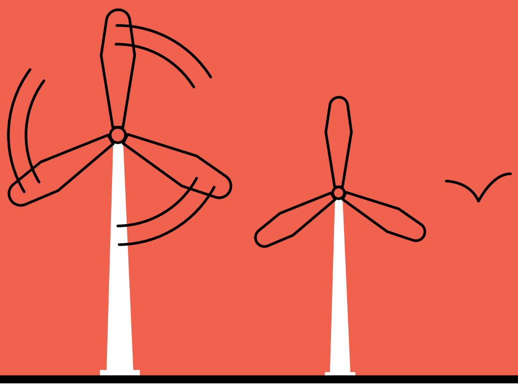
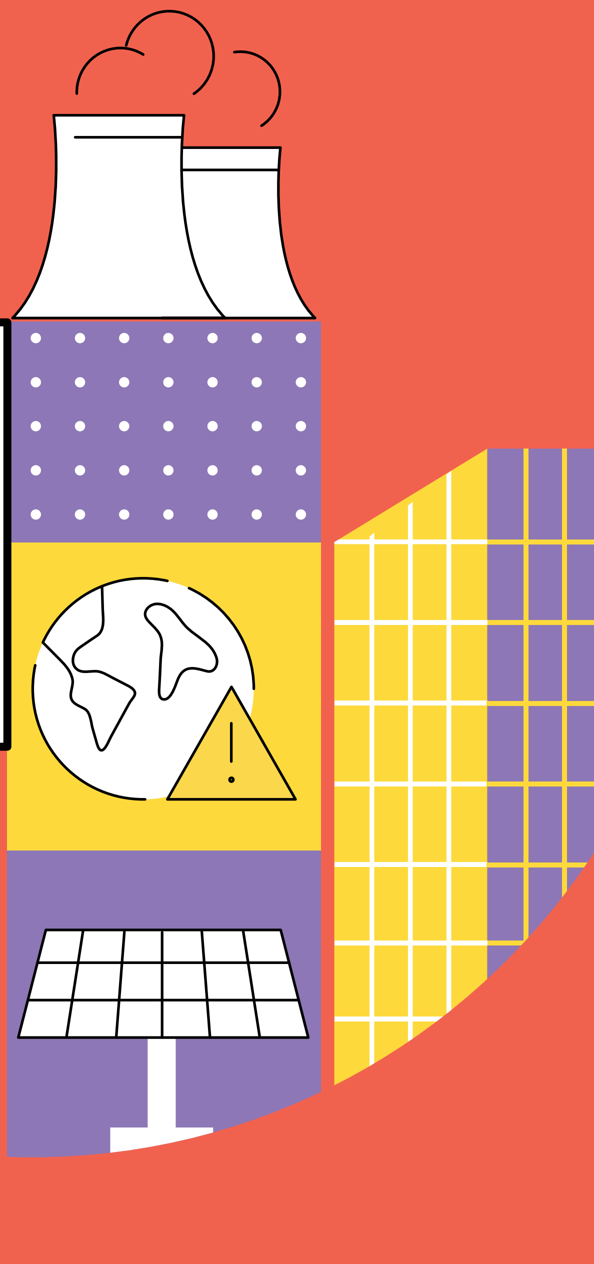


The Cost Of Fossil Gas: The Health, Economic And Environmental Implications For Cities

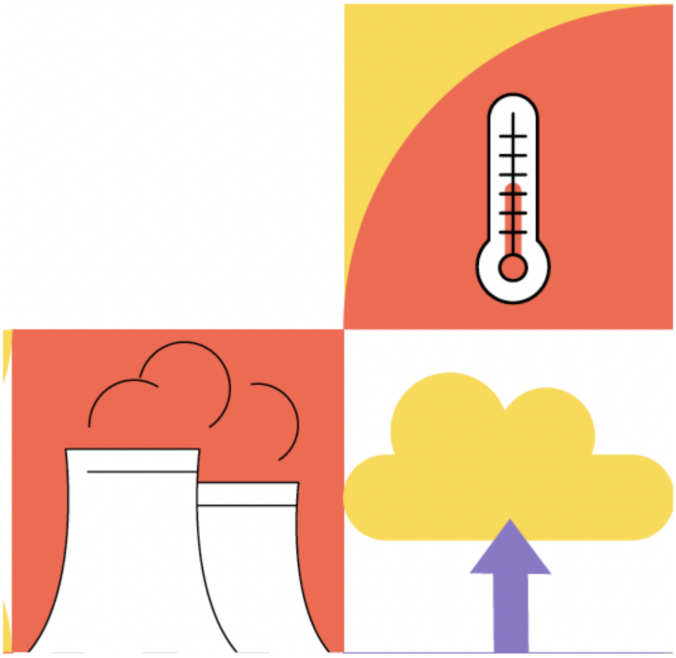


Methodology report

October 2022

C40 CITIES

Contents



Methodology summary

1.1 Developing scenarios

Our modelling is based on two main scenarios, the "current pledges scenario" and the "1.5oC scenario", developed using a global integrated assessment model, the Global Change Analysis Model (GCAM).

The **"current pledges scenario"** is based on countries' current unconditional policies and Nationally Determined Contributions (NDCs).

The **"1.5oC scenario"** is based on fossil gas use within a 1.5°C-compliant GHG emissions scenario. This includes regional net-zero targets on three different timelines, based on equity principles and burden-sharing approaches with regions grouped based on capability and responsibility to mitigate emissions.[1], [2] Higher current, historical and per capita gas usage in Global North cities, coupled with higher levels of income per capita, means that cities in high-income countries in Europe, North America, Oceania and East Asia rapidly phase-out fossil gas to reach net zero by 2040. Cities in middle-income countries in Asia, Europe, Latin America swiftly transition to renewables to reach net zero by 2050. Developing countries in Asia, Africa and Latin America, meanwhile, reach net zero in 2075.

The 1.5oC-scenario has been developed to limit temperature overshooting, minimise carbon capture and storage (CCS) (given current levels of deployment), minimise biomass (for air quality reasons), minimise nuclear sources, minimise fossil fuels, maximise renewables (solar and wind) and emphasise electrification, increase energy efficiency, and allowing total energy production to grow in emerging country regions.

We also developed a simplified scenario to assess the impact of currently planned fossil gas expansion. This **"expansion scenario"** is based on proposed gas power

---

[1] Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, 7(1), 38-43. https://doi.org/10.1038/nclimate3186

[2] Pan, X., den Elzen, M., Höhne, N., Teng, F., & Wang, L. (2017). Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science & Policy*, *74*, 49-56. https://doi.org/10.1016/j.envsci.2017.04.020

projects[3] and infrastructure.[4] Data for planned expansions is only available to 2030, so no further expansion is included - but this does not mean it is not planned. We assumed that the expanded fossil gas capacity would be kept online until 2050, a reasonable assumption given gas-fired power plants have a lifespan of at least 30 years.[5]

Our analysis comprises both downstream and upstream emissions associated with fossil gas use in cities. Upstream emissions from the extraction, production, processing, transmission and distribution account for 7% (0.36 GtCO2e) of C40 cities' cumulative fossil gas-related emissions to 2050 under the current pledges scenario. Whilst these emissions generally fall outside cities' GHG inventories, as they occur beyond city boundaries, it is important to include them to understand the full impact of fossil gas. For example, if a city consumes fossil gas with significant upstream methane leakages, this could mean that the climate impact of the city's fossil gas is equal to, or greater than, coal.

1.2 Air pollution and health modelling

The majority of the health impact from fossil gas operations derives from NOx emissions, which influence ground-level NO2, ozone and PM2.5 concentrations through photochemical reactions and pollutant dispersion. To model these impacts across C40 cities, we have used a global chemistry-transport model (GEOS-Chem) that can simulate the combined influences of physical and chemical processes. We analysed the impact of air pollutant concentrations on public health using well-established concentration response functions that relate the concentration of pollutants to mortality and morbidity risks.

[3] Global Energy Monitor (GEM). Global Gas Plant Tracker. January, 2022. https://globalenergymonitor.org/projects/global-gas-plant-tracker/

[4] Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, Gas Pipelines. January 2022., Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, LNG Terminals. January 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

[5] Sato, I., Elliott, B. & Schumer, C. (2021). What is Carbon Lock-in and How Can We Avoid It? [online]. Washington, DC. Accessed 22 June 2022 Available at: https://www.wri.org/insights/carbon-lock-in-definition

1.3 Time frames

Our analysis looks at two time periods, 2035 and 2050, to be able to compare short-term and long-term climate action as well as short-term and long-term climate and health impacts. For GHG and air pollutants we adopt 2019 as the baseline year as given the COVID-19 pandemic 2019 is a more representative year to use than 2020 or 2021. We assess the health impacts from air pollution concentration from 2020.

1.4 Developing city use-cases

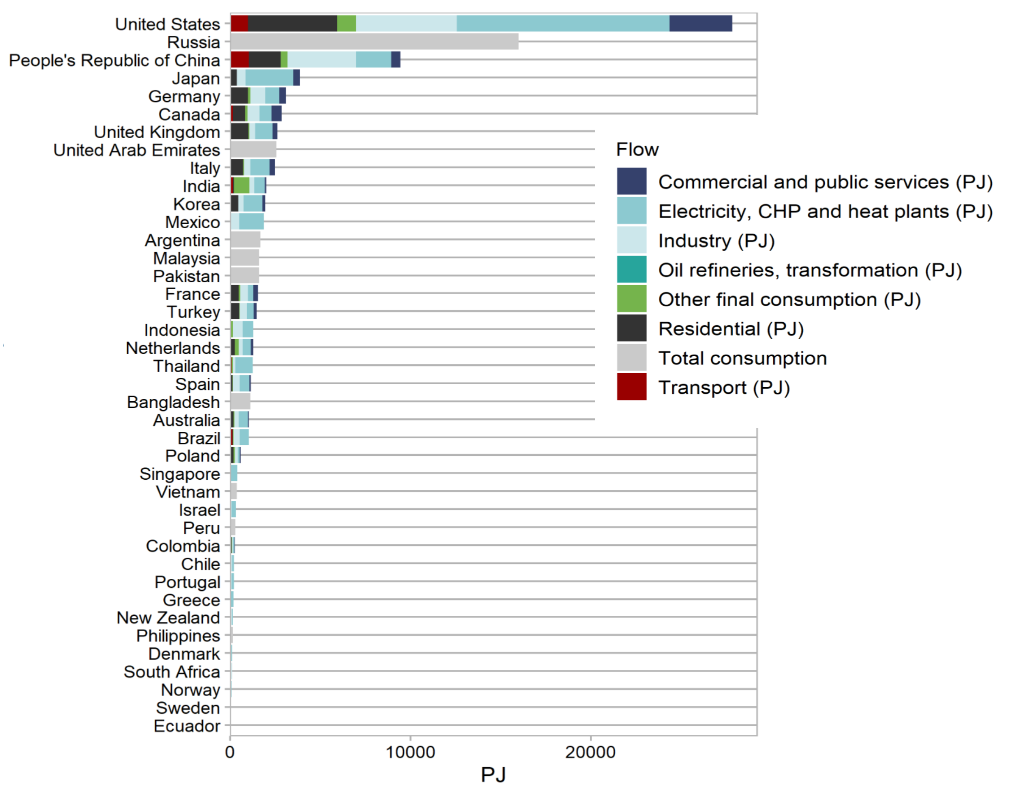
To compliment the global analysis we have also developed city use-cases where we analyse how 1.5°C-compliant fossil gas transition pathways use can play out in three C40 cities with different political contexts, varying levels of income and types of gas use. These cities are Montréal, Bogotá and Johannesburg. For this analysis, we used C40's Pathways tool to develop climate mitigation strategies, together with a literature review and interviews with city officials and local energy experts to better understand each city's unique context.

1. Gas Consumption data

Three quarters of global fossil gas consumption takes place in countries with C40 cities (Figure 1), with the U.S., Russia, European Union and the UK, China, Japan, Canada and the UAE the largest consumers among these countries. The same countries rank near the top in per capita consumption, with the exception of China. In addition, Singapore and Malaysia stand out as high consumers in per capita terms. Looking at the share of gas in total (commercial) energy consumption, Bangladesh, Pakistan and Argentina also stand out. However, in the first two, non-commercial biomass plays a major role in energy consumption and air pollutant emissions.

Figure 1 | *Fossil gas consumption in countries with C40 cities, in absolute terms, per capita and as a share of total energy supply. Source: IEA World Energy Balances*[6].

Figure: Gas use by country. Source: CREA



[6] International Energy Agency (IEA). World Energy Balances. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

Figure: Share of gas in total energy. Source: CREA

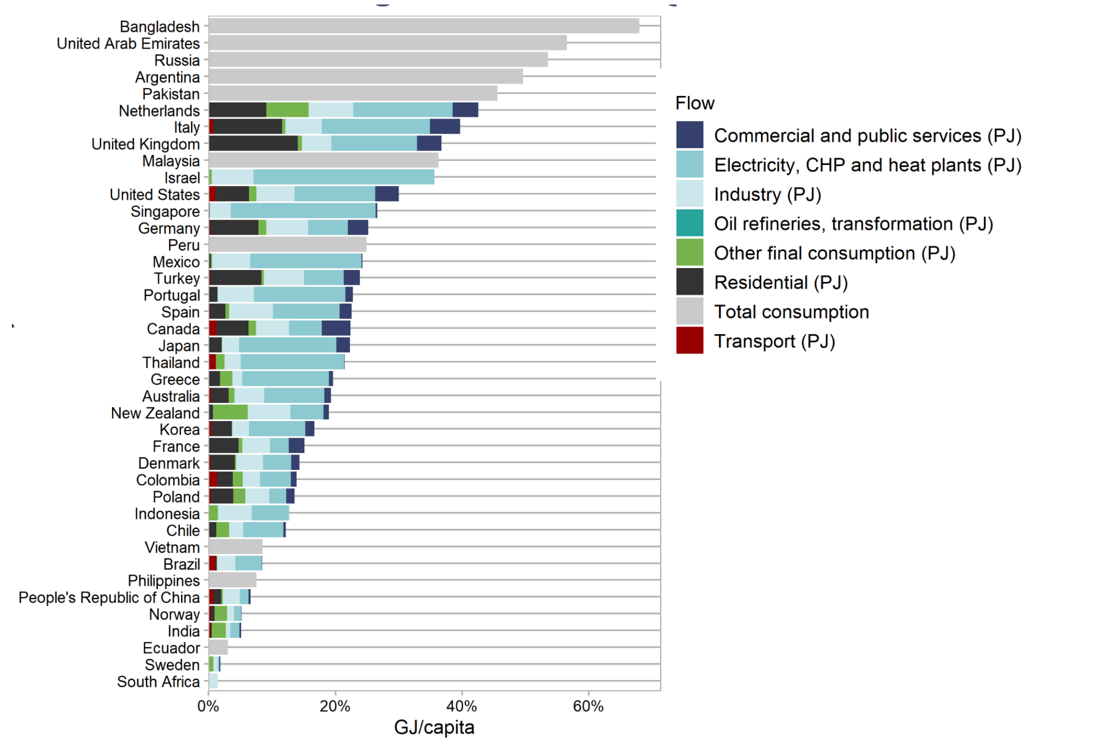


Figure: Gas energy supply per capita, 2019, colored by sector. Source: IEA

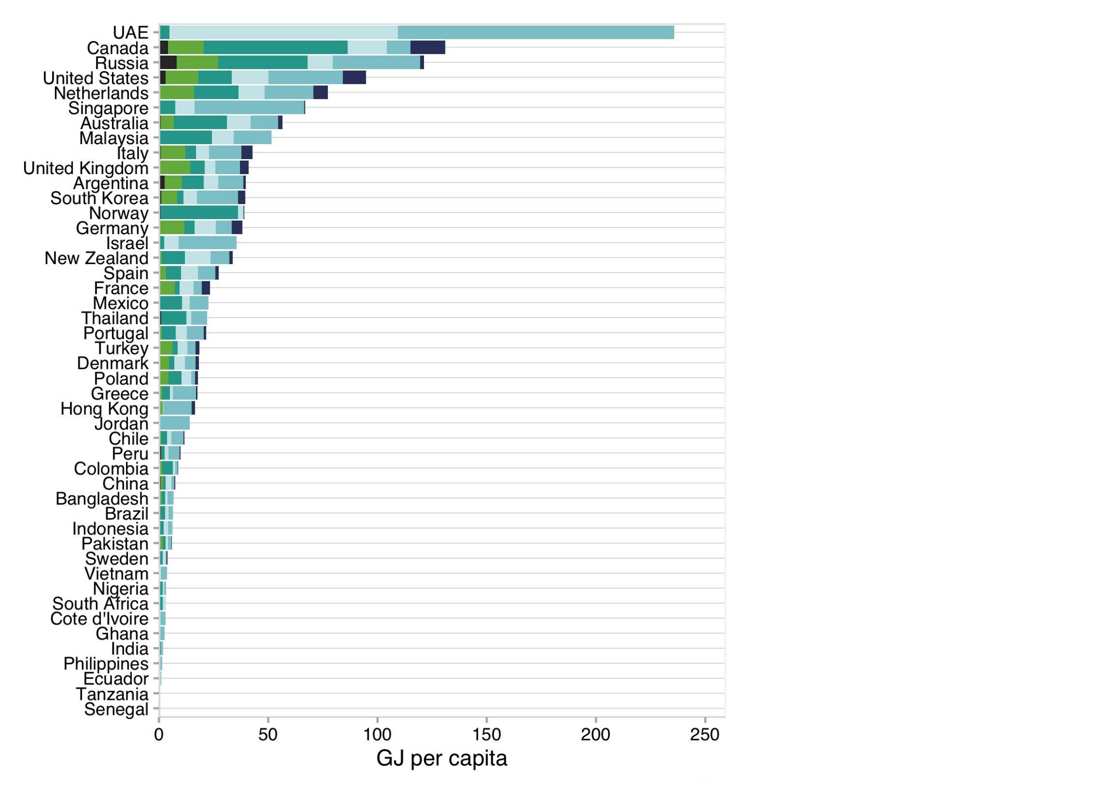
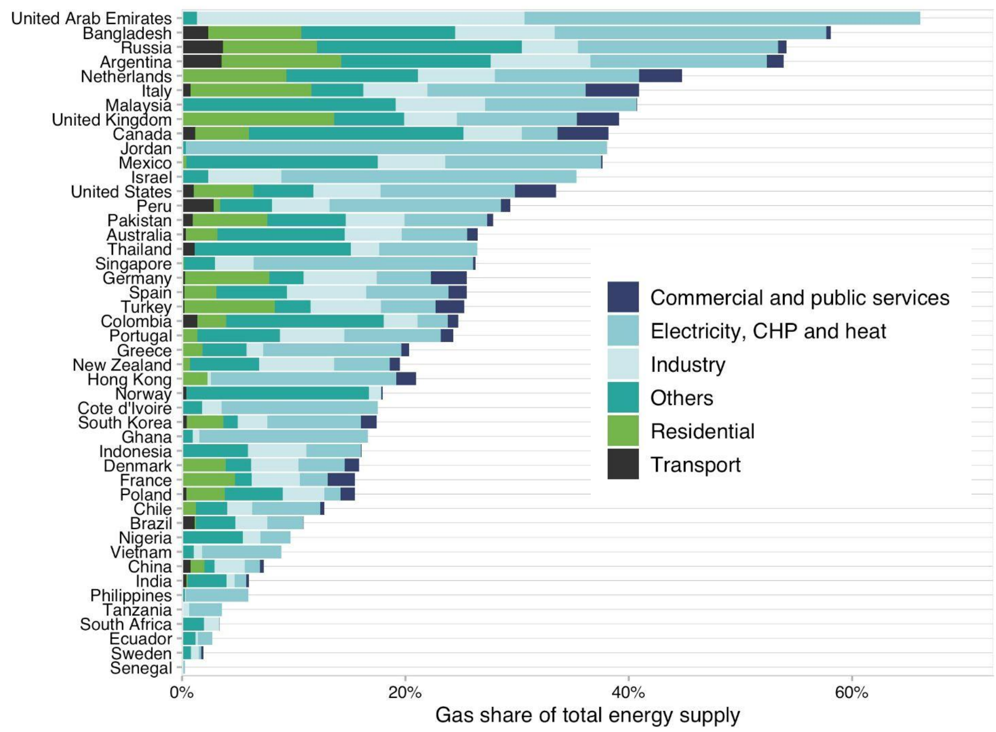


Figure: Share of gas in total energy supply, 2019, colored by sector. Source: IEA



2.1 City-level consumption data and method

The city level data was retrieved from publicly available sources (see Table 1). The goal we set out was to find data for 2019, our baseline year. Where this was not possible we collected the most recent year that was available in the public domain. Also, when city-level data was not available, we looked for county/state/provincial data for which the target city belongs to.
Data on gas consumption at city level is relatively scarce for total consumption and more so for consumption differentiated by sectors such as industry, residential and commercial. Better data are available in the public domain for US counties through the U.S. Energy Information Administration[7] and some European cities through national statistics or energy authorities. Older data for non-European cities are available and was retrieved for making estimates for 2019, extrapolating from the available year.

Table 1. *C40 city- or regional-level total, residential, industrial and commercial gas consumption, in billion cubic meters*

			Gas Consumption				
City	**Year**	**Region**	**Total bcm**	**Residential bcm**	**Industrial bcm**	**Commercial bcm**	**Data source**
Abidjan	2019	Abidjan	0.31				GOUV 2020; DGH
Accra	2020	Accra	1.05				OIES 2021
Dar es Salaam	2018	Dar es Salaam	0.65				allAfrica 2021
Durban (eThekwini)	2010	Durban (eThekwini)	0.07				Merven et al. 2017; eThekwini Municipality 2015
Ekurhuleni	2019	Ekurhuleni	0.45				Urban Energy Support 2004; estimate
Johannesburg	2008	Johannesburg	0.05				Urban Energy Support 2008; estimate
Lagos	2020	Lagos	0.22				GACN 2020
Jakarta	2011	Jakarta	1.07				Kennedy et al. 2015
Seoul	2011	Seoul	5.6				Kennedy et al. 2015

[7] U.S. Energy Information Administration (EIA). Natural Gas Consumption by End Use. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

Singapore	2020	Singapore	11.84	0.09	11.66	0.09	EMA 2021
Tokyo	2011	Tokyo	28.2				Kennedy et al. 2015
Amsterdam	2016	Amsterdam	0.7				Urban Learning
Athens	2017	Athens	0.56				Wei et al. 2018
Berlin	2019	Berlin	3.14				LAK
Heidelberg	2019	Baden-Württemberg	8.29				LAK
Istanbul	2011	Istanbul	5.91				Kennedy et al. 2015
London	2019	Outer London	3.59	0.27			GOV UK
Milan	2019	Milan	3.64		0.33		MISE
Paris	2011	Paris	6.9				Kennedy et al. 2015
Rome	2019	Rome	2.32		0.08		MISE
Venice	2019	Venice	1.48		0.35		MISE
Buenos Aires	2019	Ciudad de Buenos Aires		0.92	0.19	0.19	Enargas 2022
Bogotá	2010	Bogotá	1.17	0.4	0.24		Piña & Martínez 2014
Mexico City	2011	Mexico city	2.58				Kennedy et al. 2015
Rio de Janeiro	2019	Rio de Janeiro municipality	1.1	0.1	0.33	0.07	Rio Prefeitura 2018
São Paulo	2021	State of São Paulo	6.13	0.32	4.38	0.14	Governo do Estado de São Paulo
Austin	2019	State of Texas	132.3	6.5	51	5.6	U.S. EIA 2022
Boston	2019	State of Massachusetts	12.2	3.8	1.4	3.4	U.S. EIA 2022
Chicago	2019	State of Illinois	32.7	12.4	7.6	7.0	U.S. EIA 2022
Houston	2019	State of Texas	132.3	6.5	51	5.6	U.S. EIA 2022

Los Angeles	2019	Los Angeles County	8.54	3.46			California Energy Commission
Miami	2019	State of Florida	43.7	0.47	3.39	1.8	U.S. EIA 2022
Montréal	2019	Quebec		0.79	4.16	2.01	Statistics Canada 2022
New Orleans	2019	State of Louisiana	51.9	0.9	32.4	0.9	U.S EIA 2022
New York City	2019	State of New York	36.7	13.4	2.6	9.1	U.S. EIA 2022
Philadelphia	2019	State of Pennsylvania	45.8	6.7	7.1	4.58	U.S. EIA 2022
Phoenix	2019	State of Arizona	13.3	1.2	0.53	0.98	U.S EIA 2022
Portland	2019	State of Oregon	8.1	1.4	1.6	0.9	U.S EIA 2022
San Francisco	2019	San Francisco County	0.64	0.37			California Energy Commission
Seattle	2019	State of Washington	9.9	2.5	2.2	1.7	U.S. EIA 2022
Toronto	2019	Ontario		9.59	12.36	9.48	Statistics Canada 2022
Vancouver	2019	British Columbia		2.37	4.36	1.57	Statistics Canada 2022
Washington DC	2019	District of Columbia	0.86	0.34		0.46	U.S. EIA 2022
Delhi NCT	2011	Delhi	1.45				Kennedy et al. 2015
Karachi	2011	Karachi	1.58				Kennedy et al. 2015
Mumbai	2011	Mumbai	0.13				Kennedy et al. 2015

3. Global emissions inventory for fossil gas extraction and use

We have prepared the first global air pollutant emissions inventory that separates out emissions from fossil gas extraction, transmission and combustion.

The inventory follows a tiered approach, with the default emission inventory approach used for those countries with low gas use and emissions, and refinements for the most significant countries (see the figures in the Introduction).

The default approach was to use the CEDS[8] emission inventory system. The CEDS is the most refined and up-to-date global air pollutant and CO2 emissions inventory. It combines information from global and regional emissions inventories, latest energy and activity data, and officially reported national air pollutant emissions. The open source system allows us to update the emission estimates and to separate out gas emissions.[9]

3.1 Updating CEDS input data

We first forked the latest CEDS release, i.e. v_2021_04_21. We then updated input datasets when a new version was available, as of March 2022. This includes:

- IEA energy statistics[10]
- U.S. Greenhouse Gas Emissions and Sinks[11]
- Australia National Pollutant Inventory[12]
- Argentina Biennial update report (BUR)[13]

[8] Joint Global Change Research Institute. A Community Emissions Data System (CEDS) for Historical Emissions. http://www.globalchange.umd.edu/ceds/

[9] See visualization of the results: https://crea.shinyapps.io/ceds/

[10] International Energy Agency (IEA). World Energy Balances. May, 2022. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

[11] United States Environmental Protection Agency (EPA). Inventory of U.S. Greenhouse Gas Emissions and Sinks. April, 2022. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[12] Australian Government - Department of Climate Change, Energy, the Environment and Water. National Pollutant Inventory. http://www.npi.gov.au/

[13] United Nations - Climate Change. Argentina Biennial update report. https://unfccc.int/documents?search2=&search3=argentina&f%5B0%5D=country%3A1227

- Canada Air Pollutant and Black Carbon Emissions Inventories[14]
- Emission Database for Global Atmospheric Research (EDGAR)[15]
- European Monitoring and Evaluation Programme (EMEP)[16]
- United Nations Framework Convention on Climate Change (UNFCCC)[17]

3.2 Updating city fossil gas consumption

We have made an attempt to collect specific fossil gas consumption data for as many C40 cities, or their subnational administrative regions including provinces, states etc. (see Table 1), as possible, to refine the local CO2 and air pollutant emissions estimates specifically for the cities. When such data is not available, emissions estimates for the cities will be based on the gridded emissions inventories, which allocate national-level totals to a spatial grid using proxies such as population and economic data.

3.3 Additional data sources for countries and sectors

Gas-fired power plants within the city boundaries will be identified to the unit level using the Global Energy Monitor Global Gas Plant Tracker data (January 2022 update)[18]. For all gas-fired power plants, location (coordinates), ownership, generating capacity will be available, as well as emissions estimates based on the emissions inventories used.

For the world's largest fossil gas consumer, the U.S., we'll obtain a far more detailed picture from the EPA National Emissions Inventory 2017 data.[19] It includes all large boilers and other large emitters as point sources (with precise locations), and classifies combustion sources by fuel. Emissions from smaller boilers (residential, commercial and small industrial boilers) and gas stoves are included as nonpoint

---

[14] Government of Canada. Air Pollutant and Black Carbon Emissions Inventories online search. March, 2022. https://pollution-waste.canada.ca/air-emission-inventory/

[15] European Commission. EDGAR - Emissions Database for Global Atmospheric Research. Global Greenhouse Gas Emissions. https://edgar.jrc.ec.europa.eu/dataset_ghg60

[16] EMEP Centre on Emission Inventories and Projections. Officially reported emission data. https://www.ceip.at/webdab-emission-database/reported-emissiondata

[17] United Nations Climate Change. Greenhouse Gas Inventory Data - Flexible Queries Annex I Parties. https://di.unfccc.int/flex_annex1

[18] Global Energy Monitor (GEM). Global Gas Plant Tracker. January, 2022. https://globalenergymonitor.org/projects/global-gas-plant-tracker/

[19] United States Environmental Protection Agency (EPA). 2017 National Emissions Inventory (NEI) Data. https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data

sources, with emissions data provided on county level. Sector-level gas consumption by state will be updated to the target year for air quality simulations with energy data from the EIA.[20]

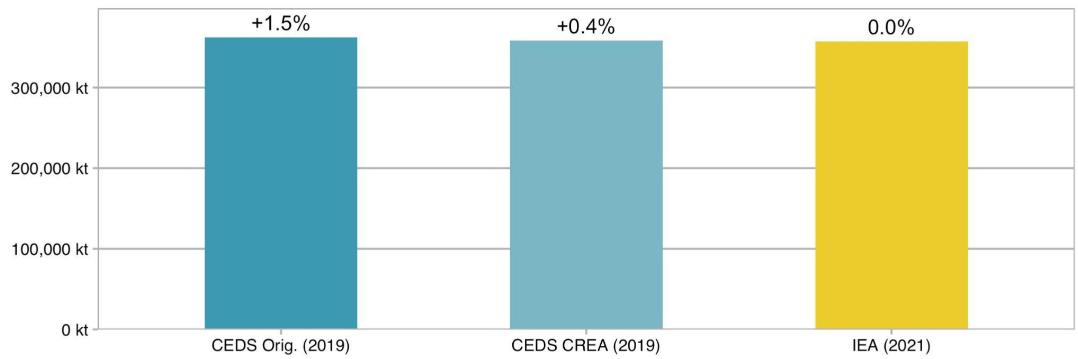
In Europe, we will use the EEA IRD data for the power and industrial sectors[21]. Emissions and locations (coordinates) of all large combustion plants and other significant emissions sources are reported on the plant level, along with their fuel input. This allows us to identify gas-fired facilities. For other sectors, national-level emissions totals reported to the CLRTAP[22] are already incorporated into CEDS.

3.4 Comparison of CEDS with IEA Methane Tracker data

In February 2022, IEA released its Global Methane Tracker 2022, which for the first time offers a complete set of country-level estimates for methane emissions from the energy sector.[23] We confronted the IEA data with the data obtained from our own run of CEDS model ("CEDS CREA") as well as the original CEDS results ("CEDS Orig.").

When considering all countries and sectors together, the methane emissions are almost identical (+0.4%), as shown in Figure 2 below.

Figure 2 *| Comparison of global methane emissions between IEA Methane Tracker and CEDS (percentage refers to the difference with IEA estimates)*



[20] United States Energy Information Administration (EIA). About SEDS. https://www.eia.gov/state/seds/

[21] European Environment Agency (EEA). Industrial Reporting database. https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial-4/eu-registry-e-prtr-lcp

[22] EMEP Centre on Emission Inventories and Projections. The Emissions Database. https://www.ceip.at/webdab-emission-database

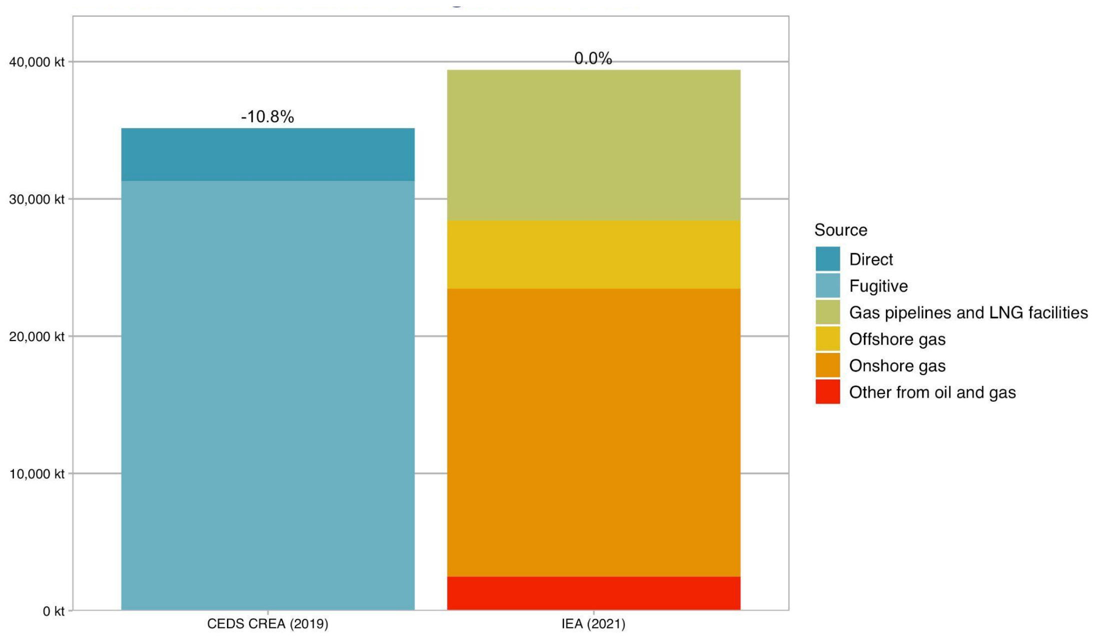
[23] International Energy Agency (IEA). Global Methane Tracker 2022. February, 2022. https://www.iea.org/reports/global-methane-tracker-2022

On a country level however, differences are more pronounced: CEDS estimations of China's emissions are 7.8% lower than IEA's, 6.9% higher for India, and 16.1% lower for the United States, the three highest emitters. See more results in Figure 3 below.

Figure 3 *| Country-level comparison of methane emissions between IEA Methane Tracker and CEDS for top 20 countries (percentage refers to the difference with IEA estimates)*

Perhaps more importantly, methane emissions associated with fossil gas remain relatively close: our estimations are 10.8% lower than IEA estimates (see Figure 4). The difference might actually be even lower given that part of IEA emissions are associated with oil.

***Figure 4** | Global methane emissions related to fossil gas entire chain, from extraction to utilisation (percentage refers to the difference with IEA estimates)*



4. Estimates of current fossil gas use and emissions in C40 cities and the regions surrounding them

The global emissions inventory developed in the previous step will enable us to estimate the gas consumption and associated greenhouse gas and air pollutant emissions by sector in the study cities and in the regions surrounding them, for example based on a radius from the city agreed with C40.

4.1 Emissions from all energy sources

Figure 5 *| NO_x Emissions by sector, from all energy sources (energy refers to energy industry - electricity, heat and other conversion)*

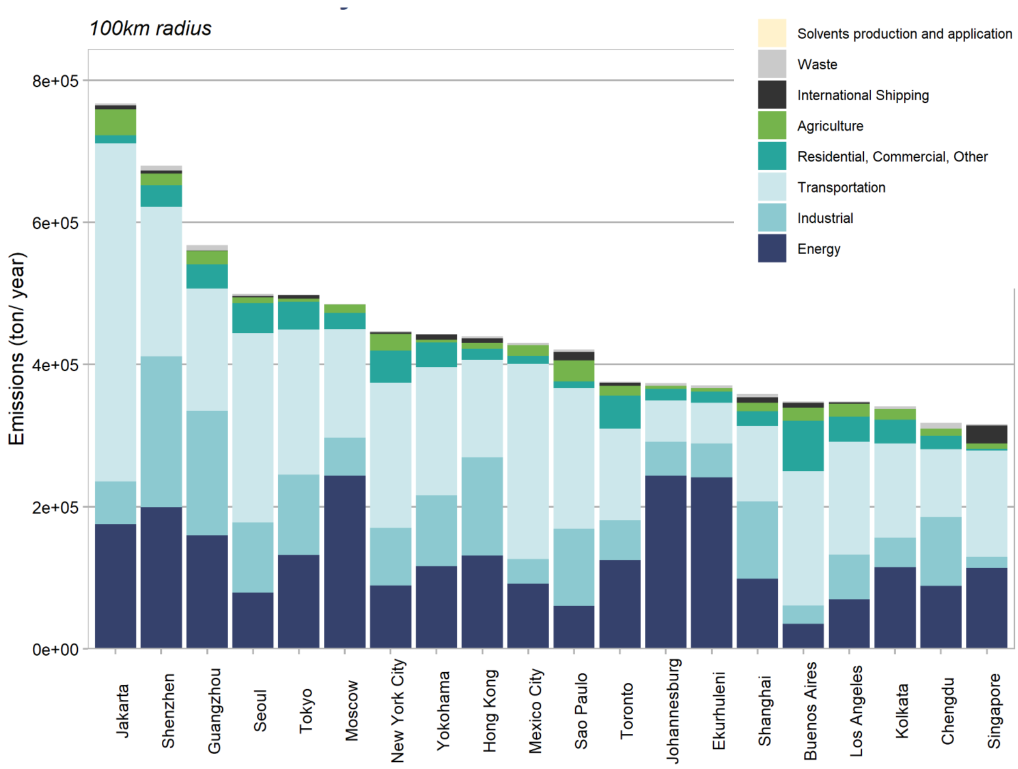
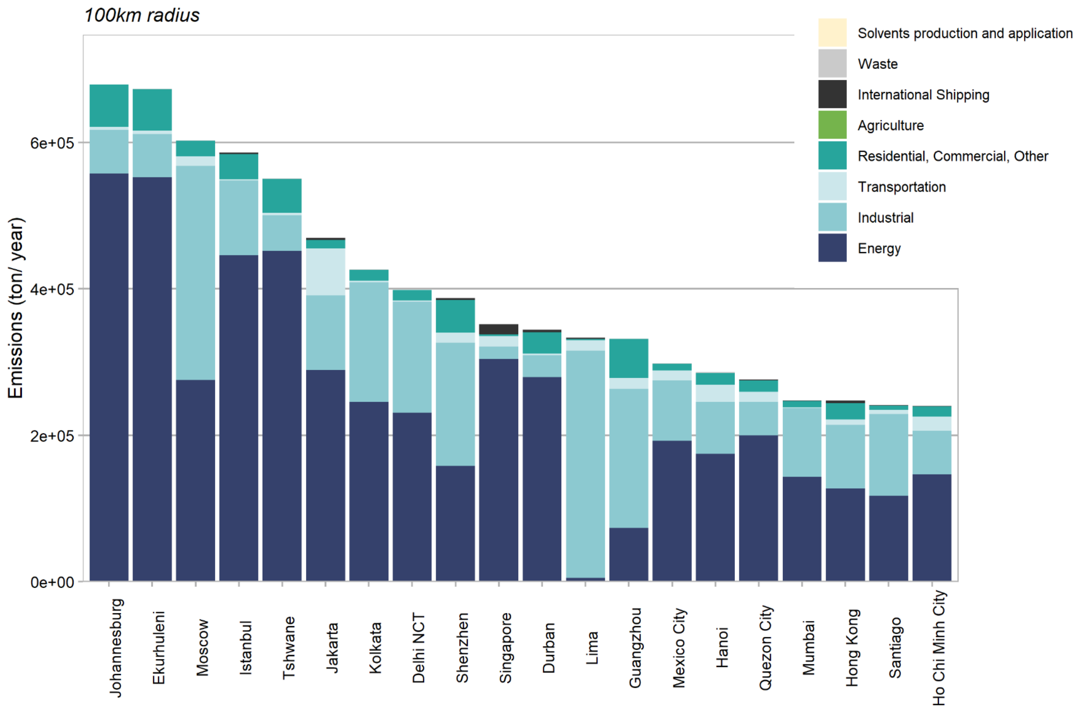


Figure 6 *| SO_2 Emissions by sector, from all energy sources (energy refers to energy industry - electricity, heat and other conversion).*



4.1 Emissions from fossil gas use only

Figure 7 | NO_x Emissions by sector, from fossil gas use

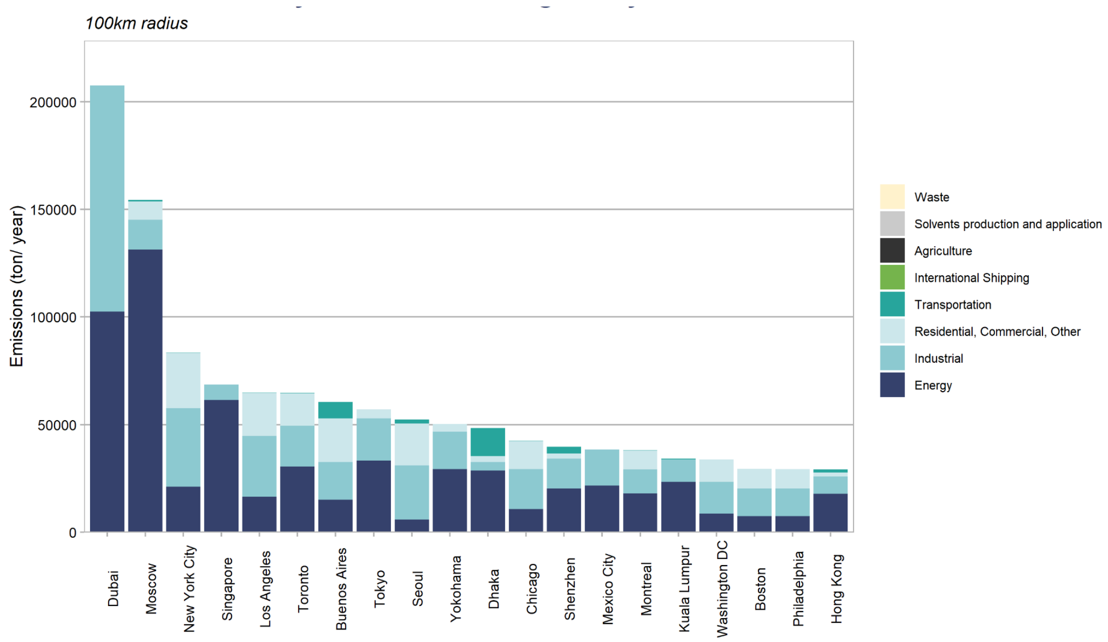
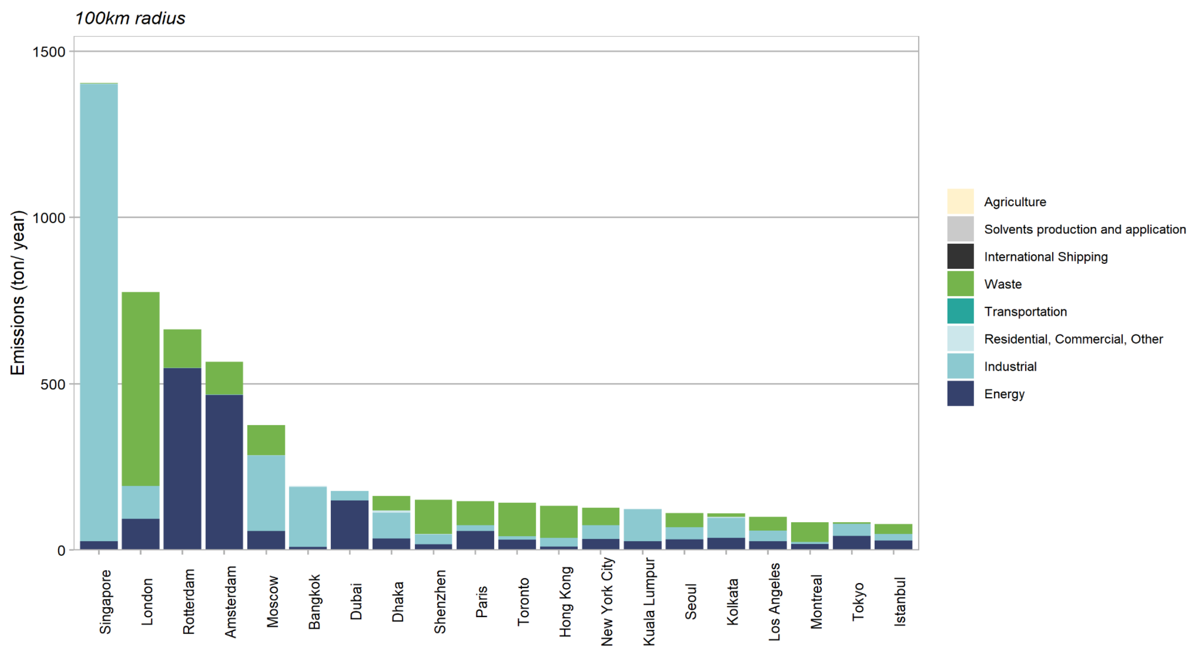


Figure 8 | NH_3 Emissions by sector, from fossil gas use



5. Mapping of planned gas infrastructure related to C40 cities

We compiled data on proposed gas power projects[24] and infrastructure[25]. The review covers planned power plants, CHP plants and infrastructure within the cities themselves but also new pipelines, terminals and gas fields connected to the gas transmission networks and power grids that supply the cities. We used this data to develop a "gas infrastructure expansion scenario" that shows the impacts of projected emissions associated with new gas infrastructure.

The expansion scenario evaluates the emissions from fossil gas infrastructure that is currently under construction or proposed, including gas pipelines, LNG import terminals and power plants. The scenario aims to capture the air quality and health impacts attributable to this planned infrastructure if it is realized. The scenario compares these impacts to an option of no gas infrastructure expansion, effectively replacing the gas use with either reduced consumption or zero emission energy sources.
Planned LNG export terminals are not included, as they would largely represent double counting with import terminals and we had no meaningful way to allocate the emissions from the eventual use of the gas spatially. In exporting countries, transboundary pipelines were assumed to have no impact on domestic gas consumption.

We assessed the potential increase in fossil gas consumption associated with new pipelines separately for trans-boundary import pipelines, pipelines originating from gas production sites, and domestic transmission and distribution pipelines. For the first two categories, average utilization was calculated from pipeline capacity in place[26] and total imports in 2019[27], and new pipelines were assumed to work at the same utilization. For domestic pipelines, we calculated average ratio of pipeline

---

[24] Global Energy Monitor (GEM). Global Gas Plant Tracker. January, 2022. https://globalenergymonitor.org/projects/global-gas-plant-tracker/

[25] Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, Gas Pipelines. January 2022., Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, LNG Terminals. January 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

[26]Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, Gas Pipelines. January 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

[27] British Petroleum (BP). Statistical Review of World Energy 2021. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

capacity to gas consumption in 2019 and applied this ratio to new pipelines. Pipelines associated with gas production sites were identified by overlaying the data from the Global Oil and Gas Extraction Tracker[28] and the Global Gas Infrastructure Tracker. Pipelines starting or terminating near an LNG terminal (within 5km) were excluded to avoid double counting with LNG import infrastructure. All proposed pipelines from Russia to EU and NATO countries were excluded as these are assumed to be permanently off the table.

Gas use by new power plants was projected based on the average utilization of existing power plants, which was calculated based on gas-fired power generation and installed capacity in 2019. We first assumed average utilization of 50% for combined cycle power plants, 65% for CHP plants and 15% for gas turbines, and calculated the expected generation for each country on this basis. This expected generation was then adjusted to match actual generation (BP 2021). The same adjustment was used for new plants. This approach takes into account the possible differences in the mix existing and planned gas plants in a country – if e.g. there are a lot of CHP plants in operation at the moment, and planned plants are mainly gas turbines (peaking plants), our expected utilization for the new plants is much lower than the current average.

GEM Global Gas Plant Tracker[29] reports whether the fuel used by new gas plant projects is LNG or pipeline gas. Many of the LNG-fired power projects include their own LNG terminal, and in some cases these terminals are not listed as separate projects in GEM Global Gas Infrastructure Tracker. We identified clusters of planned LNG-fired power plants and terminals, within a radius of 10km, and when the expected gas use by the power plants exceeded the planned terminal capacity, we assumed that additional LNG capacity would be built. When planned LNG capacity exceeded the expected gas consumption by the power plants, the rest was allocated to all consuming sectors.

Figure 9 shows the potential impact of planned expansions on gas use by country. The new gas supply from pipelines and LNG terminals was allocated to different consuming sectors (industry, power plants, buildings) based on the share of different sectors in the increase in gas consumption from the GCAM 1.5-degree to the Current Policies scenario in 2040 in each region (Figure 8). When the expected gas use by planned power plants exceeded the share allocated to the power sector, we scaled down the increase in the other sectors to make room for the demand from power plants. When the expected gas use by planned power plants exceeded the share allocated to the power sector exceeded the entire planned increase on the supply side, we assumed no increase in gas use by other sectors.
Emissions from the gas use associated with the new infrastructure were projected using emissions factors from the CEDS emissions inventory, taking into projected improvements by 2035 (see the next section). For new gas-fired power plants, given

---

[28] Global Energy Monitor (GEM). Global Oil and Gas Extraction Tracker. January, 2022. https://globalenergymonitor.org/projects/global-oil-gas-extraction-tracker/

[29] Global Energy Monitor (GEM). Global Gas Plant Tracker. January, 2022. https://globalenergymonitor.org/projects/global-gas-plant-tracker/

that the scenario looks specifically at new facilities and therefore the emissions are constrained by the emissions standards for new gas-fired power plants (Table 2), and by the emission values in the IFC EHS Guidelines for Thermal Power[30] when national regulations are more lenient.

The emissions from the gas use associated with the new infrastructure were allocated to the grid using the CEDS spatial allocation for current emissions from each sector and in each country, except for planned power plants which were assigned to grid cells based on their specific locations.

Table 2. *NOx emissions limits applied to new gas-fired power plants in different countries*

Country or Region	Limit, standardized to mg/Nm3 at 15% O2	Category	Reference
EU	35	OCGT	*BREF BAT-AEL Upper*
EU	30	CCGT	*BREF BAT-AEL Upper*
EU	60	Boiler	*BREF BAT-AEL Upper*
China	50		*GB 13223-2011: Emission Standard of Air Pollutants for Thermal Power Plants*
Mexico	413.6	Gaseous boilers, steam generators, thermal oil heaters, indirect heating ovens	*NOM-085-Semarnat-2011*
UAE	350	Fuel combustion unit, gas fuel	*Cabinet Decree No (12) of the year 2006 concerning the Protection of Air From Pollution*
UAE	70	Turbine unit, gas fuel	*Cabinet Decree No (12) of the year 2006 concerning the Protection of Air From Pollution*
India	94	>400MW	*Environmental Standards for Gas/Naptha-based Thermal Power Plants*
India	141	100-400MW	*Environmental Standards for Gas/Naptha-based Thermal Power Plants*
India	188	<100MW	*Environmental Standards for Gas/Naptha-based Thermal Power Plants*
India	188	Burning gas in conventional boiler	*Environmental Standards for Gas/Naptha-based Thermal Power Plants*

[30] REFERENCE

Philippines	500	For other new sources, as NO2	*Implementing Rules and Regulations of the Philippine Clean Air Act of 1999*
Thailand	225.6		*The Emission Standard of a Power Plant, B.E.2547*
Vietnam	250		*QCVN 22: 2009/BTNMT: National Technical Regulation on Emission of Thermal Power Industry*
Singapore	400		*Environmental Protection and Management (Air Impurities) Regulations*
Malaysia	350	Gaseous fuels	*Environmental Quality (Clean Air) Regulations 2014*
Indonesia	320	New turbines and new gas engines	*Quality Standard for Stationary Source Emissions for Thermal Power Plant Businesses and/or Activities*
South Korea	18.8		*Enforcement Rules of the Air Conservation Act*
Japan	28.2		*Chiba Prefecture Power Generation Boiler, Gas Turbine etc. NOx countermeasure guidance guidelines (used as a representative example; permit conditions and standards are determined by subnational regulators).*

***Figure 8** | Breakdown of incremental gas use by sector and GCAM region, based on the differentials between the GCAM Current Policies and 1.5-degree scenarios.*

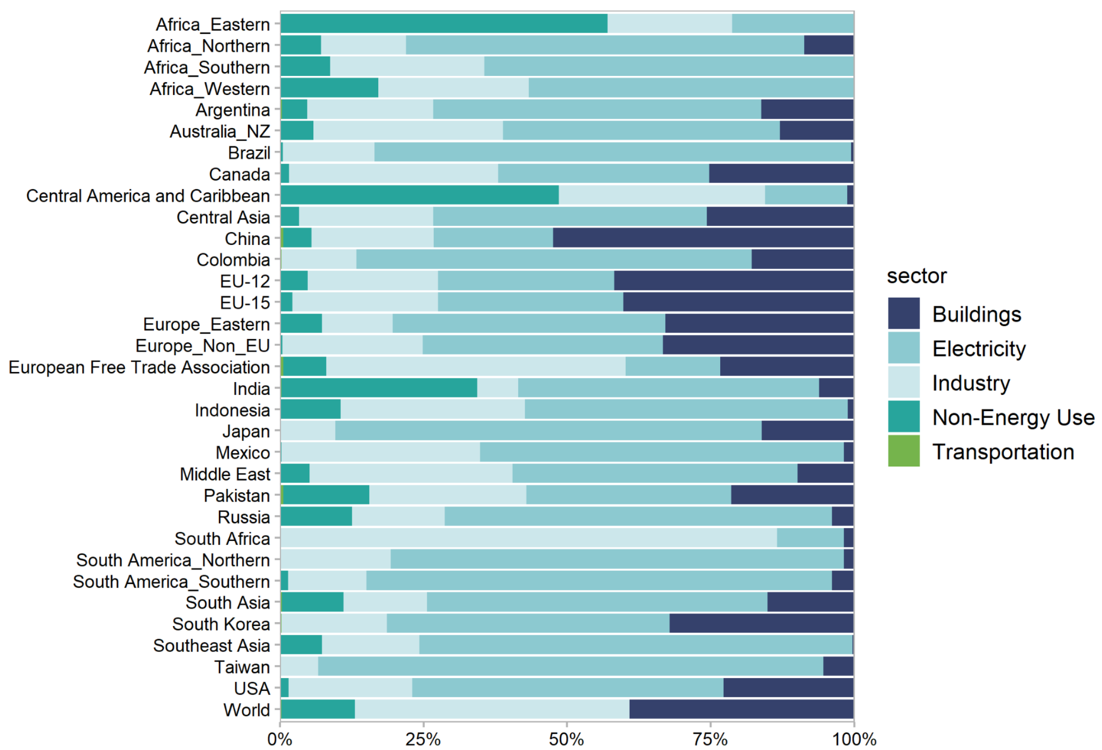
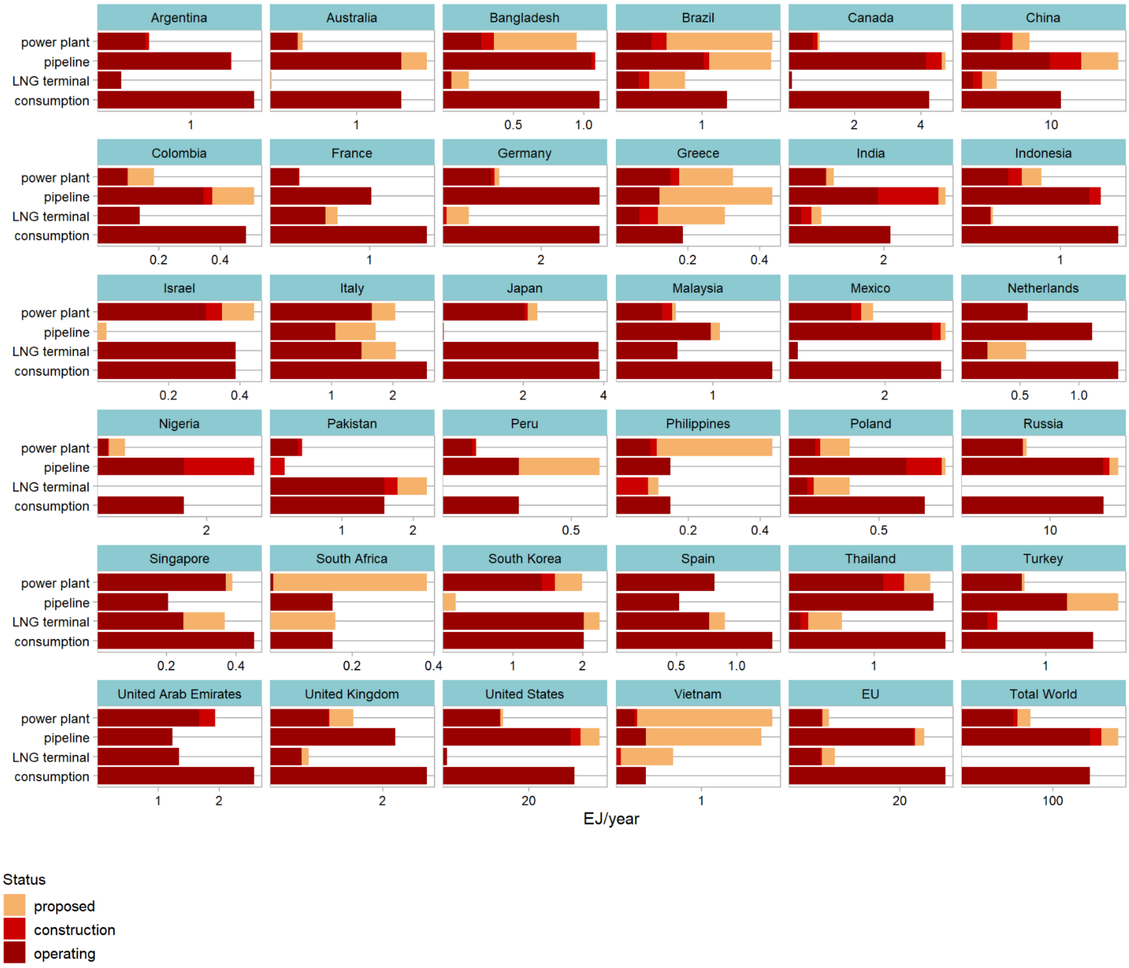


Figure 9 *| Current gas consumption in the countries with C40 cities and significant gas consumption or expansion plans. The graph shows the current gas consumption and potential gas consumption associated with infrastructure by type and status of project.*



6. Future pathways for fossil gas consumption by sector in C40 countries

The UMD/CGS will develop future pathways for fossil gas consumption by sector in C40 countries for buildings, industry and power, are developed using a global integrated assessment model (the Global Change Analysis Model, GCAM 5.4[31]).

Two scenarios are explored in this study, including These will include the reference scenario with country pledges and targets and the 1.5-degree scenario with differentiated regional net-zero targetss. GCAM produces theThe pathways are developed on at the level of the 32 world regions in the model, which areand downscaled to nationalcountry and subnationalprovince/state levels where required.

6.1 Reference scenario with country NDC pledges and net-zero targets policies

We estimatewill project the health and economic benefits of reducing fossil gas consumption from a baseline that takes into account countries' current unconditional policies and NDC pledges and long-term net-zero targets, following the methodology of Ou et al, which extends the decarbonization rates implied by the pledges[32]. For regions without long-term net-zero target, the implied decarbonization rates from the NDC pledges are extended to the post-NDC period. Table 3 shows We've compiled these pledges for all C40 countries' pledges and targets that are included in to enable the adjustment of the pathway. Sperarate emission constraints are applied to individual GCAM regions with one single economy-wide carbon price across different energy sectors, and 10% of that carbon price is applied to land-use change emissions.

When downscaling GCAM results at the Since the GCAM projects energy pathways for 32 world regions, the same reduction rates are applied to all countries within the

[31] GCAM v6 Documentation: Global Change Analysis Model (GCAM). https://jgcri.github.io/gcam-doc/

[32] Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A. A., Hultman, N., McFarland, J. R., Binsted, M., Cui, R., Fyson, C., Geiges, A., Gonzales-Zuñiga, S., Gidden, M. J., Höhne, N., Jeffery, L., Kuramochi, T., Lewis, J., Meinshausen, M., Nicholls, Z., … McJeon, H. (2021). Can updated climate pledges limit warming well below 2°C? *Science*, *374*(6568), 693–695. https://doi.org/10.1126/science.abl8976

same GCAM region from the 2019 base year value[33,34,35,36,37]. we need to downscale the effect of the NDCs to the country level. We will do this by projecting the cost-effective way to achieve a similar emission reduction from baseline as targeted by the NDCs across the whole region, and applying the changes in fuel use in different sectors under this projection to the country that the NDC target covers.

Table 3. *Current NDC pledges of all C40 countries*

Country	NDC	Link	Mitigation target	Net-Zero Target Year	Included in Climate Action Tracker?
Bangladesh	Bangladesh First NDC (updated submission)	Link	Mitigation target (unconditional and conditional elements), unconditional **5% GHG** reduction from 2012. Conditional of international support, additional **10%** GHG reduction from 2011 baseline	CO2:N/A GHG: N/A	No
Côte d'Ivoire	Cote d'Ivoire First NDC	Link	**-28% GHG** reduction from baseline	CO2:N/A GHG: N/A	No
Ecuador	Ecuador First NDC	Link	**-9% GHG** reduction from baseline	CO2:N/A GHG: N/A	No
Ethiopia	Ethiopia First NDC (updated submission)	Link	Mitigation target (unconditional and conditional elements) corresponds to a reduction of **68.8% compared to the BAU projection by 2030**. The unconditional component foresees emission reductions of 14% and the conditional component contributes to approximately 54.8% compared to the BAU projection by 2030	CO2:N/A GHG: N/A	No
Ghana	Ghana First NDC (updated submission)	Link	Absolute greenhouse gas (GHG) emission reductions of **64 MtCO2e by 2030**	CO2:N/A GHG: N/A	No

[33] T. Boden, R. Andres, G. Marland, "Global, regional, and national fossil-fuel co2 emissions (1751-2014)(v. 2017)" (Environmental System Science Data Infrastructure for a Virtual Ecosystem, 2017).
[34] International Energy Agency, World Energy Balances 2019 (2019).
[35] R. A. Houghton, Land-use change and the carbon cycle. Glob. Change Biol. 1, 275–287 (1995). doi:10.1111/j.1365-2486.1995.tb00026.x
[36] US EPA, "Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation 2015-2050" (United States Environmental Protection Agency, Washington, DC 20005, 2019).
[37] 9. P. R. O'Rourke et al., CEDS v_2021_04_21 Release Emission Data (v_2021_02_05) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4741285, (2021).

Israel	Israel First NDC (updated Submission)	Link	Unconditional absolute greenhouse gas (GHG) emissions reduction goal for **2030 of 27% relative to 2015** and an unconditional absolute GHG emissions reduction goal for 2050 of 85% relative to 2015	CO2:N/A GHG: N/A	No
Jordan	Jordan First NDC (updated submission)	Link	**31% reduction of emissions by 2030**. 5% compared to the BAU scenario unconditionally, conditionally an additional 26%	CO2:N/A GHG: N/A	No
Kenya	Kenya First NDC (updated submission)	Link	Abate GHG emissions by **32% by 2030 relative to the BAU scenario of 143 MtCO2eq**	CO2:N/A GHG: N/A	No
Malaysia	Malaysia First NDC (updated submission)	Link	Economy-wide carbon intensity (against GDP) **reduction of 45% in 2030 compared to 2005** level.	CO2:N/A GHG: N/A	No
Nigeria	Nigeria First NDC (updated submission)	Link	**Reduce GHG emissions in 2030 by 20% below business-as-usual emissions,** and increases its conditional target to **47% (around 100 MtC02 below current (2018) levels) below business-as-usual emissions in 2030, on condition of appropriate support**	CO2:N/A GHG: N/A	No
Norway	Norway First NDC (updated submission)	Link	TargetAtarget by at least **50%** and towards 55% reduction in greenhouse gas emission b**y 2030 compared to 1990 levels.**	CO2: 2063 GHG: 2069*	No
Pakistan	Pakistan First NDC (updated submission)	Link	Overall **50% reduction** of projected emissions by 2030, with a **15% (unconditional)** drop below (BAU) from the country's own resources, and an **additional 35%** (conditional)drop below BAU subject to international financial support	CO2:N/A GHG: N/A	No
Senegal	Senegal First NDC	Link	Reduce GHG emissions by **5% and 7%** (unconditional) and **23.7% and 29.5%** (conditional) compared to **BAU levels in 2025 and 2030**	CO2:N/A GHG: N/A	No
Sierra Leone	Sierra Leone First NDC (updated submission)	Link	reduce its domestic GHG emissions of **10%** by 2030 as compared to a no-policy scenario of 2015 to 2030, with an intermediary indicative mitigation target of 5% reduction by 2025 against the same baseline	CO2:N/A GHG: N/A	No
Tanzania	Tanzania First NDC (updated submission)	Link	**30-35%** reduction on national BAU emissions by2030.	CO2:N/A GHG: N/A	No
Singapore	Singapore First NDC (updated submission)	Link	36% reduction in Emissions Intensity (EI) from 2005 levels by 2030	CO2:N/A GHG: N/A	No

Argentina	Second NDC (Updated)	Link	Argentina's 2021 Paris climate pledge, laid out in its second NDC report, sets a goal of carbon neutrality by 2050 but does not specifically commit to zero-emissions electricity or a complete phase-out of coal.	CO2:2050 GHG: 2069*	Yes
Australia	First NDC (Updated)	Link	Australia's most recent NDC, submitted in October 2021, commits the country to net-zero emissions by 2050, and an emissions reduction of 26-28% below 2005 levels by 2030. The country is currently on track to reach a 35% reduction in emissions by 2030. Its goals for renewable energy are measured in terms of lowered cost, not deployment or capacity, but Australia is committed to provide A$20 billion in funding for low-carbon tech by 2030.	CO2:2042 GHG:2049	Yes
Brazil	First NDC (Updated)	Link	In its most recent NDC, submitted in December 2020, Brazil committed to reduce its emissions in 2030 by 43% below 2005 levels. Brazil states that its targets are compatible with reaching carbon neutrality by 2060, but does not explicitly commit to doing so in its NDC.	CO2:2050 GHG: 2075*	Yes
Canada	First NDC (Updated)	Link	Canada's most recent NDC, submitted in July 2021, sets a target of reducing emissions by 40-45% below 2005 levels by 2030. Canada has also committed to reach net-zero emissions by 2050. Two provinces, Nova Scotia and Alberta, committed to phase out coal by 2030 in the NDC. These two provinces also set renewable energy targets of 80% and 30%, respectively, by 2030.	CO2: 2045 GHG: 2050	Yes
Chile	First NDC (Updated)	Link	In its most recent NDC, submitted in April 2020, Chile established an unconditional carbon budget not to exceed 100 MtCO2e in the period 2020 to 2030. It considers this an intermediate goal to reach net-zero emissions by 2050. The country has also committed to phase out coal-fired power by 2040.	CO2:N/A GHG: N/A	Yes

China	First NDC (Updated)	Link	China's updated NDC, submitted in October 2021, pledged for the country to reach a peak in CO2 emissions before 2030 – with "best efforts to peak early" – and to bring the installed capacity of wind and solar power to more than 1,200 gigawatts (GW). China also officially added its goal of achieveing carbon neutrality "before 2060" into the latest pledge. According to the NDC, China will "strictly control" coal-fired power generation projects, and "strictly limit" the increase in coal consumption over the 14th Five-Year Plan period (2021-2025) and phase it down in the 15th Five-Year Plan period (2026-2030). At the UN General Assembly in September 2021, President Xi pledged that China "will not build new coal-fired power projects abroad".	CO2:2051 GHG: 2060	Yes
Colombia	First NDC (Updated)	Link	Colombia's Paris climate pledge, laid out in the 2020 revision of its NDC report, calls for a 51% reduction in greenhouse gas emissions by 2030, with the country approaching carbon neutrality by 2050.	CO2: 2049 GHG: 2080*	Yes
Denmark	First NDC (Updated)	Link	Denmark, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
France	First NDC (Updated)	Link	France, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Germany	First NDC (Updated)	Link	Germany, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Greece	First NDC (Updated)	Link	Greece, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Hong Kong		N/A	In its 2021 Climate Action Plan, Hong Kong said it will strive to phase out coal as a power generation source by 2035 and to achieve net-zero electricity generation before 2050.	CO2:N/A GHG: N/A	Yes

India	First NDC (Archived)	Link	In its most recent NDC, submitted in October 2016, India committed to reduce the emissions intensity of its GDP by 33-35% below 2005 levels by 2030. It also aims to generate 40% of its power from non-fossil fuel sources by 2030. India plans to "continue to dominate power generation in future," but has mandated that all new coal plants use supercritical technology. In 2016, India had also established a tax of INR 200 (USD 3.2) per tonne of coal, which generated INR 170.84 billion (USD 2.7 billion) that was used on renewable energy projects.	CO2:2071 GHG: 2084*	Yes
Indonesia	First NDC (Updated)	Link	Indonesia's most recent NDC, submitted in July 2021, has two levels of commitments, depending on the amount of international aid received. Its unconditional commitment is to reduce emissions by 29% below a Business-As-Usual Scenario (BAU) by 2030, under which Indonesia would emit an estimated 2.87 GtCO2e in 2030. Indonesia also committed to generate at least 23% of its energy from renewable energy by 2025 and at least 31% in 2050. Indonesia has also said it will generate at least 30% of its energy from coal in 2025, and at least 25% in 2050.	CO2:2060 GHG: 2074*	Yes
Italy	First NDC (Updated)	Link	Italy, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Japan	First NDC (Updated)	Link	In its most recent NDC, submitted in October 2021, Japan committed to reduce its emissions by 46% below 2013 levels by 2030. Japan has also committed to reach net-zero emissions by 2050.	CO2:2049 GHG: 2050	Yes
Mexico	First NDC (Updated)	Link	Mexico's most recent NDC, submitted in December 2020, has two levels of commitments, depending on the amount of international aid received. Its unconditional commitment is to reduce emissions by 22% below a Business-As-Usual Scenario (BAU) by 2030, while its commitment conditional on international aid is an emissions reduction of 36% below BAU by 2030. These targets would result in 210 and 347 Mt CO2eq of emissions reductions in 2030, respectively.	CO2:2061 GHG: 2071*	Yes
Netherlands	First NDC (Updated)	Link	Netherlands, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes

New Zealand	First NDC (Updated)	Link	In its most recent NDC, submitted in November 2021, New Zealand commits to an emissions reduction of 50% below gross 2005 levels by 2030. New Zealand is targeting net-zero emissions by 2050, with the exception of biogenic methane emissions, which will be reduced 24 to 47% below 2017 levels. The NDC also includes a goal of 100% renewable electricity by 2035 and a firm commitment for New Zealand to phase out coal by 2037.	CO2:2042 GHG: 2049	Yes
Peru	First NDC (Updated)	Link	Peru's Paris climate pledge, laid out in its NDC report (2020 revision), calls for a 30% to 40% reduction in greenhouse gas emissions by 2030 but does not stipulate any specific reduction in electricity generation from coal or other fossil fuels.	CO2:N/A GHG: N/A	Yes
Philippines	First NDC (Archived)	Link	In its first NDC, submitted in April 2021, the Philippines committed to a 75% emissions reduction by 2030 below the Business-As-Usual Scenario (BAU). Of the 75% emissions reduction, 2.71% is unconditional, and 72.29% is conditional on international financial support. Under BAU, the Phillipines would emit a total of 3,340.3 Mt CO2eq from 2020 to 2030.	CO2:N/A GHG: N/A	Yes
Poland	First NDC (Updated)	Link	Poland, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2043 GHG: 2047	Yes
Portugal	First NDC (Updated)	Link	Portugal, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Russia	First NDC (Archived)	Link	In its first NDC, submitted in November 2020, Russia committed to reduce its emissions by 70% below 1990 levels by 2030.	CO2:2053 GHG: 2060	Yes
South Africa	First NDC (Updated)	Link	In its most recent NDC, submitted in September 2021, South Africa committed to peak its annual GHG emissions at 398-510 Mt CO2-eq between 2021-2025, and lower them to 350-420 Mt CO2eq from 2026-2030.	CO2:2050 GHG: 2054*	Yes
South Korea	First NDC (Updated)	Link	In its most recent NDC, submitted in December 2020, South Korea committed to reduce its emissions by 24.5% below 2017 levels by 2030, which will result in a cumulative emissions reduction of 709.1 Mt CO2eq from 2021-2030. South Korea also committed to increase its share of renewable energy up to 20% by 2030 and 30-35% by 2040.	CO2:2048 GHG: 2050	Yes

Spain	First NDC (Updated)	Link	Spain, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Sweden	First NDC (Updated)	Link	Sweden, as an EU member state, signed the EU's most recent NDC, in which the EU pledged to reduce emissions by 55% below 1990 levels by 2030; it is also adhering to the EU goal of net-zero by 2050.	CO2:2047 GHG: 2051	Yes
Thailand	First NDC (Updated)	Link	In its most recent NDC, submitted in October 2020, Thailand committed to an emissions reduction of 20% below the Business-As-Usual Scenario (BAU) by 2030, with the potential to reduce emissions by 25% with sufficient international financial support. Under BAU, Thailand would emit 555 Mt CO2eq in 2030.	CO2:N/A GHG: N/A	Yes
Turkey	First NDC (Archived)	Link	In its most recent NDC, submitted in October 2021, Turkey committed to reduce its emissions by 21% below the Business-As-Usual Scenario (BAU) by 2030. This would result in an emissions reduction of 246 Mt CO2eq from the BAU projection of 1,175 Mt CO2eq in 2030.	CO2:N/A GHG: N/A	Yes
United Arab Emirates	Second NDC (Archived)	Link	In its second NDC, submitted in December 2020, the United Arab Emirates (UAE) committed to reduce its emissions for the year 2030 by 23.5%, relative to the Business-As-Usual (BAU) scenario. The country would emit 310 Mt CO2eq in 2030 under BAU. The UAE also committed to increase the share of clean energy, including renewables and nuclear, to 50% of its installed power capacity mix by 2050.	CO2:N/A GHG: N/A	Yes
United Kingdom	First NDC (Updated)	Link	In its most recent NDC, submitted in December 2020, the United Kingdom committed to reduce its emissions by at least 68% below 1990 levels by 2030. The UK has also committed to a legally-binding target of reaching net-zero emissions by 2050.	CO2:2047 GHG: 2051	Yes
United States	First NDC (Updated)	Link	In its most recent NDC, submitted in April 2021 after rejoining the Paris Climate Accords, the United States committed to reduce emissions by 50-52% below 2005 levels by 2030. The United States has also set a goal of generating 100% of its electricity from carbon pollution-free sources by 2035. Although the targets in its NDC put the US on a trajectory to achieve carbon neutrality by 2050, the US does not firmly commit to this net-zero target.	CO2:2045 GHG: 2050	Yes

Vietnam	First NDC (Updated)	Link	In its most recent NDC, submitted in September 2020, Vietnam committed to reduce its emissions by 9% below the Business-As-Usual Scenario (BAU) by 2030, with a possibility of a 27% emissions reduction below BAU contingent on sufficient international aid. Vietnam would emit 927.9 Mt CO2eq in 2030 under BAU.	CO2:N/A GHG: N/A	Yes

*Net-zero years indicated with an asterisk were not reported by that particular country, but extrapolated based on existing trends within that region

7. 1.5°C scenario with differentiated regional net-zero targets

The 1.5°C- compatible emissions pathway scenario includes regional national net-zero targets on three different timelines, where GHG emissions decline immediately after 2020 and reach net zero by 2040, 2050, and 2075, respectively (Table 4). These timelines reflect existing literature on different equity principles and burden-sharing approaches of emissions reductions across regionswith GCAM regions grouped based on existing literature when each could be reasonably expected to reach net zero CO2 and GHG emissions. The rationale for these groupings was based on previous literature that explored the IPCC's equity approaches towards climate mitigation. [38, 39] of the key countries. Sperarate emission constraints are applied to individual GCAM region with one single economy-wide carbon price across different energy sectors, and 10% of that carbon price is applied to land-use change emissions.

Table 4: *1.5°C compatible scenario GCAM regions and net-zero emissions timelines*

GCAM-Region	Net-Zero Year
Africa_Eastern	2075
Africa_Southern	2075
Africa_Western	2075
Argentina	2050
Australia_NZ	2040
Brazil	2050
Canada	2040
China	2050
Colombia	2050

[38] Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), 38-43. https://doi.org/10.1038/nclimate3186

[39] Pan, X., den Elzen, M., Höhne, N., Teng, F., & Wang, L. (2017). Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science & Policy*, *74*, 49-56. https://doi.org/10.1016/j.envsci.2017.04.020

EU-12	2040
EU-15	2040
Europe_Non_EU	2050
European Free Trade Association	2040
India	2075
Indonesia	2075
Japan	2040
Mexico	2050
Middle East	2050
Pakistan	2075
Russia	2050
South Africa	2050
South America_Southern	2075
South Asia	2075
South Korea	2040
Southeast Asia	2075
USA	2040

Overall, unabated Global gas use decreases globally in the 1.5° C- compatible scenario when compared with the reference NDC baseline scenario as the share of primary energy shifts further from fossil fuel dependency. Certain regions may observe higher gas use in the near term due to more rapid coal phaseout under 1.5C, which does not continue in the long run. Starting in 2025, regional carbon prices are applied to reach net-zero GHG emissions by 2050 in the U.S., the E.U., Canada, Japan, and South Korea, and net-zero CO2 emissions by 2050 in China and the rest of the world. Carbon prices are applied to all sectors of the economy and emission reductions occur where it is most economical.

These pathways arewill be used to derive air pollutant emissions projections on the country and grid level out to 2050.

To reflect the views of the C40 cities network on the most plausible and sustainable approaches to emissions reductions, the 1.5-degree scenario in GCAM is one specific pathway towards global 1.5c that is featured with: will be calibrated to account for specific parameters:

- Different regional net-zero emission timelines based on burden-sharing approaches;

- Limited temperature overshooting;
- LowMinimise fossil fuels, including natural gas, share;
- HighMaximise renewables share (solar and wind);
- and emphasize Rapid electrification; as a solution
- Low Minimise the dependence on CCS; as much as possible
- Low dependnce on Minimise biomass and nuclear sources;
- Reasonably increasing the level of energy efficiency
- Growing total energy production in emerging countries regions

8. Air quality modeling

The project covers a range of different sectors, geographies and pollutants. The majority of the health impact from fossil gas operations derives from NOx emissions, which influence ground-level NO2, ozone and PM2.5 concentrations through photochemical reactions and pollutant dispersion. To model these impacts across the C40 cities, we will use a global chemistry-transport model.

Chemistry-transport models that calculate solutions of 3-D continuity equations for the concentrations of chemical species (including the effects of emissions, transport, chemistry, and deposition), are effective in simulating the combined influences of physical and chemical processes affecting the spatio-temporal distribution of key chemical species in Earth's atmosphere.

CTM are driven by pre-calculated meteorological fields that may come from a free-running general circulation model (GCM) but are usually from reanalysis fields that assimilate atmospheric observations to provide a realistic description of atmospheric emissions, wet deposition, and transport.

In this work, we make use of the GEOS-Chem CTM (https://geos-chem.seas.harvard.edu/), originally described by Bey et al. (2001), which is driven by MERRA2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) meteorological input from the Goddard Earth Observation System (GEOS) of the NASA Global Modeling and Assimilation Office (GMAO), provided with a resolution of 0.5°×0.625°. In particular, we selected the high-performance version of GEOS-Chem (GCHP 13.4.0, https://gchp.readthedocs.io/en/13.4.0/) engineered to take advantage of massively parallel architectures which allow GEOS-Chem users to run atmospheric chemistry simulations at high grid resolutions and global scale (Easthamet al., 2018).

GCHP uses a cubed-sphere geometry which splits the surface of a sphere into six equal-sized faces. The grid resolution used in this project (referred to as C180) subdivides each face into 180 cells leading to a grid cell spacing of about 50 km

(approximately 0.5°×0.625°) all over the world. Vertically, the atmosphere is discretized into 72 hybrid-sigma layers, ranging from the surface to 1 Pa at the upper edge, approximately 80 km above sea level. The temporal time step at C180 is 5 minutes. GCHP outputs hourly averages of atmospheric concentrations of different air pollutants for each grid cell and every altitude level.
We use CREA optimised values of emissions based on the CEDS (Community Emissions Data System, McDuffie et al., 2020) global inventory for the baseline year 2019, available at https://data.pnnl.gov/dataset/CEDS-4-21-21. ().

To keep the computational load manageable, we model only 4 months of 2019, January, April, July and October, in order to capture daily, monthly and seasonal variability of atmospheric composition and transport. GCHP is run in parallel over 480 cores, using the distributed memory architecture of Puthi supercomputer, at CSC - IT CENTER FOR SCIENCE (https://research.csc.fi). Each simulation period is preceded by a 7-day spin-up run. We output hourly concentrations of both aerosols (PM2.5, PM10) and five different gaseous species (CO2, NO, NO2, SO2, O3) at ground level. The operative definition of PM2.5 and PM10 in Geos-Chem can be found at http://wiki.seas.harvard.edu/geos-chem/index.php/Particulate_matter_in_GEOS-Chem.

Due to the complex nature and global scale of the simulations, the number of scenarios we can model within a reasonable timeframe and cost is limited. We perform a set of nine model runs that can address all the research questions outlined in the Request for Proposals:

- Baseline simulation for current air quality, using the default CEDS emission inventory.
- Zero-out simulation to model the contribution of fossil gas emissions to current air pollution levels.
- Future baseline simulations based on scaling energy sector emissions according to the reference scenario, for 2035 and 2050.
- Future zero-out simulations to model the contribution of fossil gas emissions in 2035 and 2050 under the 1.5°C scenario and the reference scenario.
- A future "gas expansion" simulation with emissions associated with new, planned developments identified above added to the 2035 baseline.

Based on the results from these simulations, we extract the estimated contribution of fossil gas emissions to air pollutant concentrations in the C40 cities and in the countries with C40 cities, as the difference between the results for the reference scenario and the zero-out or expansion scenarios.

8.1 Air pollutant emissions projections for GCAM scenarios

To project emission control improvements, i.e. changes in emissions factors, over time, we fit linear models to national-level CEDS data from 2000 to 2019 for each fuel and sector, with time and GDP per capita as the independent variables. As expected, this approach projects fast improvements in power sector emissions controls, slower but still significant improvements in the transport and industrial sectors, while the residential sector sees no improvement in emissions factors for direct fuel use. There are some cases where emissions increase over time and with GDP, such as ammonia emissions from vehicles as catalytic converters are required.

We use the energy input data from GCAM scenarios on the regional level to scale country- and city-level energy use, together with the projected emissions factors, which are the same in all scenarios. The exception are gas-fired power plants in the expansion scenario, as the scenario looks specifically at new facilities and therefore the emissions are constrained by the emissions standards for new gas-fired power plants.

To take into account the effect of the deployment of CCUS on future emissions, we assume that SO2 emissions are reduced by 85% at facilities using CCUS, based on the European Environment Agency's technical report.[40] We also assume additional ammonia emissions of 0.24 kg per tonne of CO2 captured, following the study by Heo et al. (2015).[41] Emissions of other pollutants per unit of fuel input are assumed to be unaffected; the energy penalty associated with carbon capture will tend to increase emissions per unit of power generated, but this is taken into account in the GCAM data on fuel consumption.

[40] European Environment Agency (EEA). EEA Technical Report 2011. Air pollution impacts from carbon capture and storage (CCS). NO 14/2011.
https://www.eea.europa.eu/publications/carbon-capture-and-storage/download

[41] Heo, J., McCoy, S.T., & Adams, P.J. 2015. Implications of Ammonia Emissions from Post-Combustion Carbon Capture for Airborne Particulate Matter. *Environ. Sci. Technol.* 49: 5142-5150. DOI: 10.1021/acs.est.5b00550

Figure 10 | Log-linear regressions fitted to the data on historical national average emissions factors and GDP per capita for different fuels and for selected sectors. These relationships were used to project the improvements in emission control performance into the future. Note log scale on y-axis.

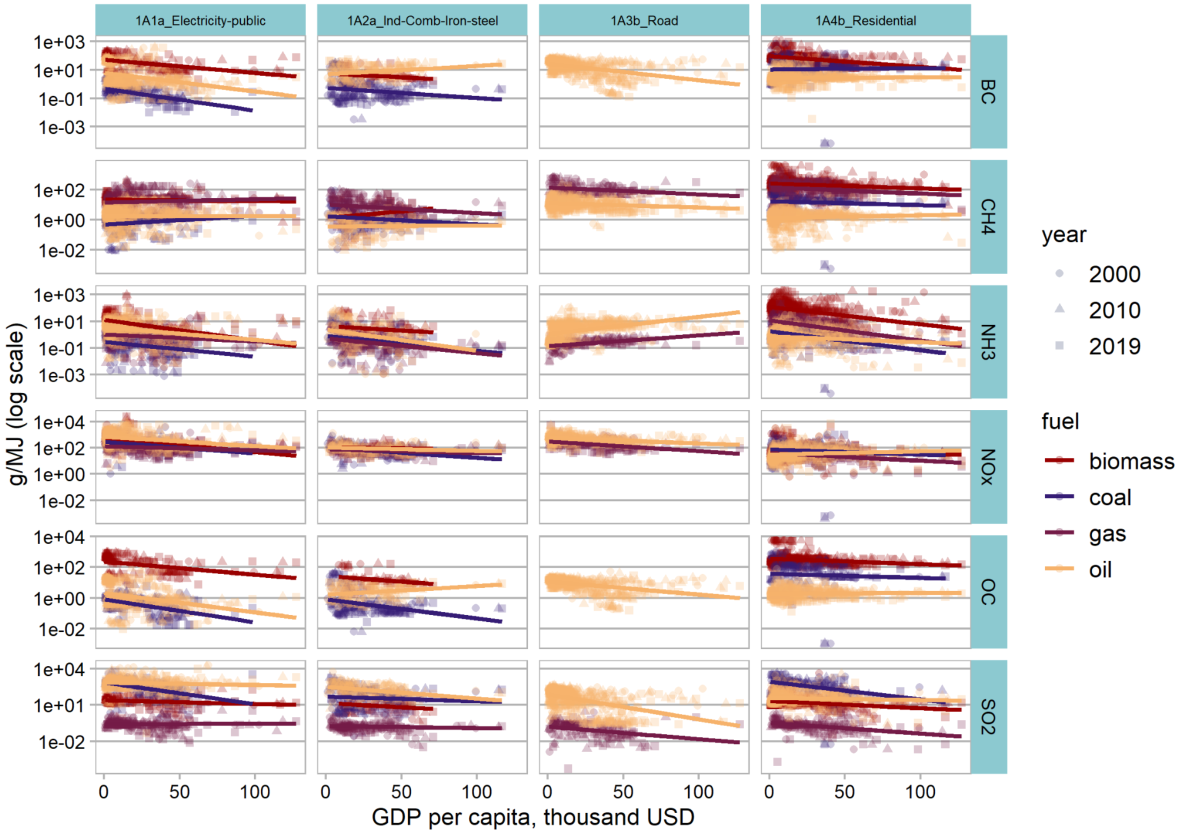
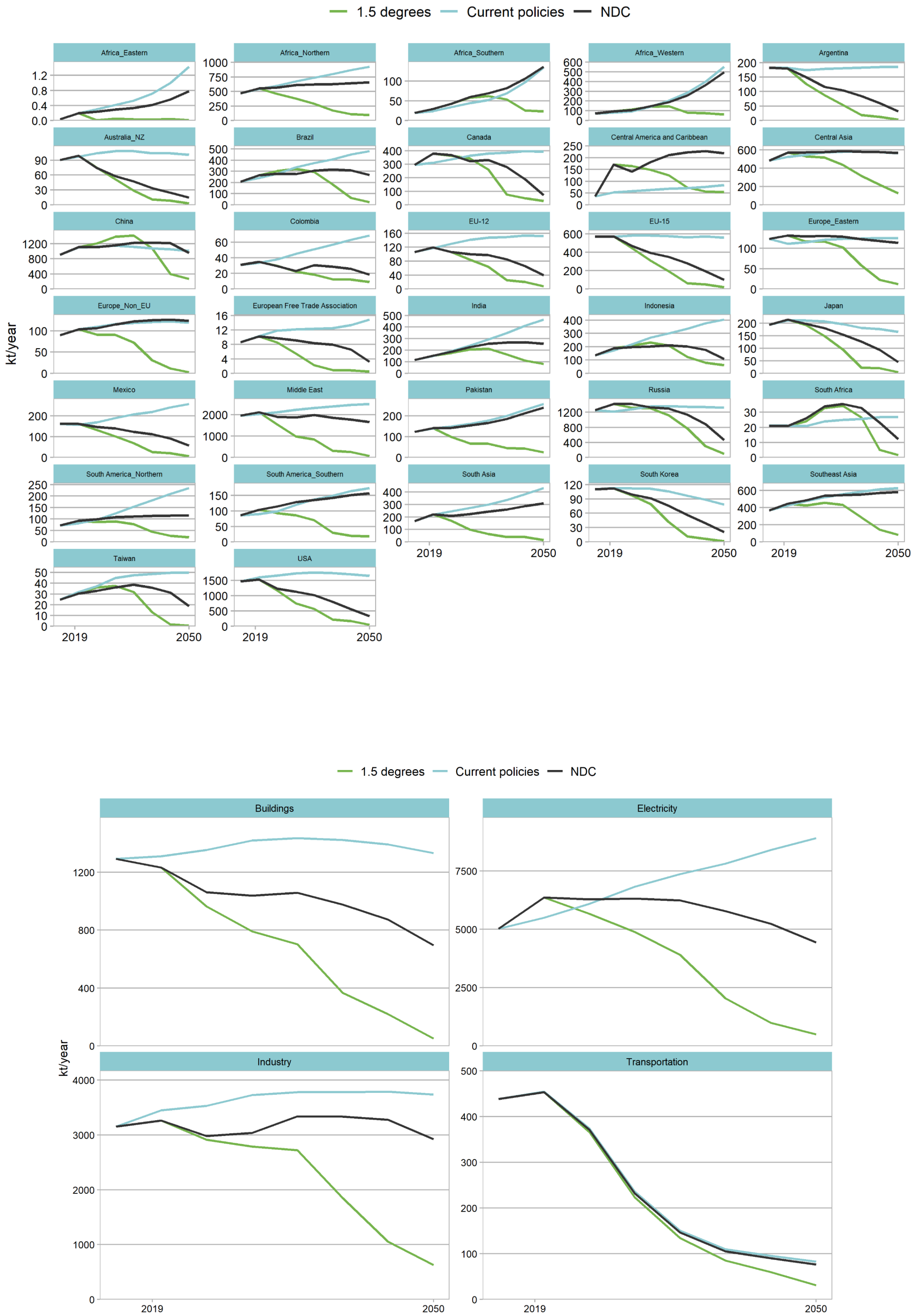


Figure 11 | Projected NOx emissions by GCAM region and by sector in the different scenario



8.2 References

Australian Government - Department of Climate Change, Energy, the Environment and Water. National Pollutant Inventory. http://www.npi.gov.au/

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., Li, Q., Liu, H. Y., Mickley, L. J., and Schultz, M. G.: Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation, J. Geophys. Res.-Atmos., 106, 23073–23095, https://doi.org/10.1029/2001JD000807, 2001.

Breysse, P. N., Diette, G. B., Matsui, E. C., Butz, A. M., Hansel, N. N., & McCormack, M. C. (2010). Indoor Air Pollution and Asthma in Children. *Proceedings of the American Thoracic Society*, 7(2): 102–106. https://doi.org/10.1513/pats.200908-083RM

British Petroleum (BP). Statistical Review of World Energy 2021. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

British Petroleum (BP). Statistical Review of World Energy 2022. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Buonocore, J. J., Salimifard, P., Michanowicz, D. R., & Allen, J.G. *Environmental Research Letters*, May 5, 2021. DOI: 10.1088/1748-9326/abe74c

Dėdelė, A., & Miškinytė, A. (2016). Seasonal variation of indoor and outdoor air quality of nitrogen dioxide in homes with gas and electric stoves. *Environmental Science and Pollution Research*, *23*(17): 17784–17792. https://doi.org/10.1007/s11356-016-6978-5

Eastham, S. D., Long, M. S., Keller, C. A., Lundgren, E., Yantosca, R. M., Zhuang, J., Li, C., Lee, C. J., Yannetti, M., Auer, B. M., Clune, T. L., Kouatchou, J., Putman, W. M., Thompson, M. A., Trayanov, A. L., Molod, A. M., Martin, R. V., and Jacob, D. J.: GEOS-Chem High Performance (GCHP v11-02c): a next-generation implementation of the GEOS-Chem chemical transport model for massively parallel applications, Geosci. Model Dev., 11, 2941–2953, https://doi.org/10.5194/gmd-11-
2941-2018, 2018.

EMEP Centre on Emission Inventories and Projections. Officially reported emission data. https://www.ceip.at/webdab-emission-database/reported-emissiondata

European Commission. EDGAR - Emissions Database for Global Atmospheric Research. Global Greenhouse Gas Emissions. https://edgar.jrc.ec.europa.eu/dataset_ghg60

European Environment Agency (EEA). EEA Technical Report 2011. Air pollution impacts from carbon capture and storage (CCS). NO 14/2011. https://www.eea.europa.eu/publications/carbon-capture-and-storage/download

European Environment Agency (EEA). Industrial Reporting database. https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial-4/eu-registry-e-prtr-lcp

Fard, R. F., Naddafi, K., Yunesian, M., Nodehi, R. N., Dehghani, M. H. & Hassanvand, M.S. The assessment of health impacts and external costs of natural gas-fired power plant of Qom. *Environmental Science and Pollution Research*, August 2016; 23: 20922-20936. https://doi.org/10.1007/s11356-016-7258-0

GCAM v6 Documentation: Global Change Analysis Model (GCAM). https://jgcri.github.io/gcam-doc/

Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, Gas Pipelines. January 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

Global Energy Monitor (GEM). Global Gas Infrastructure Tracker, LNG Terminals. January 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

Global Energy Monitor (GEM). Global Gas Plant Tracker. January, 2022. https://globalenergymonitor.org/projects/global-gas-plant-tracker/

Global Energy Monitor (GEM). Global Oil and Gas Extraction Tracker. January, 2022. https://globalenergymonitor.org/projects/global-oil-gas-extraction-tracker/

Government of Canada. Air Pollutant and Black Carbon Emissions Inventories online search. March, 2022. https://pollution-waste.canada.ca/air-emission-inventory/

Heo, J., McCoy, S.T., & Adams, P.J. 2015. Implications of Ammonia Emissions from Post-Combustion Carbon Capture for Airborne Particulate Matter. *Environ. Sci. Technol.* 49: 5142-5150. DOI: 10.1021/acs.est.5b00550

Hölscher, B., Heinrich, J., Jacob, B., Ritz, B., & Wichmann, H. E. (2000). Gas cooking, respiratory health and white blood cell counts in children. *International Journal of Hygiene and Environmental Health*, *203*(1): 29–37. https://doi.org/10.1078/S1438-4639(04)70005-X

International Energy Agency (IEA). Global Methane Tracker 2022. February, 2022. https://www.iea.org/reports/global-methane-tracker-2022

International Energy Agency (IEA). World Energy Balances: Overview. August, 2021. https://www.iea.org/reports/world-energy-balances-overview

International Energy Agency (IEA). World Energy Balances. May, 2022. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

Joint Global Change Research Institute. A Community Emissions Data System (CEDS) for Historical Emissions. http://www.globalchange.umd.edu/ceds/

Lebel, E.D., Finnegan, C. J., Ouyang, Z. & Jackson, R.B. (2022). Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes. *Environ. Sci. Technol.*, *56*(4): 2529-2539. https://doi.org/10.1021/acs.est.1c04707

McDuffie, E., Smith, S., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E., Zheng, B., Crippa, M., Brauer, M., and Martin, R.: CEDS_GBD-MAPS: Global Anthropogenic Emission Inventory of NOx, SO2, CO, NH3, NMVOCs, BC, and OC from 1970–2017 (2020_v1.0), Zenodo [data set], https://doi.org/10.5281/zenodo.3754964, 2020.

Nicole, W. (2014). Cooking Up Indoor Air Pollution: Emissions from Natural Gas Stoves. *Environmental Health Perspectives*, *122*(1), A27–A27. https://doi.org/10.1289/ehp.122-A27

Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A. A., Hultman, N., McFarland, J. R., Binsted, M., Cui, R., Fyson, C., Geiges, A., Gonzales-Zuñiga, S., Gidden, M. J., Höhne, N., Jeffery, L., Kuramochi, T., Lewis, J., Meinshausen, M., Nicholls, Z., … McJeon, H. (2021). Can updated climate pledges limit warming well below 2°C? *Science*, *374*(6568), 693–695. https://doi.org/10.1126/science.abl8976

Seals, B. & Krasner, A. (2020). Gas Stoves: Health and Air Quality Impacts and Solutions. Rocky Mountain Institute,

Physicians for Social Responsibility, Mothers Out Front, and Sierra Club, 2020.
https://rmi.org/insight/gasstoves-
pollution-health

Steinzor, N., Subra, W. & Sumi, L. Investigating Links between Shale Gas Development and Health Impacts through a Community Survey Project in Pennsylvania. *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy*. 2013;23(1):55-83. doi:10.2190/NS.23.1.e

United Nations - Climate Change. Argentina Biennial update report.
https://unfccc.int/documents?search2=&search3=argentina&f%5B0%5D=country%3A1227

United Nations Climate Change. Greenhouse Gas Inventory Data - Flexible Queries Annex I Parties. https://di.unfccc.int/flex_annex1

United States Energy Information Administration (EIA). About SEDS.
https://www.eia.gov/state/seds/

United States Environmental Protection Agency (EPA). Inventory of U.S. Greenhouse Gas Emissions and Sinks. April, 2022.
https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

United States Environmental Protection Agency (EPA). 2017 National Emissions Inventory (NEI) Data.
https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data

U.S. Energy Information Administration (EIA). Natural Gas Consumption by End Use.
https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

9. The health impact of fossil gas

The survey will cover existing work on the health impacts of the main air pollutants associated with the fossil gas industry, the role of the industry in air pollutant emissions, ambient air pollution as well as health impacts across relevant geographies. We will cover the health impacts of indoor air pollution from fossil gas, although there are few meaningful quantitative results in the literature.

Growing evidence indicates that gas is far from a clean form of fuel. Pollution occurs during most stages of gas production, such as gas extraction and processing, and from pipeline leakage. Several studies have emerged on the health impacts of gas in the United States in the past year. A study by Buonocore et al. (2021)[42] examined mortality caused by outdoor PM2.5 of stationary sources including coal plants and gas plants. Their findings showed that in 2017 gas emissions in the US caused more deaths than coal in 19 states. Buonocore et al. (2021) also found that the share of gas-related premature deaths increased from 2008 levels of around 11-14% to 21% in 2017.

A health survey with self-reporting data, also conducted in the US[43], investigated the health symptoms of those living near gas development areas in Pennsylvania, and looked at whether symptoms worsened after shale gas development commenced. The closer the respondents lived to gas facilities, the percentage of those experiencing health problems was higher including symptoms such as throat irritation, sinus problems and severe headaches.

Fard et al. (2016)[44] studied the health and economic impacts of the Qom gas-fired power plant in Iran, and their results showed that the prevalent health impact was restricted activity days (RAD), and that the main costs incurred due to long-term mortality, restricted activity days, and chronic bronchitis.

---

[42] Buonocore, J. J., Salimifard, P., Michanowicz, D. R., & Allen, J.G. *Environmental Research Letters*, May 5, 2021. DOI: 10.1088/1748-9326/abe74c

[43] Steinzor, N., Subra, W. & Sumi, L. Investigating Links between Shale Gas Development and Health Impacts through a Community Survey Project in Pennsylvania. *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy*. 2013;23(1):55-83. doi:10.2190/NS.23.1.e

[44] Fard, R. F., Naddafi, K., Yunesian, M., Nodehi, R. N., Dehghani, M. H. & Hassanvand, M.S. The assessment of health impacts and external costs of natural gas-fired power plant of Qom. *Environmental Science and Pollution Research*, August 2016; 23: 20922-20936. https://doi.org/10.1007/s11356-016-7258-0

Heating and cooking contribute to indoor pollution. Stanford scientists (Lebel et al. 2022)[45] studied the negative impacts of using natural gas stoves indoors. Natural gas stoves emit methane and nitrogen oxides, which can increase respiratory diseases. They found that Californian residents with poor ventilation might exceed EPA national guidelines for 1-hour NO2 exposure within a few minutes of using a gas stove. Another report by Seals and Krasner (2020)[46] points to similar results in the USA and notes that children are especially at risk of developing respiratory illnesses (e.g. childhood asthma, lung infections) due to gas stove use and indoor pollution caused by these stoves. They examined the main pollutants — including $PM_{2.5}$, NO_x, NO_2, carbon monoxide and formaldehyde — associated with gas stoves and the effects on health caused by these pollutants with high levels of exposure.

Many other studies support these findings on indoor air pollution and gas stove use, including Nicole's (2014)[47] study on the emissions of gas stoves and therefore indoor air quality reaching harmful levels. Hölscher et al. (2000)[48] found higher white blood cell counts and respiratory symptoms and infections in German children living in households with gas appliances. Dėdelė and Miškinytė (2016)[49] compared indoor and outdoor NO2 levels and also examined indoor NO_2 levels with households using gas stoves or electric stoves. Indoor NO2 concentrations were higher than outdoor levels when using a gas stove during all seasons, and were also higher compared to households with electric stoves. A review by Breysse et al. (2010)[50] found that indoor particulate matter and NO2 levels are linked to higher cases of asthma in children.

---

[45] Lebel, E.D., Finnegan, C. J., Ouyang, Z. & Jackson, R.B. (2022). Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes. *Environ. Sci. Technol., 56*(4): 2529-2539. https://doi.org/10.1021/acs.est.1c04707

[46] Seals, B. & Krasner, A. (2020). Gas Stoves: Health and Air Quality Impacts and Solutions. Rocky Mountain Institute,
Physicians for Social Responsibility, Mothers Out Front, and Sierra Club, 2020.
https://rmi.org/insight/gasstoves-pollution-health

[47] Nicole, W. (2014). Cooking Up Indoor Air Pollution: Emissions from Natural Gas Stoves. *Environmental Health Perspectives*, *122*(1), A27–A27. https://doi.org/10.1289/ehp.122-A27

[48] Hölscher, B., Heinrich, J., Jacob, B., Ritz, B., & Wichmann, H. E. (2000). Gas cooking, respiratory health and white blood cell counts in children. *International Journal of Hygiene and Environmental Health*, *203*(1): 29–37. https://doi.org/10.1078/S1438-4639(04)70005-X

[49] Dėdelė, A., & Miškinytė, A. (2016). Seasonal variation of indoor and outdoor air quality of nitrogen dioxide in homes with gas and electric stoves. *Environmental Science and Pollution Research*, *23*(17): 17784–17792. https://doi.org/10.1007/s11356-016-6978-5

[50] Breysse, P. N., Diette, G. B., Matsui, E. C., Butz, A. M., Hansel, N. N., & McCormack, M. C. (2010). Indoor Air Pollution and Asthma in Children. *Proceedings of the American Thoracic Society*, *7*(2): 102–106. https://doi.org/10.1513/pats.200908-083RM

10. Assessment of the health impacts and health costs

The assessment of current and future health impacts, as well as the associated economic costs, will follow the methodology of the research provided by CREA to C40 under the project "Coal-free cities: the health and economic case for a clean energy revolution."

11. Methane uplifting

Natural gas consumption in a country is associated with methane fugitive emissions along its supply chain, from the gas fields to the consumption point. In this study, we accounted for:

- domestic fugitive emissions along transmission lines;
- domestic fugitive emissions associated with local gas production; and
- imported fugitive emissions associated with the gas production in other countries.

11.1 Methodology

The fugitive emissions themselves are taken directly from CEDS corresponding sectors, namely *Fugitive-NG-distr* and *Fugitive-NG-prod*. For each fossil gas production country, we derive a methane emission factor using fossil gas production data from BP Statistical Review of World Energy.[51]

The next step consists in associating country A fossil gas consumption to country B fossil gas production. To do so, we leverage gas trade movement data for LNG and pipeline gas, also from BP Statistical Review of World Energy, as well as gas consumption data from CEDS.

Imported fugitive emission is then computed as the product of the producing country's emission factor with the imported volumes from that country.

When trade movement data combines several countries in a region, we use a weighted average using either consumption or production as weights. Only countries which are net importers are included in the breakdown. Net importers are determined in two ways with respective degrees of importance. First, a country is a net importer if the consumption number is higher than the production. Then, if the country's status as a net importer still could not be assessed, its presence as an exporter in the trade movement data becomes the deciding factor.

Double counting is avoided by deriving averaged emission factors first, and then multiplying by the quantity of gas consumed.

51 https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/oil-gas-and-coal-trade.html (accessed 8.22.22)

12. Phase 2 and 3

Buro Happold and University College London (UCL) Energy Institute were commissioned by C40 to lead the delivery of Phase Two and Three of C40 Cities 'Health, Economic and Environmental Impacts of Fossil Gas' research. This document provides an overview of the methodology applied to successfully deliver the study.

12.1 Supporting documentation

This study compliments the Phase One work undertaken by the University of Maryland (UoM) and Centre for Research on Energy and Clean Air (CREA). Analysis undertaken in Phase One has been used in Phase Two and Three, in addition to tools also produced by C40. The methodologies for these resources are set out elsewhere. Key supporting documentation for which methodologies are set out elsewhere by others include:

- Data outputs (primarily from the Global Change Analysis Model (GCAM)) produced by CREA and UoM as part of the Health, Economic and Environmental Impacts of Fossil Gas, Phase One.
- Pathways Models, produced by C40 Cities.
- Pathways Cost Calculator Tool (PACC), produced by C40 Cities.

12.2 Critical scope items to note

Based on the Request for Proposals (RfP) prepared by C40, the study was limited to:

- The following sectors: power, buildings, and industry.
- The following energy transition: fossil gas to renewable electricity, focussing on wind or solar (utility scale and rooftop).
- The following three use cases: rapid phase out, swift transition, and leapfrog (no definition for these was provided in the RfP, these are discussed further below).
- The number of interviews was limited to five no. for Phase Two and three no. per city for Phase Three (Buro Happold actually facilitated an additional two interviews in Phase Three based on agreement with C40).

13. Research Methodology - Phase Two

Phase Two of the commission sets out global and regional narratives for a transition from gas to renewable energy. These narratives are underpinned by robust evidence gathered through a mixed methods approach. Buro Happold and UCL produced two deliverables: a technical report (containing the detailed evidence base and regional narratives) and a headlines report of global narratives.

13.1 Approach to scoping the literature review

At the beginning of the project Buro Happold and UCL developed a long list of possible research questions based on the content of the RfP. This long-list was reviewed and refined through meetings with C40, ensuring that the questions developed were aligned with the needs of the various audiences and aims of the research. The scoped questions could broadly be categorised as either: economic and financial, geopolitical, social and demographic, or technical.

13.2 Undertaking the literature review

Buro Happold performed a literature review to respond to these questions. The literature review generally focused on collating secondary evidence from academic, institutional and expert sources. Some primary evidence was drawn in from Phase One, particularly to support analysis of existing fossil gas and renewable energy production across regions. Buro Happold also produced a 'call for evidence' that set out the scope of the project and questions being explored. This was circulated within Buro Happold and C40's networks to gather evidence from experts in the field.

The evidence was collated in an excel document (shared with C40) that identified the key headlines and characteristics of each source (type, scope, limitations etc).

13.3 Refining the narratives

Through discussion, Buro Happold and C40 refined the questions that were to be explored in the global and regional narratives. This review was based on the evidence found in the literature review, which revealed where evidence was strongest and which questions were most pertinent to the study's goals. The final set of questions are summarised below:

- Gas and renewables today;

- Switching from gas to renewables;
- Gas as a transition fuel;
- The impacts of switching from gas to renewables;
- Regulating the switch from gas to renewables;
- Financing the switch from gas to renewables;
- Key geo-political challenges; and
- A just transition.

13.4 Interviews

The literature review was accompanied by a set of interviews to gather the insights of global and regional experts on the topics of fossil gas, renewables and energy transitions. In addition, the interviews addressed gaps in the evidence and the projects team's knowledge.

To select interviewees, Buro Happold reflected on the content of the literature reviews, literature review questions and selected regions (discussed below) to produce a long list of possible interviewees. In line with the scope of works, only five interviews were facilitated. The project team also sought to gather a diverse set global and sector perspectives. Final interviewees were:

- Amos Burudi Wemanya, Senior Renewable Energy Advisor, Power Shift Africa;
- Cristian Carraretto, Head of Sustainable Business and Infrastructure, Energy Transition, European Bank for Reconstruction and Development;
- Gyorgy Dallos, Senior Campaign Strategist, Climate & Energy, Greenpeace International;
- Ingrid Behrsin, Interim Programme Director for Renewable Energy Programmes, Global Energy Monitor;
- Jenny Martos, Research Analyst, Global Energy Monitor;
- Julie Joly, Director of O&G programmes, Global Energy Monitor;
- Lucile Dufour, International Policy Advisor, International Institute for Sustainable Development; and
- Mikhaila Crosby, Responsible Investment Associate, Real Assets, Aviva Investors.

All calls were recorded for the purposes of note taking but recordings were not / will not be shared wider. Buro Happold sent summary notes to all attendees and invited them to check these, to ensure the project team understood the interviewees' responses correctly. All interviewee responses were anonymised in the final deliverable and Buro Happold sought to provide supporting evidence for all statements, where possible.

13.5 Approach to selecting regions

A global narrative was produced for each of the questions. Regional narratives were produced for the following questions, these questions were scoped and agreed with C40:

- Economic dependence on gas and renewables;
- The cost of gas and renewables;
- Gas as a transition fuel;
- Impacts on gas producing economies;
- Improving the regulatory landscape;
- Scaling green finance; and
- Employment prospects.

C40 determined the regions for which narratives where to be produced, based on their understanding of context and priority. Where produced, regional narratives covered: Europe, Latin America, South Africa and the United States of America.

13.6 Production of global and regional narratives

Buro Happold led the production of two deliverables:

- A technical report: this is a long-format report documenting the outcomes across all questions (set out above) in detail, including global and (where agreed) regional narratives. This report provided a summary of the evidence rather than making recommendations.
- A headlines report: this is a digestible report that can be used by readers to understand the overarching findings from Phase Two. This output also contained a summary of recommendations that cities might take to enable and accelerate a transition from gas to renewables, with examples.

Buro Happold led the production of the report, with UCL and C40 providing technical reviews. All outputs were produced on the understanding that they will not be published. Rather C40 will be using the outputs to produce a report for the World Mayors' Summit and other communications over the following nine months or so.

14. Research Methodology - Phase three

Phase Three of the commission provides a deep dive into three city use cases: Johannesburg (leapfrog), Bogota (swift transition) and Montreal (rapid phase out). This set out what such an energy transition may mean for each city, and how the municipality may support and accelerate this. A mixed methods approach of modelling; literature review and interviews was used. Buro Happold produced a combined technical report containing the outcomes of the work for all three cities. In addition, a revised Pathway and PACC model was developed for each city.

14.1 Use case definition and city selection

Within the RfP C40 set out the premise of the three use case contexts, but did not define these or the cities that were to be used for each. Buro Happold and C40 collaborated to develop a common understanding of the use cases and C40 led the process of onboarding cities that aligned with these.

Use case: Leap frog
Context: A city in which there is extremely limited or no fossil gas network or usage across the sectors considered in the study.
City selected: Johannesburg, South Africa

Use case: Rapid phase out
Context: A city that has well established fossil gas network and gas usage but also has (relative to others) high institutional, financial or other such powers or support to accelerate the transition.
City selected: Montreal, Canada

Use case: Swift transition
Context: A city that has well established fossil gas network and gas usage but also has (relative to others) low institutional, financial or other such powers or support to accelerate the transition.
City selected: Bogota, Colombia

The original intention was to have deeper engagement with cities by asking them to 'sign up as a participant' to the programme. Difficulties onboarding and the rapid nature of the study meant that the study was run without formal participation from cities. However, cities did contribute through interviews and reviewed the final reports.

14.2 Approach to the literature review

In addition to the Phase 2 outputs, Buro Happold undertook a specific Phase Three literature review. The literature review focused on collating secondary evidence to build an understanding of the city context through the following questions:

- What is the city context (including an overview of the city itself, the energy system structure and the municipalities powers)?
- How is fossil gas used today (across buildings, power and industry)?
- What is the planned future of fossil gas and renewables (including national, regional and city-wide plans for the development of fossil gas and renewables)?
- How might the city make the transition a reality (including summary of key challenges and opportunities, which were used to determine the model inputs (discussed later) and inform the development of recommendations)?

14.3 Interviews

Interviews were used to address gaps in the literature review and to develop a deeper understanding of the city. The set-up, facilitation and dissemination of interviews followed the same approach as set out in Phase Two. Buro Happold again sought to engage with a cross section of the cities energy system stakeholders. A full list of interviewees is set out below.

Bogota, Colombia:

- Angelica M. Ospina Alvarado, Technical Director, Colombian Council for Sustainable Construction
- Carolina Urrutia, Secretary of the Environment, City of Bogota
- Giovanni Andres Pabon Restrepo, Energy Policy Lead, Transforma
- Juan Ricardo Ortega Lopez, Chief Executive Officer, Grupo Energía Bogotá
- Lucas Builes Giraldo, PhD, University College London
- Melissa Ferro, Technical Specialist, Colombian Council for Sustainable Construction

Johannesburg, South Africa:

- Anders Cajus Pedersen, Chief Power Systems Officer, African Development Bank Group
- Bhekumuzi Dean Bhebhe, Campaigner, Power Shift Africa
- Jo Anderson, Research and Knowledge Management Coordinator, Green Building Council South Africa

- Werner van Zyl, Associate Director for Economic Development, Buro Happold

Montreal, Canada:

- Billal Tabaichount, Ecological Economics, Vivre en Ville
- Frederic Krikorian, Vice President Sustainable Development, Public and Governmental Affairs, Energir
- Jean-Philippe Hardy, Managing Consultant, Dunsky Energy+Climate
- Jonathan Theoret, Head of Transport, Energy and Building Division, Office of Ecological Transition and Resilience, City of Montreal
- Karina Buist-Tactuk, Municipal and Governmental Affairs, Energir
- Samuel Page-Plouffe, Director Public and Government Affairs, Vivre en Ville
- Sebastian Wagner, Engineer Team Leader, Office of Ecological Transition and Resilience, City of Montreal
- Stephanie Lopez, Advisor Green Buildings and Infrastructure, Vivre en Ville
- Valerie Anne Brouillard, Environment and Climate Change Engineer, City of Montreal

14.4 Approach to modelling

Buro Happold and C40, in collaboration with CREA and UoM, workshopped a number of possible approaches to modelling. Initially these options sought to draw on the outputs of GCAM so that the outcomes from Phase Three could be aligned Phase One. However, the complexity of GCAM and programme of Phase One resulted in the decision to adopt a different approach.

As part of Deadline 2020, C40 developed a suite of tools to help cities prepare baseline carbon emission inventories and trajectories and to aid of the design of greenhouse gas emission reduction programmes. This tool is known as Pathways. Pathways allows cities to produce scenarios; generally, cities produced a planned (i.e., emission trajectories based on planned actions) and ambitious (i.e., what cities believe is ambitious but politically, financial and otherwise feasible) scenarios. Within Pathways, forecast emissions from the modelled scenarios are compared to a Paris, 1.5°C-aligned set of targets that factor in a fair share distribution.

Rather than develop a new tool, the project team utilised the Pathways tool. For each city, Buro Happold developed a new scenario – 'gas phase out' – and compared the greenhouse gas emission reductions achieved within this scenario to those in the ambitious scenario produced by the city. The literature review and interviews provided the basis for making the assumptions for the inputs to Pathways under the gas phase out scenario. The assumptions were guided by the context of the city (i.e., unique opportunities, challenges and powers) but also by the use cases and a vision of what ambitious and urgent climate action may consist of within these. Buro Happold developed a proposal for the gas phase out inputs, these were reviewed and refined with C40 to finalise them.

In addition to calculating the forecast greenhouse gas emission reductions Buro Happold undertook economic modelling utilising the PACC toolkit developed by C40. The scope of PACC is limited to interventions in the power and buildings sector, therefore model outputs exclude industrial actions included within Pathways.

It must be noted that Buro Happold were responsible only for updating the inputs (e.g., percentage replacement of low efficiency natural gas boilers over time) to both Pathways and PACC models for each city. No changes were made to other parts of the Pathways or PACC models (i.e., multipliers, proxies, calculations or otherwise).

14.5 Developing recommendations

Buro Happold lead the development of the recommendations. These were developed by considering the context of the city (i.e. unique opportunities, challenges and powers), identified through the interviews and literature review. Utilising the outcomes of Phase Two, Buro Happold developed a framework that was used to systematically consider the actions the municipality could take – categorised as enabling, institutional, physical and financial actions.

14.6 Production of city narratives

Buro Happold led the production of the deliverables:

- A technical combined report: this includes a write up of the findings, modelling outcomes and recommendations for each city.
- Pathways model: for each city, Buro Happold shared with C40 the baseline model and an updated model with the Gas Phase Out scenario included.
- PACC model: for each city, Buro Happold shared with C40 an updated PACC model aligned to the revised Pathways inputs.

Buro Happold led the production of the report with UCL and C40 providing technical reviews. Montreal reviewed and provided comments on the report that were incorporated prior to the report being issued. Bogota are expected to provide a review and comments also. Johannesburg have not reviewed the final report prior to it being issued.