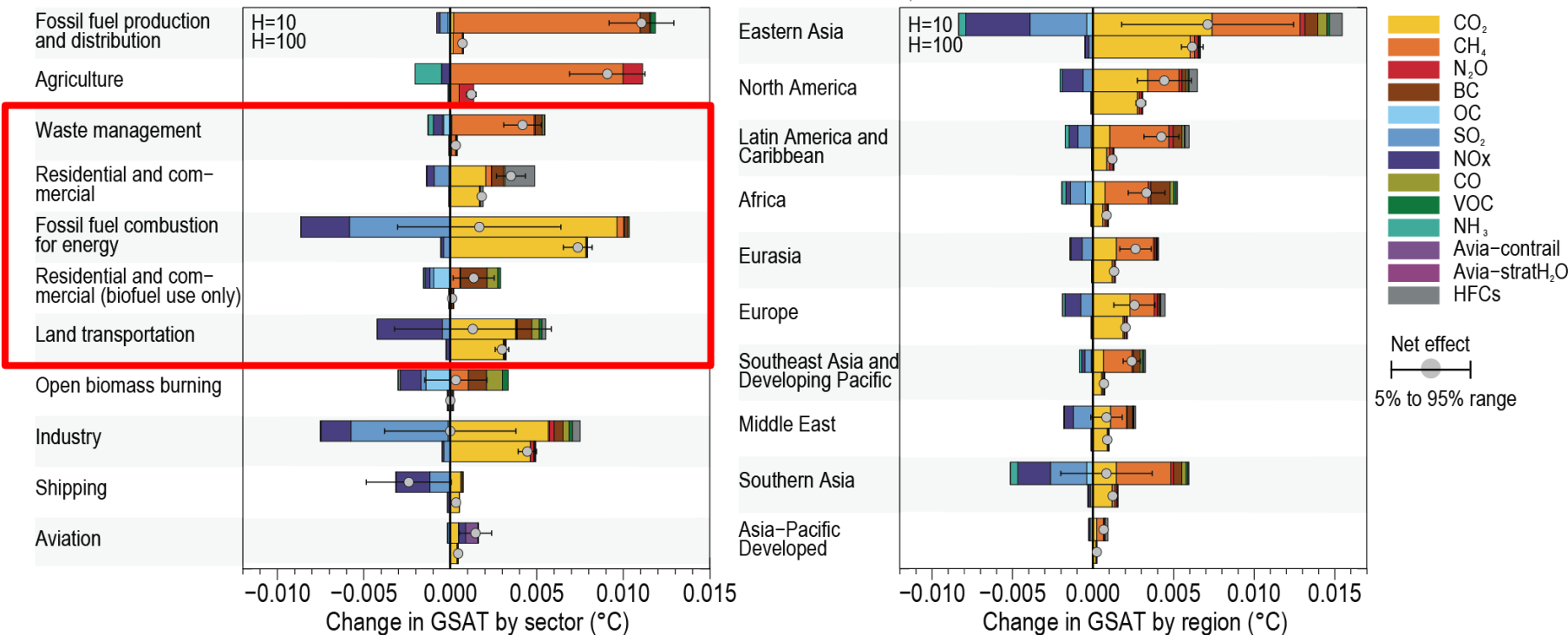
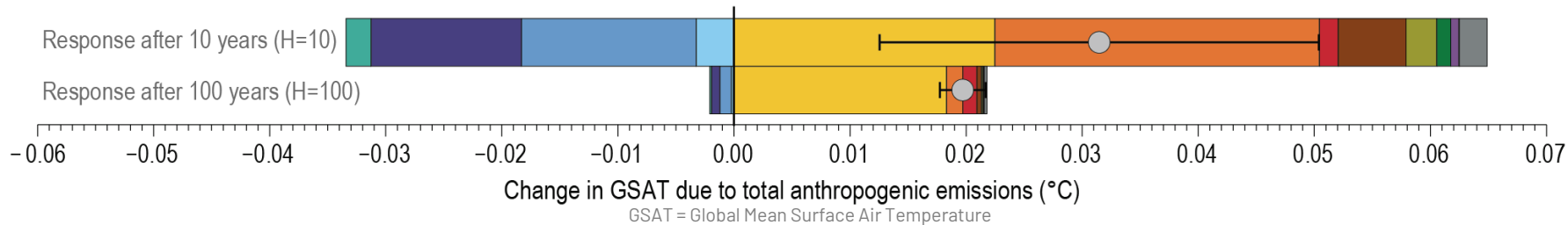
	London (2018)	Mexico City (2018)	Medellin (2019)
Population	3.9 Million	9 Million	2.5 Million
Per Capita GDP	\$182,000	\$21,000	\$7,000
CO ₂ e (all GHGs at BASIC+*)	37.5 Mt	46.6 Mt	3.4 Mt
% from CO ₂	80%	89%	78%
% from CH ₄	14%	10%	20%
% from N ₂ O	1%	1%	2%
% from HFCs	4.7%	0.2%	NE
% from PFCs (mostly NF ₃)	0.2%	NE	NE
% from SF ₆	0.0001%	NE	NE

*Basic+ is an inventory reporting level that covers all scope 1 and scope 2 sources except from imported waste as well as scope 3 emissions from the stationary energy and transportation sectors.

Source: GHG Interactive Dashboard Data. 2020. London, UK: C40 Cities Climate Leadership Group. Available at: https://www.c40knowledgehub.org/s/article/C40-cities-greenhouse-gas-emissions-interactive-dashboard?language=en_US

All sources contain a mix of GHGs, SLCPs and other climate-impactful air pollutants.

Effect of a one year pulse of present-day emissions on global surface temperature



Global Mean Temperature Response 10 and 100 years following one year of 2014-level emissions

Source: IPCC WGI, 2021, Fig 6.16 (see references)

Red box identifies sectors most relevant for urban Scope 1 and 2 emissions

Urbanization and income affect urban GHG emissions.

Urbanization has historically increased GHG emissions.

- The urbanization and adjustment of industrial structure has historically driven energy consumption and carbon emissions.

The transition from lower-income to higher-income urban structure affects the mix of pollutants.

- The shift from **agricultural economies** (with more methane from waste and wastewater and N₂O emissions from agriculture) to **industrial economy** (more CO₂, HFC/PFC/SF₆ emissions from industries and buildings) will shift the main contributing gases.

The scope of emission sources will also change as cities become denser, industrialize and outsource energy and food supply.

- Increasing wealth enables enhanced treatment of waste/wastewater, reducing Scope 1 methane emissions.
- The magnitude of upstream emissions will vary as a function of upstream energy sources, transportation patterns and agricultural/food supply chains (Stronger consumer demand for energy and meat may increase Scope 3).

As cities develop an increase in carbon footprint is not inevitable.

- Local regulation can reduce Scope 1 emissions.
- Local and national regulation can impact Scope 3.

Urban mitigation summary

Sector	Key pollutants	Mitigation options	Potential impacts of urban planning
Transportation	CO ₂ , Diesel particulate, HFCs (auto air conditioning)	Electrify light duty, DPFs/clean fuels for heavy duty, low-carbon public transit options and Transit-oriented development	Planning for mixed-use and compact development that is coordinated with public and non-motorized transportation options, as well as the provision of public electric vehicle charging infrastructure, can reduce transportation emissions.
Power	CO ₂ , CH ₄ (upstream fossil fuel production), SF ₆ (electrical switches)	EE/RE w grid optimization, solar microgrids	Building regulations can enable the adoption of distributed renewable energy.
Industrial Point Sources	CO ₂ , PFCs (Aluminum and electronics manufacture), SF ₆ (magnesium casting), HFCs (fire retardants, aerosols, foams), N ₂ O (nitric and adipic acid production)	EE & materials efficiency, circular material flows and adopt emerging primary processes for PFCs, Alternative materials for switches and alternative processes for electronics/ magnesium manufacture for SF ₆ , Careful use of F ₂ .	Compact and coordinated development, as well as updated regulations, can reduce the quantity of construction materials required for buildings and infrastructure (primarily cement and steel), which reduces embodied emissions associated with manufacturing these materials.
Waste/Wastewater	CH ₄	ISWM, expand/tertiary WW treatment	Cities can reduce methane from waste by increasing waste collection, minimizing open dumping and uncontrolled landfilling, managing landfill gas, and diverting organic waste from landfills.
Buildings	CO ₂ (combustion of fossil-fuels), BC/OC (combustion of residential solid biofuels); HFCs (A/C)	RE/EE w/modern energy services for residential cooking & heating, materials efficiency for construction, low-GWP alternatives for A/C	Density, building height and building design impact the energy efficiency of buildings.
Food systems	CH ₄ (livestock), N ₂ O (fertilizer application), HFCs (refrigeration), BC/OC (Open burning of crop residue)	Local/sustainable agriculture; shift food preferences	Planning that enables farmer's markets and urban farming can support local agriculture and reduce emissions associated with food packaging and transport.

To explore the GHG benefit of various options, see tools for modeling future scenarios at the city level [here](#).

Source: Authors

Key takeaways

- CO₂ constitutes the majority of city emissions.
- The mix of non-CO₂ GHGs can vary. Contributions from methane and nitrous oxide depend on the degree of upstream fossil fuel production/extraction, agricultural practices, and the volume of waste produced and how it is disposed.
- HFCs, PFCs and SF₆ are smaller contributors, often not estimated at the municipal level, and may require global action and regulation.
- Key city actions include reducing fossil fuel use through renewable energy, energy efficiency, integrated solid waste management, enhanced wastewater treatment, electrification of transportation, compact and coordinated urban growth, and local food production/food choice.
- Key sources emit a mix of pollutants. This means that reducing emissions can yield not only climate benefits, but also public health, agriculture, energy and economic benefits, as eliminating key sources can eliminate a wide range of pollutants simultaneously.

Acknowledgments

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