Synthesis of Arctic Council Member and Observer Country Emissions of Black Carbon and Methane

ABC-iCAP Project Technical Report 2

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Citation

Matthews, B., K. Seuss, B. Ullrich, S. Schindlbacher, 2023. Synthesis of Arctic Council Member and Observer Country Emissions of Black Carbon and Methane. Arctic Black Carbon impacting on Climate and Air Pollution (ABC-iCAP) Project Technical Report 2. December 2023 iv+47pp.

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Acknowledgment

The authors would like to thank all other colleagues who contributed to the production and review of this report.

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Layout and technical production

Burnthebook, United Kingdom (www.burnthebook.co.uk)

This project is funded by the European Union

The report was prepared as one of the deliverables under the project *Arctic Black Carbon impacting on Climate and Air Pollution (ABC-iCAP)*, funded by the European Union.

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Contents

Executive Summary

Arctic near-surface air temperatures are increasing at a rate three times faster than in the rest of the world. While reductions in the emission of carbon dioxide are critical to mitigating global and Arctic climate change, the required reductions of carbon dioxide may not be achieved in time to delay a rapid thawing of the Arctic. Targeting shorter-lived climate forcing agents, such as black carbon (BC) and methane (CH_4), is therefore important to mitigate climate change in the Arctic. Recognizing this, the Ministers of the Arctic Council adopted the framework *Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action*. Under this framework the Arctic States committed to take "enhanced, ambitious, national and collective action to accelerate the decline in our overall black carbon emissions and to significantly reduce our overall methane emissions". Furthermore, within the scope of this Framework, an aspirational collective goal to reduce overall BC emissions in 2025 by 25-33% compared to 2013 was agreed. To implement the Framework, the Arctic Council Member and Observer States are formally encouraged to report inter alia national estimates of BC and CH_4 emissions on a biennial frequency. This report, produced under the EU-funded *Arctic Black Carbon impacting on Climate and Air Pollution* (ABC-iCAP) project, synthesizes available, up-to-date national BC and CH_4 emission inventories of the Arctic Council Member and Observer States that are reported under the Air Convention of the United Nations Economic Commission for Europe (UNECE) and the United Nations Framework Convention on Climate Change (UNFCCC). Where gaps in national estimates exist, the report also uses national emission inventories published in scientific literature or made available to the ABC-iCAP project by national inventory experts. To complement the national estimates, this synthesis also integrates independent BC and CH_4 emission estimates from the well-established global inventory datasets, GAINS and EDGAR. This report therefore provides a timely indication on whether the goals and targets of the Arctic Council Framework are on track to be met.

In 2020, total BC and total CH_4 emissions of the Arctic Council Member States were, according to national estimates, 431 Gg BC and 42489 Gg CH_4, respectively. Corresponding 2020 totals of the Arctic Council Observer States were 1274 Gg BC and 92624 Gg CH_4 according to gap-filled national estimates. While total emission levels vary somewhat between the national estimates and those derived from the independent GAINS and EDGAR datasets, the estimates agree to a large extent on the direction of the trends in total Member and Observer emissions since 2013. Generally, the different data sources indicate that collective Arctic Council Member and Observer emissions of CH_4 have increased since 2013. This observation underlines that more action on sources of CH_4 is required if the Arctic Council Member and Observer States are to collectively realize a key goal of the Arctic Council Framework in significantly reducing overall methane emissions. In contrast, the reported and independent data all indicate that significant reductions in overall BC emissions of the Arctic Council Member and Observer States have been made. Compared to collective BC emission levels in 2013, the respective 2020 emissions constitute annual decreases in BC emissions that range from 1.7 to 2.5 % per year for the Arctic Council Member States and 3 to 4.7% per year for the Arctic Council Observers. If such trends continued, Arctic Council Member and Observer States would collectively reduce BC emissions in 2025 by 20.4-30% and 36-56.4% compared to 2013 levels. It should however be noted that it is only the national data that indicate an annual trend in collective Arctic Council Member emissions, which is consistent with the aspirational goal of reducing overall emissions in 2025 by 25-33%. If the annual trends derived from the GAINS and EDGAR datasets were to continue, Arctic Council Member States would collectively reduce BC emissions in 2025 by 20.4-21.6%.

Analysis of the national emission estimates for selected priority sectors revealed that reductions in emissions from road and off-road transport have been important drivers of

This report was produced for the EU-funded project *Arctic Black Carbon impacting Climate and Air Pollution (ABC-iCAP)*, which promotes collaborative actions to reduce black carbon and methane emissions from specific source sectors impacting the Arctic, including open burning / wildland fires.

the overall reductions in Arctic Council Member emissions of BC. This of course adds additional uncertainty in extrapolating 2013-2020 trends, given that 2020 emissions from road transport were likely significantly impacted by the COVID-19 pandemic. Fugitive emissions from oil and gas contribute significantly to the level and trends in the collective BC and CH_4 emissions of the Arctic Council Member States. Although CH_4 emissions from oil and gas have declined since 2013, BC emissions from gas flaring, predominantly from Russia, have increased significantly between 2013 and 2020. Finally, considering the overall goal of the Framework to mitigate the impact of BC and CH_4 on the Arctic climate, it is important that sources of emissions which are not (fully) included in the national inventories and the collective emission reduction goals of the Arctic Council Framework are not overlooked. According to independent estimates of the International Council on Clean Transportation, BC emissions from shipping in the IMO Arctic waters, which are relatively small in level, have more than doubled between 2015 and 2021. However, differences between these estimates and those derived from a global shipping emissions dataset (The CAMS-GLOB-SHIP dataset of the Copernicus Atmospheric Monitoring Service) require further investigation. Nonetheless, the synthesis clearly highlights the significance of BC emissions from wildfires. Although most national BC inventories do not include wildfire emissions, the available national estimates of BC emissions from wildfires in Russia and the US totaled 200 Gg BC in 2013 and 384 Gg BC in 2020.

By utilizing multiple sources of up-to-date national and independent emissions data, this synthesis provides an important and timely indication on recent BC and CH_4 emission trends of the Arctic Council Member and Observer States. Of course, it should be noted that substantial gap-filling had to be applied to national emission estimates, particularly those of the Observer States. Nonetheless, with respect to potential future syntheses of AC Member and Observer emission inventories, it is important to note developments in international climate and air pollution policy that will/could lead to enhanced reporting of national CH_4 and BC emission inventories. All Arctic Council Member and Observer States are Parties to the Paris Agreement and, starting in 2024, will all be obliged to report GHG emission inventories on a biennial basis at least. Furthermore, the GHG inventories of all Parties will be subjected to thorough and regular reviews. Under the UNECE Air Convention, BC remains a voluntary pollutant under the new reporting guidelines. Therefore, an enhancement of reporting of BC emission inventories comparable to the enhanced reporting of CH_4 emission inventories under the Paris Agreement is, in the near to medium term, unlikely. Nevertheless, it is important to mention current international policy developments that could stimulate the sharing and exchange of emissions data on air pollutants (including BC) beyond the UNECE countries. The new International Forum for International Cooperation on Air Pollution (FICAP) is a platform that aims to extend collaboration regarding work on air pollution to regions outside the UNECE. FICAP could be a new forum for enhanced international cooperation on inter alia the development and reporting of national emission inventories. Parallel to this initiative, an expert group of the IPCC task force on national greenhouse gas inventories (TFI) is currently working on developing an inventory methodology report for SLCFs including BC and other climate relevant air pollutants. The TFI methodology report will have a global scope and could constitute an important technical stimulus to enhanced sharing of emissions data within FICAP and other international fora on climate change and air pollution.

Introduction and background

1

Arctic climate change and the importance of methane and black carbon

Arctic near-surface air temperature has increased by an annual average of 3.1°C in the 49 years between 1971 and 2019, which is three times faster than in the rest of the world (AMAP, 2021). A recent assessment by Rantanen et al. (2022) even found that the warming is nearly four times faster than the globe since 1979, a phenomenon known as Arctic amplification. Multiple factors have been proposed to explain the potential causes of Arctic amplification, including enhanced ocean heating and ice-albedo feedback due to diminishing sea ice, near-surface air temperature inversion, cloud feedback and ocean heat transport (Rantanen et al., 2022 and references therein).

Reductions in the emission of carbon dioxide are the backbone of any meaningful effort to mitigate climate forcing. However, reductions of carbon dioxide may not be achieved in time to delay a rapid thawing of the Arctic. Therefore, targeting shorter-lived climate forcing agents (SLCF), such as black carbon (BC) and methane (CH_4)[1], is important to mitigate climate change in the Arctic (AMAP, 2015a). Previous assessments on the impacts of methane and black carbon (AMAP, 2015a; AMAP, 2015b) estimated that a quarter of the total predicted Arctic warming of around two degrees could be avoided by 2050, if all technically feasible, global SLCF emissions-reduction measures aimed at addressing warming agents (particularly BC and CH_4) were implemented.

Methane has a lifetime of around ten years (Nicely et al., 2017) and is globally well mixed. Atmospheric methane levels are influenced by natural as well as anthropogenic emission sources. There are very large reservoirs of methane in the Arctic Ocean seabed and on land in the soils and lake sediments of the Arctic. Therefore, whether or not Arctic (and global) methane concentrations can be lowered depends not only on mitigation of anthropogenic methane sources but also on whether the release of methane from natural sources can be constrained (AMAP, 2015b).

Black carbon has been defined by Bond et al. (2013) as a distinct type of carbonaceous material that is formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties. Black carbon strongly absorbs visible light, is insoluble in water and common organic solvents and has a vaporization temperature near 4000 K. Pure black carbon particles rarely occur in the atmosphere since soon after emission they become mixed with other aerosol components in the atmosphere. Black carbon-containing aerosols warms the atmosphere directly by absorbing solar radiation and indirectly by accelerating snow/ice melt when deposited (Bond et al., 2013). However, it is important to note that as a component of particulate matter, BC is co-emitted with other species such as organic carbon (OC) and sulphur containing aerosols that act as cloud condensation nuclei and have an effective radiative forcing that is negative (AMAP, 2015a).

Black carbon is not only an important climate-forcer, but is also a pollutant impacting human health. Epidemiological studies provided evidence of the association of cardiopulmonary morbidity and mortality with exposure to black carbon. Toxicological studies suggest that black carbon may operate as a universal carrier of a wide variety of chemicals of varying toxicity to the human body (Jensen et al., 2012).

1 Methane is only considered a SLCF by some communities (AMAP 2021).

Arctic Council Framework on black carbon and methane

Acknowledging that emissions of BC and CH_4 have a substantial impact on the Arctic and that their reductions could lead to near-term climate, health and economic benefits in the Arctic, the Ministers of the Arctic Council adopted the framework *Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action* at the 9th ministerial meeting in April 2015. In the Framework, Arctic States commit to take "enhanced, ambitious, national and collective action to accelerate the decline in our overall black carbon emissions and to significantly reduce our overall methane emissions" and to submit biennial national reports on countries' existing and planned actions to reduce black carbon and methane, national inventories of these pollutants and, if available, projections of future emissions. To help implement these commitments, the Framework established an *Expert Group on Black Carbon and Methane* (*EGBCM*). The task of the EGBCM is to produce a biennial, high-level "Summary of Progress and Recommendations" report based on the national reports and other relevant information. These reports are presented to Arctic Council Ministers at their biennial meetings (Arctic Council, 2015).

In 2017, at the 10th ministerial meeting, the Arctic Council Member States adopted the first Pan-Arctic report on collective progress to reduce black carbon and methane emissions by the Arctic States and numerous Observer States and its recommendations, including an aspirational collective goal to collectively reduce black carbon emissions by 25-33% below 2013 levels by 2025 (Arctic Council, 2017a; Arctic Council, 2017b). In its 3rd progress report from 2021, which was based on national information submitted in early 2020, the EGBCM assessed that Arctic States have reduced their collective black carbon emissions by 20% in 2018, compared to 2013, and are on track to meet the aspirational goal for black carbon reductions by 2025. Furthermore, the EGBCM assessed that collective methane emissions by Arctic States have increased by 2% from 2013 to 2018, and are projected to continue increasing to 2025 (Arctic Council, 2021a). In 2021, at the 12th Ministerial meeting of the Arctic Council, Arctic Council Member States agreed to consider possible updates to the aspirational goal for black carbon reductions and noted that additional action and measures are needed to significantly reduce overall methane emissions (Arctic Council, 2021b).

Objective of this report

Biennial reporting under the *Framework for Action for Enhanced Black Carbon and Methane Emissions Reductions* (henceforth referred to as the *Arctic Council Framework*) has been interrupted since the start of the Russia-Ukraine war in 2022 and the EGBCM has thus not been able to continue its work. The last publically available national reports were submitted in 2020 and 2021. However, for Russia the latest, publically available national report dates back to 2015, and some Observer States are yet to submit a report. This synthesis report aims to fill the current gaps in monitoring of black carbon and methane emissions of the Arctic Council Member and Observer States. This report synthesizes available, up-to-date national BC and CH_4 emission inventories of the Arctic Council Member and Observer States that are reported under the Air Convention[2] of the United Nations Economic Commission for Europe (UNECE) and the United Nations Framework Convention on Climate Change (UNFCCC)[3]. Where gaps exist, national emission inventories published in scientific literature are taken to surrogate missing reporting data. In addition to the national inventory estimates, this synthesis integrates independent BC and CH_4 emission estimates from well-established global inventory datasets. Given the aforementioned pause on reporting under the Arctic Council Framework, this report provides a timely indication on whether the goals and targets of the Framework are on track to be met.

2 The UNECE Convention on Long-Range Transboundary Air Pollution is often abbreviated as the Air Convention. https://unece.org/sites/default/files/2021-05/1979%20CLRTAP.e.pdf

3 https://unfccc.int/resource/docs/convkp/conveng.pdf

Methods

2

Data sources

National emission inventories reported under the UNECE Air Convention and the UNFCCC

All of the eight Arctic Council Member States are Parties to both the UNECE Air Convention and the UNFCCC. As such, Arctic Council Member States are required to annually report national inventories of air pollutant and greenhouse gas emissions under the respective conventions. While the reporting of emissions of many air pollutants (e.g. the main pollutants) is mandatory under the UNECE Air Convention, the reporting of BC emissions is instead *encouraged* by the UNECE Executive Body Decisions 2013/3[1] and 2013/4[2]. In contrast to the option of voluntary reporting of BC under the UNECE Air Convention, the reporting of CH_4 emissions under the UNFCCC is mandatory for the Arctic Council Member States. As so-called Annex I Parties to the UNFCCC, the AC Member countries are required by the Conference of Parties (COP) Decision 24/CP.19[3] to report national emissions of CH_4 (together with emissions and removals of the other greenhouse gases not controlled by the Montreal Protocol) in their inventory submissions. Under both the UNECE Air Convention and the UNFCCC, the emission inventory submissions consist of both an inventory report (Informative Inventory Report (IIR) under the UNECE Air Convention; National Inventory Report (NIR) under the UNFCCC) and spreadsheet tables containing the aggregated and source-sector level activity data and emission estimates (NFR tables under the UNECE Air Convention; CRF tables under the UNFCCC).

Many of Arctic Council Observer States are also Parties to both the UNECE Air Convention and the UNFCCC. However, lying outside of the UNECE domain, the Asian Arctic Council Observer States, China, India, Japan, Singapore and South Korea, are not Parties to the Air Convention and are neither obliged by an international agreement to compile and report national emission inventories of air pollutants nor formally encouraged to share such data. In contrast, all Arctic Council Observer States are Parties to the UNFCCC; however, not all are Annex I Parties and therefore are not bound by the above reporting requirements for GHG emission inventories. As Non-Annex I Parties, China, India, Singapore and South Korea are instead required to share inventory estimates of national emissions of GHGs (including CH_4) in their Biennial Update Reports (BURs)[4] and National Communication (NCs) reports[5].

For the purpose of this synthesis report, the most up-to-date national inventory estimates of BC and CH_4 emissions that were submitted by the Arctic Council Member and Observer States under the respective conventions before the end of 2022 were collected. For those states that are Parties to the Air Convention, the 2022 submissions (IIRs and NFR Tables) were downloaded from the website of the Air Convention's *Centre for Emission Inventories and Projections* (CEIP)[6]. Likewise, respective data (NIRs and CRF Tables) for the countries that are Annex I Parties to the UNFCCC were gathered from the UNFCCC website[7]. For the countries that are Non-Annex I Parties, all BURs and NCs were downloaded from the UNFCCC website[8]. However, given that quantitative emissions data in BURs

1 Adoption of Guidelines for Reporting Emissions and Projections Data under the Convention on Long-range Transboundary Air Pollution, https://unece.org/DAM/env/documents/2013/air/eb/2013_3.pdf

2 Reporting of emissions and projections data under the Convention and its protocols in force, https://unece.org/DAM/env/documents/2013/air/eb/2013_4.pdf

3 Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention, https://unfccc.int/documents/8105

4 Decision 2/CP17 Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, https://unfccc.int/documents/7109

5 Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention, https://unfccc.int/documents/3217

6 https://www.ceip.at/ https://unfccc.int/documents/3217 status-of-reporting-and-review-results/2022-submission

7 https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-inventory-submissions-2022

8 BURs, https://unfccc.int/BURs; NCs, https://unfccc.int/non-annex-I-NCs

and NCs are not provided in CRF tables, the available CH_4 emissions data had to be manually copied from the BUR and NC documents and inserted into a central spreadsheet file.

Independent emission estimates

To complement the national BC and CH_4 emission inventories reported by the AC Member and Observer States under the UNECE Air Convention and the UNFCCC, respectively, this synthesis integrates respective emission estimates from independent sources. For this purpose, two prominent, independent datasets of international air pollutant and GHG emissions were utilized:

1. The Emissions Database for Global Atmospheric Research (EGDAR)[9] that is compiled and regularly updated by the Joint Research Centre (JRC) of the European Commission; and
2. The Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS)[10] dataset that is compiled and regularly updated by the International Institute for Applied Systems Analysis (IIASA).

While the emission estimates are compiled independently, it is important to note that both the independent and the reported emission inventories utilize, to varying extents, the same sources of emission factors and national activity data. For instance, national energy balance data that are used to compile the official national emission inventories are often reported elsewhere (e.g. to the IEA) and are used by the EDGAR and GAINS models. Likewise, the independent and the reported emission inventories utilize, again to varying extents, emission factors from the EMEP/EEA Guidebook (EMEP/EEA, 2019) and the IPCC 2006 Guidelines (IPCC, 2006), as well as the IPCC 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019).

This synthesis uses the most up-to-date GAINS and EDGAR estimates that were available/could be sourced at the time of data collection. For GAINS, IIASA provided their latest estimates of BC emissions for all the UNECE countries, as well as Arctic Council Observer States outside of the UNECE. Additionally, GAINS estimates of global CH_4 emissions (Höglund-Isaksson et al., 2020) that were contributed to the Global Methane Budget (Saunois et al., 2020) were also made available to this synthesis work. Both the GAINS BC and CH_4 emission estimates covered the years 1990, 1995, 2000, 2005, 2010, 2015 and 2020. The corresponding EDGAR estimates were taken from the EDGAR project website, where these data are freely available. For CH_4, the most up-to-date version of GHG estimates at the time of data collection, the *Global Greenhouse Gas Emissions* version EDGARv7.0[11], was incorporated into the synthesis. In the case of BC, the synthesis utilized the most up-to-date version of the *Global Air Pollutant Emissions* dataset, EDGARv6.1[12]. Both EDGAR datasets provide annual estimates of emissions starting in 1970. However, while the GHG emission (including CH_4) time series of EDGAR v7.0 extends to 2021, EDGARv6.1 provides annual estimates of air pollutant (including BC) emissions up to 2018.

The integration of the reported and the above independent emission estimates allows the synthesis to incorporate and analyze three individual inventory estimates per emitted species and per Arctic Council Member State:

1. A national estimate reported under the UNECE Air Convention or under the UNFCCC
2. An independent estimate from GAINS
3. An independent estimate from EDGAR

In the case of the AC Observer States that are outside the UNECE, reported BC emission inventories are not available. For India, Japan, Singapore and South Korea, we used data from the HTAP v3 mosaic as surrogate data for nationally-compiled BC emission estimates. The HTAP dataset is compiled by the UNECE's *Task Force on Hemispheric Transport of Air Pollution* and the v3 mosaic[13] in fact sources nationally-compiled estimates for Japan and South Korea. These national estimates were produced by the *National Air Emission Inventory and Research Center* (NAIR) of South Korea, the *Ministry of the Environment*, Japan (MOEJ) and the *National Institute of Environmental Studies* (NIES), Japan. In the case of Japan, the *Japan Automobile Research Institute* (JARI) kindly provided a revised national BC inventory for the years 2010 to 2017 through the *Collaborative Research Group on GHG-SLCF Emission Inventories*[14] at NIES. The dataset is an update and revision of the estimates that were originally included in the HTAP v3 mosaic dataset. For India and Singapore, HTAP relies on an independent regional dataset, *Regional*

9 https://edgar.jrc.ec.europa.eu/

10 https://iiasa.ac.at/models-tools-data/gains

11 https://edgar.jrc.ec.europa.eu/dataset_ghg70

12 https://edgar.jrc.ec.europa.eu/dataset_ap61

13 https://edgar.jrc.ec.europa.eu/dataset_htap_v3

14 https://esd.nies.go.jp/en/about/organization/inventory/

Emission inventory in ASia (REASv3.2.1[15]), which was also compiled by NIES, Japan. As a whole, the HTAP v3 mosaic provides annual air pollutant emission estimates for the period 2000-2018. While HTAPv3/REASv3.2.1 also provide estimates for China, this synthesis utilized a national inventory dataset (ABaCAS-EI v2.0 dataset) that was compiled by Chinese institutions (Tsinghua University, Beijing; State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing; and the Jiaotong University, Beijing) and recently published in ESSD (Li et al., 2023). The dataset provides annual CO_2 and air pollutant (including BC) emission estimates for the years 2005 and 2021.

Finally, due to gaps in the reported time series for the BC emissions of the US and Russia, additional national emissions data were sourced. The US Environment Protection Agency (US EPA) kindly provided additional BC emissions data to the 2011, 2014 and 2017 estimates that had been reported under the UNECE Air Convention. The US EPA provided an estimate of 2020 BC emissions, and furthermore provided a higher-resolution sector breakdown of BC emissions for 2020 and the previous years. To date, Russia has not yet reported BC emission inventories under the UNECE Air Convention. As a surrogate for the national estimate, the synthesis incorporated a national BC inventory that was compiled by the Izrael Institute of Global Climate and Ecology, Moscow, and recently published in the journal, *Russian Meteorology and Hydrology*. This paper by Ginzburg et al. (2022) contains an aggregated sector-level BC emission time series for the years 2010 to 2020.

Finally, it is important to note that the above emission estimates from the reported inventories, as well as from the aforementioned independent datasets, do not included estimates of emissions from international shipping. National shipping emissions are included; however, these are typically limited to shipping activities in inland waters or journeys into international waters that start and end at national ports. Given that emissions from shipping in Arctic waters represent a focus of this study, analyses of these specific emissions were done using estimates from two independent sources:

- The International Council on Clean Transportation (ICCT)[16]
- The CAMS-GLOB-SHIP dataset of the Copernicus Atmospheric Monitoring Service (CAMS)[17]

The ICCT recently published estimates of BC shipping emissions in Arctic waters for the years 2015 to 2021[18]. The shipping emissions modeled by the ICCT are based on AIS shipping traffic data modeled using the Systematic Assessment of Vessels Emissions (SAVE) model and aligned with the IMO 4th GHG study (ICCT, 2017). The ICCT considered all shipping activities occurring within *Arctic waters*, as defined by the International Maritime Organization (IMO), as well as a 2021 estimate for all shipping activities in the *Geographic Arctic* (>58.95°).

To complement these estimates, a subset of the CAMS-GLOB-SHIP dataset was used. Under the CAMS service portfolio, the *CAMS2_61 – Global and European emission inventories* data products (Denier van der Gon et al, 2023) are generated and include inter alia the CAMS ship emissions dataset, CAMS-GLOB-SHIP (Denier van der Gon et al., 2023). The shipping emissions contained within CAMS-GLOB-SHIP were modelled using the Ship Traffic Emission Assessment Model (STEAM, Johansson et al., 2017; Jalkanen et al., 2016) of the Finnish Meteorological Institute (FMI), which uses Automatic Identification System (AIS) data to describe ship traffic activity. The dataset version used in this study, CAMS-GLOB-SHIP_v3.2[19], provides gridded estimates of emissions of air pollutants and GHGs from shipping for the years 2000 to 2021. For this synthesis, BC and CH_4 emissions were extracted and emissions occurring at latitudes above 58.95° were aggregated to respective yearly regional totals.

Data processing and analysis

The emission datasets described above were downloaded and processed centrally in the programming environment R[20]. For the years in the respective time series, where emission estimates were available, no corrections or adjustment of the original data were made. Gap-filling procedures were only implemented in certain cases where no estimates were made for the years 2013 and 2020. Linear interpolation was applied to fill 2013 data gaps in the reported BC data of the US, as well as the reported CH_4 data of China, India and Singapore. Linear interpolation was furthermore applied to derive 2013 estimates for both the GAINS CH_4 and BC

15 https://www.nies.go.jp/REAS/index.html#REASv3.2.1

16 https://theicct.org/

17 https://atmosphere.copernicus.eu/

18 https://cleanarctic.org/2023/03/29/join-april-13th-webinar-reducing-black-carbon-emissions-and-other-impacts-from-shipping-on-the-arctic-pre-ppr-10/

19 https://eccad.sedoo.fr/#/metadata/462

20 https://www.r-project.org/

datasets of all countries given the five-year interval of the time series. For the year 2020, reported emissions (or surrogate national emissions) also had to be gap-filled in certain cases. For CH_4, this was done by extrapolating from the latest available year in the respective time series and using annual linear trends derived from respective 2015 and 2020 GAINS estimates. This was done for the CH_4 emissions of China, India, Singapore and South Korea by extrapolating from the years 2014, 2016, 2018 and 2018, respectively. For BC emissions, the surrogate national emissions of India, Japan, Singapore and South Korea for 2020 had to be gap-filled due to the 2000-2018 coverage of the HTAP v3 dataset. In this case, 2020 emissions were modelled from the available 2015 emission estimates based on respective national 2015:2020 emission ratios from GAINS. The rationale for implementing this extrapolation, instead of an extrapolation from the available 2018 estimates using an annual linear trend from GAINS, was that the latter would potentially underestimate the 2020 reductions in BC emissions caused by the COVID-19 pandemic (Guevara et al., 2022), which are indeed considered in the GAINS 2020 estimates. The extrapolation from the 2015 base level, using 2015:2020 emission ratios from GAINS, was thus considered more appropriate for gap-filling the 2020 surrogate national estimates of BC emissions.

After implementing above processing and gap-filling procedures, the emission estimates from the aforementioned datasets, in their different source sector resolutions, were harmonized and aggregated into the following sectoral split:

- Fuel combustion and Industry (IPCC sectors 1A and 2)
- Fugitive emissions (IPCC sector 1B)
- Agriculture (IPCC sector 3)
- Waste (IPCC sector 5)

Graphs were generated to demonstrate the trends and levels in national total emissions (and aggregate sector contributions) of the individual AC Member and Observer States, as well as trends and levels for the Member and Observer blocs as a whole. Given the context of the Arctic Council Framework, 2020 changes in BC and CH_4 emissions against respective 2013 base levels were calculated.

The above analysis of aggregated emissions at the country and AC Member/Observer bloc level was complemented by analyses of emissions from the following priority source sectors:

- Road transport
- Off-road transport
- Residential combustion
- Oil and gas flaring
- Open burning of agricultural residues
- Open burning of waste
- Wildfires
- Shipping in Arctic waters

Note that the above choice of sources includes the priority sectors for BC given the focus of the ABCiCAP project on BC. Consequently, important priority sectors for CH_4 (emissions from landfills and livestock) are not included in this synthesis.

Similar to the analyses of aggregate emissions at country and AC Member/Observer bloc level, emission levels and trends were analyzed at the country and bloc level for the above source sectors. However, the analysis of levels and trends in sectoral emissions were limited to national emissions estimates of the Arctic Council Member States. Only in the case of shipping emissions in Arctic waters, were the independent estimates of ICCT and FMI datasets used. Furthermore, this analysis focuses on the regional emission levels and trends, rather than on respective contributions from the Arctic Council Member States.

Finally, in addition to the description of sectoral emission levels and trends, the synthesis also investigated, where applicable, the inventory methods used by the Artic Council Member States to generate the reported BC and CH_4 emissions from the above source sectors (except for the regional shipping emissions). Where activity data and source level emissions were reported in the respective NFR/CRF tables, the respective IIRs/NIRs were analyzed to categorize whether the simplest inventory methodology was applied (*Tier 1*), or whether a more complex method (*Higher tier* i.e. *Tier 2* or *Tier 3*) had been implemented. The results of this technical analysis are included in Annex II.

Results and discussion

3

Reporting of national black carbon and methane emission inventories

According to the Arctic Council repository where the *National Reports* submitted under the Arctic Council Framework are made available[1], most of the National Reports containing estimates of national BC and CH_4 emission were last submitted by the AC Member States in 2020 (Table 1). The US submitted its latest report in 2021, while Russia's last submission was back in 2015. The coverage of the emission time series varies between the countries and the emitted species; however, almost all reported time series contain emissions for at least the period 2013 to 2017/2018. In contrast, Russia's last submission in 2015 contains BC emissions for the year 2013 only, while CH_4 emissions are provided for the period 1990-2012.

A similar pattern in terms of the year of the last submission and the coverage of the emission time series is also observed for the Arctic Council Observer States (Table 2). The latest available national reports were generally submitted in 2020, although the latest reports of the Netherlands and South

Table 1. Overview of BC and CH_4 emissions reporting by the Arctic Council Member States under the Arctic Council Framework, the UNECE Air Convention and the UNFCCC considering national reports/national inventories submitted up to 2022

Country	Arctic Council		UNECE Air Convention		UNFCCC	
	Status	**Reporting (year of last national report submission; time series reported)**	**Status**	**Reporting (Year of last inventory submission; time series reported)**	**Status**	**Reporting (year of last inventory submission; time series reported)**
Canada	Member	2020; BC 2013-2017 CH_4 2005-2017	Party	2022; 2013-2020	Annex I Party	2022; 1990-2020
Denmark	Member	2020; BC 2013-2018 CH_4 1990-2017	Party	2022; 1990-2020	Annex I Party	2022; 1990-2020
Finland	Member	2020; BC 1990-2018 CH_4 1990-2018	Party	2022; 1990-2020	Annex I Party	2022; 1990-2020
Iceland	Member	2020; BC 1990-2018 CH_4 1990-2018	Party	2022; 1990-2020	Annex I Party	2022; 1990-2020
Norway	Member	2020; BC 1990-2018 CH_4 1990-2018	Party	2022; 1990-2020	Annex I Party	2022; 1990-2020
Russia	Member	2015; BC 2013 CH_4 1990-2012	Party	NR*	Annex I Party	2022; 1990-2020
Sweden	Member	2020; BC 2013-2018 CH_4 2010-2018	Party	2022; 2000-2020	Annex I Party	2022; 1990-2020
The United States	Member	2021; BC 2011, 2014 & 2017 CH_4 1990-2018	Party	2022; 2011, 2014 and 2017	Annex I Party	2022; 1990-2020

*not reported

1 Arctic Council Arctic States 2020 National Reports on Enhanced Black Carbon and Methane Emissions Reductions: https://oaarchive.arctic-council.org/items/3687a38c-af68-4eec-b0b9-fc3a855d988d; Arctic Council Observer States 2020 National Reports on Enhanced Black Carbon and Methane Emissions Reductions: https://oaarchive.arctic-council.org/items/05fa90a8-9893-4987-ac53-e1ec7f650ee9

Table 2. Overview of BC and CH_4 emissions reporting by the Arctic Council Observer States under the Arctic Council Framework, the UNECE Air Convention and the UNFCCC considering national reports/national inventories submitted up to 2022

Country	**Arctic Council**		**UNECE Air Convention**		**UNFCCC**	
	Status	**Reporting (Year of last national report submission; time series reported)**	**Status**	**Reporting (Year of last inventory submission; time series reported)**	**Status**	**Reporting (Year of last inventory submission; time series reported)**
France	Observer	2020; BC 1990-2019 CH_4 1990-2019	Party	2022; 1990-2020	Annex I	2022; 1990-2020
Germany	Observer	2020; BC 2000, 2005, 2010, 2013-2018 CH_4 1990, 2000, 2010-2018	Party	2022; 1990-2020	Annex I	2022; 1990-2020
Italy	Observer	2020; BC 1990-2018 CH_4 1990-2018	Party	2022; 1990-2020	Annex I	2022; 1990-2020
The Netherlands	Observer	2017; BC 1990-2015 CH_4 1990-2015	Party	2022; 1990-2020	Annex I	2022; 1990-2020
Poland	Observer	2020; BC 1990-2018 CH_4 1990-2018	Party	2022; 1990-2020	Annex I	2022; 1988-2020
Spain	Observer	2020; BC 2000-2018 CH_4 1990-2018	Party	2022; 2000-2020	Annex I	2022; 1990-2020
Switzerland	Observer	2020; BC 1990, 1995, 2000-2018 CH_4 2000-2018	Party	2022; 1980-2020	Annex I	2022; 1990-2020
United Kingdom	Observer	2020; BC 2013-2017 CH_4 2013-2017	Party	2022; 1990-2020	Annex I	2022; 1990-2020
Japan	Observer	2020; BC 2012 & 2015 CH_4 1990-2018	Non-party	NA	Annex I	2022; 1990-2020
South Korea	Observer	2017; BC 2014 CH_4 1990, 2010-2014	Non-party	NA	Non-Annex I	2021 (BUR4); 1990-2018
Singapore	Observer	NR*	Non-party	NA	Non-Annex I	2022 (BUR5); 1994, 2000, 2010, 2012, 2014, 2016, 2018
India	Observer	2020; CH_4 2014	Non-party	NA	Non-Annex I	2021 (BUR3); 1994, 2000, 2010, 2016
China	Observer	NR*	Non-party	NA	Non-Anex I	2018 (BUR2); 1994, 2005, 2010, 2012, 2014

*not reported

Korea were submitted in 2017, and China and Singapore are yet to submit such a report under the Arctic Council. Again, the coverage of the emission time series varies between the countries and the emitted species, though in comparison to the Arctic Council Member States, gaps are more prevalent. China and Singapore have yet to report on BC and CH_4 emissions, while the report of India contains only estimates of CH_4 emissions for 2014 and no estimate of BC emissions. In contrast to its 1990-2018 time series of national CH_4 emissions, Japan's 2020 report provides BC estimates for two single years (2012 and 2015). South Korea's 2017 report contains CH_4 emissions for 1990 and 2010-2014; however, BC emission estimates are provided for the year 2014 only.

The time that has passed since the last Arctic Council report submissions, as well as the aforementioned gaps in some of those reported time series underline the potential importance of sourcing and synthesizing other more up-to-date and more complete sources of BC and CH_4 emission estimates.

China, India, Japan Singapore and South Korea of course lie outside the UNECE and have neither the requirement nor the opportunities to report emission inventories of air pollutants (including BC) under the Air Convention. Nevertheless, the remaining Arctic Council Member and Observer States are all Parties to the Air Convention and, despite BC being a non-mandatory pollutant, almost all of these countries have reported time series of national BC emissions. With the exceptions of Canada, Russia and the United States, the 2022 submissions of all other Arctic Council Member and Observer States that are Parties to the UNECE Air Convention reported BC emissions time series that covered at least all years between 2000 and 2020. In contrast, Canada's 2022 submission under the UNECE Air Convention provided BC emissions for the years 2013 to 2020. The 2022 submission of the United States under the UNECE Air Convention provided BC emissions for the years 2011, 2014 and 2017 and no updates were provided in their 2023 submission. Furthermore, in contrast to the other reporting UNECE Air Convention Parties, the US' NFR data submission contains only the national total emissions of BC (and the other air pollutants). An aggregated sector split of BC emissions was, however, provided in a separate spreadsheet attached to the 2022 submission. Furthermore, as mentioned in the Methods chapter, the US EPA kindly provided a more resolved source sector split of BC emissions, together with a cross-walk to the GNFR sector system, as well as a full BC inventory for the year 2020. Finally, Russia has yet to report a BC emission inventory under the UNECE Air Convention.

Given that CH_4 is a mandatory GHG under the UNFCCC, all Arctic Council Member and Observer States have reported CH_4 emissions under this convention. The 2022 UNFCCC submissions of all Arctic Council Member and Observer States that are Annex I Parties contained CRF Tables with CH_4 emissions for the full 1990-2020 time series. For the four remaining Arctic Council Observer States that are Non-Annex I Parties under the UNFCCC, the CH_4 emission time series that could be extracted from all BURs/NCs were less complete. While South Korea reports a full annual time series of CH_4 emissions for the period 1990-2018, Singapore's BUR/NC submissions yielded CH_4 emission estimates for the year 1994, and then emissions estimates for every 2nd year in the period between 2000 and 2018. For China, CH_4 emissions for the years 1994, 2005, 2010, 2012 and 2014 could be extracted from the BURs/NCs reported up until 2022, while for India, the CH_4 emissions were provided for the years 1994, 2000, 2010 and 2016.

Aggregate levels and trends in black carbon and methane emissions

Emission levels and trends of the Arctic Council Member States

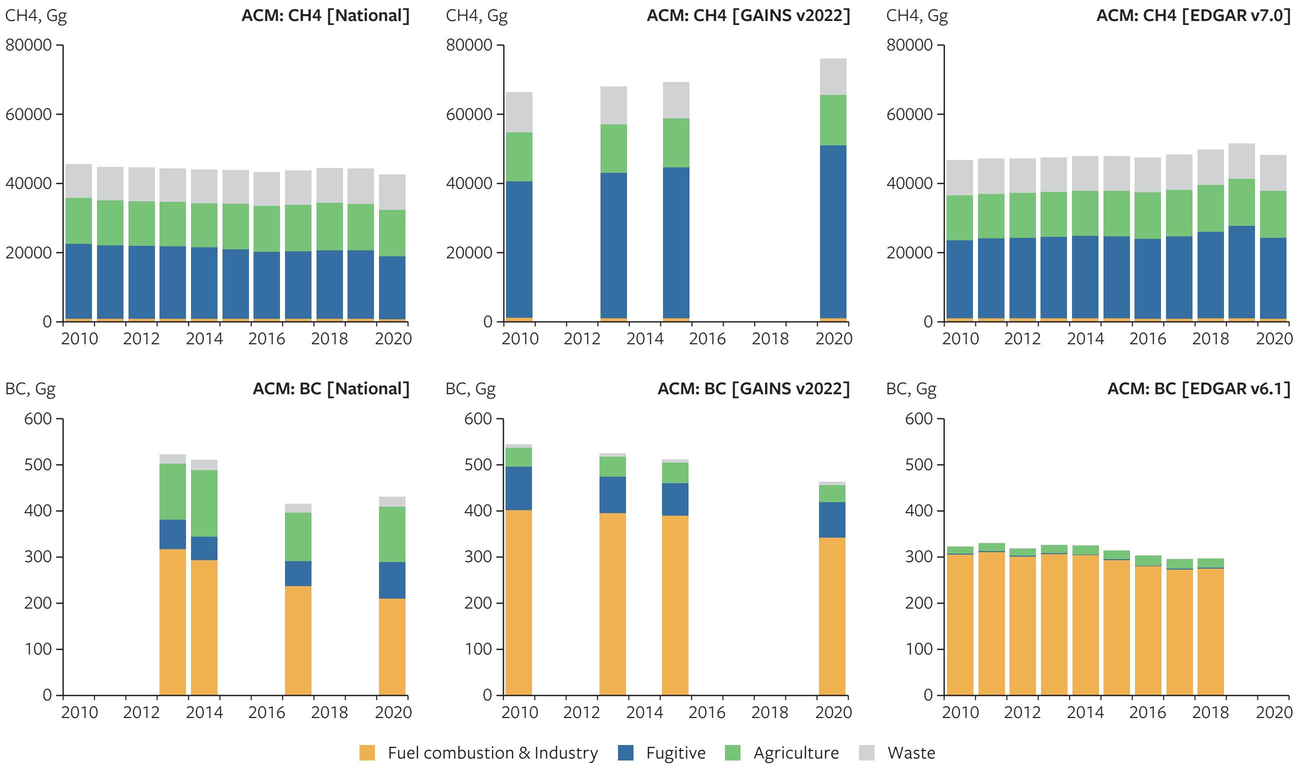
In 2020, BC emissions of the eight Arctic Council Member States amounted to 431 Gg BC according to the data reported (Table 3; Figure 1). Compared to 2013 total emissions (523 Gg BC), the 2020 emissions represent an average annual decrease of 2.5% per year. Similar emission levels and trends are given by the GAINS dataset. According to GAINS, 2020 emissions were estimated at 464 Gg BC, representing a 1.7% per year decrease on 2013 levels (525 Gg BC). According to EDGAR estimates, 2018 emissions (298 Gg BC) have decreased by 1.8% per year compared to 2013 levels (327 Gg BC). The trend according to the reported emissions indicate that the Arctic Council Member States are on a path consistent with achieving the aspirational goal of a 25-33% reduction in BC emissions compared to the 2013 base year. Assuming a linear decrease in emissions between 2013 and 2025, achieving the 2025 aspirational goal would require an annual emission reduction rate of 2.08 to 2.75% per year. In contrast to the reported estimates, the independent estimates indicate slower annual emission reduction rates (1.7% per year, GAINS; 1.8% per year, EDGAR) than that required by the aspirational goal. Furthermore, it should be noted that while the 2013-2020 reduction rate of the reported emissions appears consistent with the trajectory to the aspirational goal, the rate of reduction in emissions appears to have decelerated over the 2013-2020 period. As a bloc, BC emissions decreased between 2013 and 2017 by 5.12 % per year, while between 2017 and 2020 total emissions have in fact increased by 1.25% per year. The change in trajectory is mostly explained by declining emission reductions of the US on the one hand, and increasing BC emissions of Russia on the other.

Indeed as Table 3 shows, relative to the change in total Arctic Council Member emissions since 2013, the US trend in absolute terms makes the largest contribution. According to the reported estimates, the change in US BC emissions between 2013 and 2020 represents a decrease of 20.5 Gg BC per year compared to the overall Member trend of -13.1 Gg BC per year. Meanwhile, the next largest absolute contribution to the total trend comes from Russia, whose BC emissions increase between 2013 and 2020 constitutes a change of +9.2 Gg BC per year. While large decreases in US emissions relative to the total Member trend appear to be corroborated by the respective GAINS and EDGAR estimates, neither the sign nor magnitude of the trend in Russian emissions is confirmed by both independent datasets (-0.3 Gg BC per year, GAINS; +0.6 Gg BC per year, EDGAR). While the

Table 3. Black carbon emissions levels and trends of the Arctic Council Member States for the years 2013 and 2020 (2018 for EDGAR) according to national and independent estimates.

Country	2013 BC Emissions (Gg BC)			2020 (2018) BC Emissions (Gg BC)			Change in Emissions since 2013 (Gg BC per year)			Change in Emissions since 2013 (% change per year)		
	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR
CA	37.1	49.6	42.9	29.0	47.5	36.9	-1.2	-0.3	-1.2	-3.1	-0.6	-2.8
DK	2.9	3.9	2.2	1.9	2.1	2.4	-0.2	-0.3	0.0	-5.2	-6.6	1.8
FI	4.6	4.6	8.1	3.2	3.1	9.2	-0.2	-0.2	0.2	-4.5	-4.6	2.6
IS	0.1	0.4	0.1	0.1	0.3	0.1	0.0	0.0	0.0	-4.9	-3.3	4.3
NO	3.9	7.6	3.7	2.9	4.6	3.0	-0.1	-0.4	-0.2	-3.6	-5.7	-4.0
RU	125.6	197.9	40.2	190.3	195.8	43.5	9.2	-0.3	0.6	7.4	-0.1	1.6
SE	3.2	4.7	6.6	2.0	2.5	6.8	-0.2	-0.3	0.0	-5.4	-6.8	0.7
US	345.0	256.0	223.2	201.8	207.9	195.6	-20.5	-6.9	-5.5	-5.9	-2.7	-2.5
Total	**522.5**	**524.6**	**327.1**	**431.2**	**463.7**	**297.6**	**-13.1**	**-8.7**	**-5.9**	**-2.5**	**-1.7**	**-1.8**

Figure 1. Total methane (top row) and black carbon (bottom row) emissions of the Arctic Council Member States according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available for all Member States and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.



independent datasets should not be viewed as a verification *yardstick* in this synthesis, the variations in estimates between the reported and independent emission estimates can be indicative of potential uncertainties. Indeed, in absolute emission levels, the largest range across the reported and independent 2013 estimates is observed for Russia (157 Gg BC range between the minimum estimate of 40.2 and the maximum estimate of 197.6 Gg BC).

The US and Russia, followed by Canada, are the largest contributors to the levels and trends in total Arctic Council Member emissions of BC. Nonetheless, it is important that trends in the smaller-emitting Member States are not overlooked. After the US, the largest relative decreases in reported emissions relative to 2013 levels are observed for Sweden (-5.4 % per year), Denmark (-5.2 % per year) and Iceland (-4.9 % per year). With the exception of Russia, the reported emissions of all other Arctic Council Member States have decreased since 2013, ranging from -5.9 % per year for the US to -3.1 % per year for Canada. The GAINS dataset, at least in terms of sign, corroborates these reported decreases; however, the sign of the EDGAR trend estimates diverge for some countries. Only for Canada, Norway and the US, do all three datasets indicate decreasing trends in national BC emissions since 2013.

In contrast to the BC emissions described above, relative changes in CH_4 emissions of the Arctic Council Member States since 2013 have been more modest (Table 4; Figure 1). According to the reported and independent estimates, total Arctic Council Member emissions in 2020 ranged between 42489 (reported estimates under the UNFCCC) and 76073 Gg CH_4 (GAINS). Compared to respective 2013 levels, relative changes in emissions over the period ranged from -0.56 (reported) to +1.68% (GAINS) per year. Comparable to the sign of the BC trends in reported data, reported CH_4 emissions of all Member countries apart from Russia decreased between 2013 and 2020. Nonetheless, it should be noted that these relative decreases and the relative increase for Russia (0.18 % per year) are significantly smaller than the respective relative changes in reported BC emissions (-3.12 % to -0.31 % per year). Perhaps reflecting these comparatively smaller changes between 2013 and 2020, the sign of the trends at national and bloc level vary between the reported and independent estimates. Only for Denmark, Finland, Norway, and Sweden, do all three datasets indicative a decreasing trend in CH_4 emissions. At the bloc level, the GAINS and EDGAR datasets indicate increases in total Arctic Council Member emissions over the 2013-2020 period (0.19 % and 1.68 % per year, respectively), in contrast to the decrease in total emissions according to the reported data.

Under the Artic Council Framework, there is no aspirational, quantitative goal for reducing CH_4 emissions, such as that for BC. Nevertheless, under this Framework, the Arctic Council Member States did commit to *significantly reduce our overall methane emissions*. According to this synthesis, it is difficult to conclude with confidence that total CH_4 emissions of the Arctic Council Member States have decreased since 2013. In contrast to BC emissions, the independent emission estimates of GAINS and EDGAR do not corroborate the overall decrease in reported CH_4 emissions since 2013, and instead indicate that overall CH_4 emissions have increased during this seven-year period. The disagreement in trends in total CH_4 emissions can be largely attributed to the varying trend estimates for the three highest emitting Member States. For Canada, Russia and the US, the change in 2020 CH_4 emissions compared to 2013 levels vary between -146 to +70 Gg CH_4 per year, +3 to +304 Gg CH_4 per year and -208 and +1089 Gg CH_4 per year, respectively. These national level variations represent large ranges, especially considering that the trend in total Member CH_4 emissions varies between -249 and +1145 Gg CH_4.

Emission levels and trends of the Arctic Council Observer States

The Arctic Council Framework for Action is formally an agreement between the eight Arctic Council Member States. Nonetheless, the text of the agreement explicitly encourages the Arctic Council Observer States to participate in the implementation of the Framework and furthermore acknowledges that mitigation action by the Observer States is vital for the overall success of the Framework. It is therefore relevant to consider the level and trends in the BC and CH_4 emissions of these countries.

Table 4. Methane emissions levels and trends of the Arctic Council Member States for the years 2013 and 2020 according to national and independent estimates.

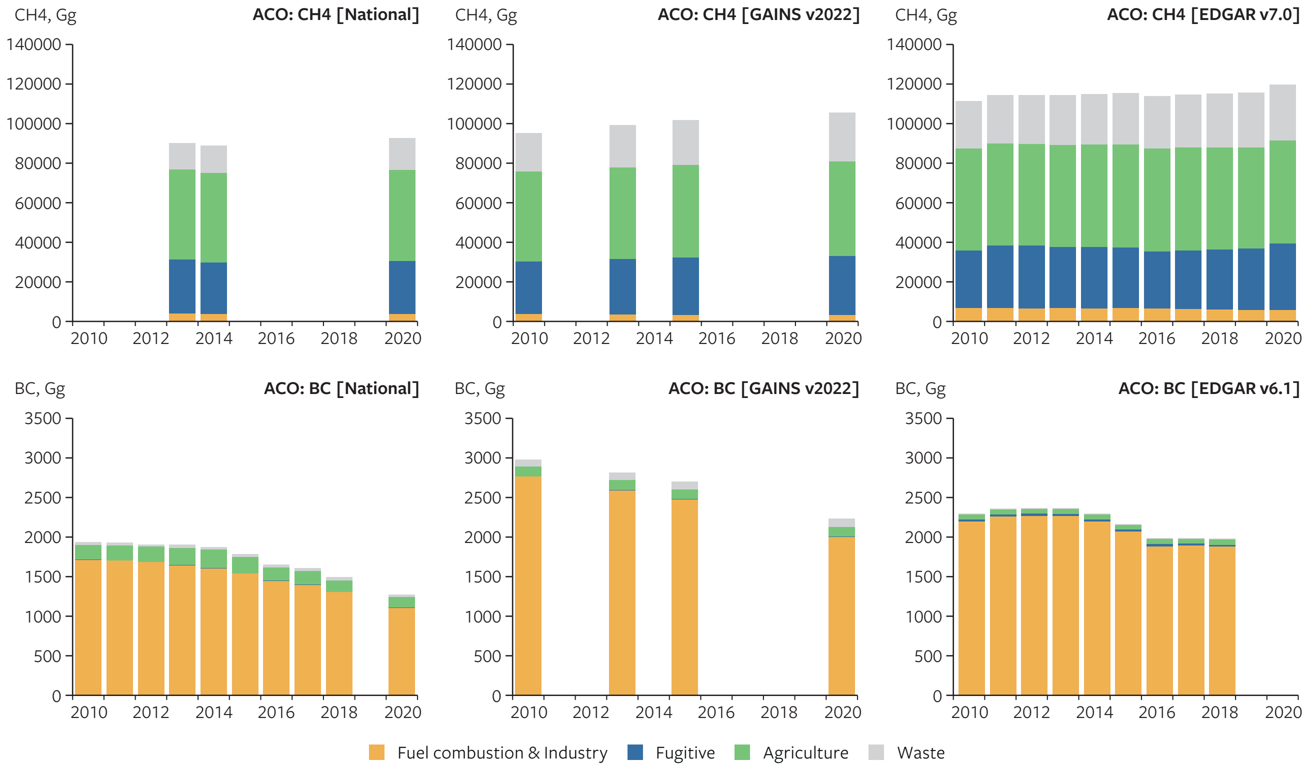
Country	2013 CH_4 Emissions (Gg CH_4)			2020 CH_4 Emissions (Gg CH_4)			Change in Emissions since 2013 (Gg CH_4 per year)			Change in Emissions since 2013 (% change per year)		
	National	**GAINS**	**EDGAR**	**National**	**GAINS**	**EDGAR**	**National**	**GAINS**	**EDGAR**	**National**	**GAINS**	**EDGAR**
CA	4691	4929	4223	3667	5417	4473	-146.33	69.73	35.72	-3.12	1.41	0.85
DK	291	286	345	285	269	323	-0.92	-2.38	-3.09	-0.31	-0.83	-0.90
FI	200	221	902	176	174	735	-3.37	-6.69	-23.83	-1.69	-3.03	-2.64
IS	25	27	19	24	26	21	-0.14	-0.17	0.19	-0.59	-0.61	0.96
NO	211	247	824	188	224	755	-3.25	-3.27	-9.80	-1.54	-1.32	-1.19
RU	11820	28126	15354	11968	28144	17488	21.11	2.58	304.86	0.18	0.01	1.99
SE	191	212	481	164	181	451	-3.85	-4.42	-4.27	-2.01	-2.08	-0.89
US	26803	34012	25375	26017	41637	23923	-112.33	1089.24	-207.56	-0.42	3.20	-0.82
Total	**44232**	**68060**	**47523**	**42489**	**76073**	**48169**	**-249.08**	**1144.63**	**92.21**	**-0.56**	**1.68**	**0.19**

Reflecting the larger number of countries and the substantial size of some of the respective national economies, total BC and CH_4 emissions from the Observer States are higher than the respective total emissions of the Member States. In 2020, total BC emissions based predominantly on reported data and national estimates were 1274 Gg BC, while the GAINS and EDGAR estimate total 2020 emissions at 2229 and 1979 Gg BC, respectively (Table 5; Figure 2). The

Table 5. Black carbon emissions levels and trends of the Arctic Council Observer States for the years 2013 and 2020 (2018 for EDGAR) according to national and independent estimates.

Country	2013 BC Emissions (Gg BC)			2020 (2018) BC Emissions (Gg BC)			Change in Emissions since 2013 (Gg BC per year)			Change in Emissions since 2013 (% change per year)		
	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR
CH	1.9	1.9	2.2	1.0	1.4	2.0	-0.1	-0.1	0.0	-6.5	-3.5	-1.5
CN	796.6	1267.0	1481.2	410.3	1035.6	1112.6	-55.2	-33.1	-73.7	-6.9	-2.6	-5.0
DE	18.5	21.3	19.4	10.2	12.3	19.2	-1.2	-1.3	0.0	-6.4	-6.0	-0.2
ES	55.5	28.9	19.1	41.0	20.2	18.4	-2.1	-1.3	-0.1	-3.7	-4.3	-0.8
FR	36.3	33.2	25.4	18.8	17.3	23.3	-2.5	-2.3	-0.4	-6.9	-6.8	-1.7
GB	19.4	21.1	13.7	15.6	14.1	14.2	-0.5	-1.0	0.1	-2.8	-4.7	0.6
IN	893.8	1302.3	709.2	720.3	1033.0	700.6	-24.8	-38.5	-1.7	-2.8	-3.0	-0.2
IT	25.6	34.1	20.0	15.8	22.2	19.1	-1.4	-1.7	-0.2	-5.5	-5.0	-0.9
JP	13.2	21.7	31.2	7.3	13.4	25.9	-0.8	-1.2	-1.1	-6.3	-5.4	-3.4
KR	15.2	17.8	15.5	9.9	12.7	15.6	-0.8	-0.7	0.0	-5.0	-4.1	0.1
NL	3.8	4.9	3.1	2.1	2.5	2.9	-0.3	-0.3	0.0	-6.6	-6.8	-1.5
PL	20.6	56.2	21.8	16.6	39.6	22.9	-0.6	-2.4	0.2	-2.7	-4.2	1.0
SG	1.7	1.7	2.4	5.5	4.9	2.1	0.5	0.5	-0.1	30.7	27.8	-3.0
Total	**1902.3**	**2811.9**	**2364.4**	**1274.4**	**2229.4**	**1978.7**	**-89.7**	**-83.2**	**-77.1**	**-4.7**	**-3.0**	**-3.3**

Figure 2. Total methane (top row) and black carbon (bottom row) emissions of the Arctic Council Observer States according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available for all Observer States and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.



considerably higher independent estimates are largely due to the higher independent estimates for China, and in the case of GAINS, the higher estimate for India. These two countries represent the highest–emitting countries of the Observer States, with their 2020 estimates ranging from 410 Gg (national estimate) to 1036 Gg (GAINS) for China, and from 701 Gg (EDGAR) to 1033 Gg (GAINS) for India. Despite the range in BC emission estimates for China, India and other Observer States, the different datasets nonetheless indicate a considerable and comparable relative decrease in BC emissions between 2013 and 2020. According to estimates based mainly on national estimates, the decrease in BC emissions between 2013 and 2020 amounts to a relative decline of 4.7% per year. According to the GAINS and EDGAR data, the decrease has been slower yet nonetheless at 3 and 3.3% per year, respectively. If these trends were to continue, the Observer States, as a whole, would be on course to reduce their 2025 emissions by 36-56.4% compared to 2013 levels.

Similar to BC, the total CH_4 emissions of the Observer States are higher than total CH_4 emissions of the Member States, with emissions from China and India contributing the large majority (Table 6; Figure 2). According to the CH_4 emissions reported under the UNFCCC (albeit with considerable gap-filling of the Non-Annex I countries China and India), total Observer emissions of CH_4 amounted to 92624 Gg, with China and India contributing 57397 and 20888 Gg CH4, respectively. In contrast to the decrease in BC emissions over time, the reported and independent data indicate that total Observer CH_4 emissions have increased since 2013. It should be noted that despite the overall increase, positive and negative trends can be observed amongst the individual Observer States. For instance, the reported and independent datasets all indicate clear relative decreases on 2013 levels for Germany, France, Japan and Netherlands of 0.8 % year or more. Nevertheless, the reported and independent datasets indicate that the CH_4 emissions of China and India have increased between 2013 and 2020 by 380-735 Gg and 140 and 419 Gg CH4 per year, respectively. Consequently, total Observer CH_4 emissions over the 2013-2020 period have increased by 366-896 Gg per year or 0.4-0.9% per year. Despite the relative agreement in terms of trends across datasets, it is important to recall that the reported CH_4 emission time series of China and India extend only to the years 2014 and 2016. The respective 2020 estimates thus had to be gap-filled by extrapolating from these years to 2020 using the relative annual trends derived from the 2015 and 2020 CH_4 estimates given by GAINS.

National inventory estimates of black carbon and methane emissions from selected sectors

The previous chapter described the level and trends in total Member and Observer emissions of BC and CH_4, as well as respective levels and trends in the total emissions of the individual countries. Figure 1 and Figure 2, respectively, show the contributions of aggregate sectoral emissions to the levels and trends for the Member and Observer blocs.

Table 6. Methane emissions levels and trends of the Arctic Council Observer States for the years 2013 and 2020 according to national and independent estimates.

Country	2013 CH_4 Emissions ($Gg\ CH_4$)			2020 CH_4 Emissions ($Gg\ CH_4$)			Change in Emissions since 2013 ($Gg\ CH_4$ per year)			Change in Emissions since 2013 (% change per year)		
	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR	National	GAINS	EDGAR
CH	195	231	202	183	209	202	-1.6	-3.1	0.1	-0.8	-1.4	0.0
CN	54736	51297	66263	57397	56441	71005	380.1	734.8	677.4	0.7	1.4	1.0
DE	2279	2103	2741	1961	1710	2450	-45.4	-56.1	-41.5	-2.0	-2.7	-1.5
ES	1499	1703	1639	1510	1565	1764	1.5	-19.7	17.8	0.1	-1.2	1.1
FR	2363	2449	2821	2186	2207	2621	-25.4	-34.5	-28.5	-1.1	-1.4	-1.0
GB	2159	2625	1952	1869	2108	1860	-41.4	-73.8	-13.2	-1.9	-2.8	-0.7
IN	19909	31207	29335	20888	34142	30953	139.9	419.3	231.2	0.7	1.3	0.8
IT	1800	2017	1742	1711	1836	1612	-12.7	-25.9	-18.6	-0.7	-1.3	-1.1
JP	1204	1723	2280	1136	1581	2078	-9.7	-20.2	-28.8	-0.8	-1.2	-1.3
KR	1300	1060	1593	1324	1072	1704	3.4	1.8	15.9	0.3	0.2	1.0
NL	735	724	964	679	597	773	-8.0	-18.1	-27.3	-1.1	-2.5	-2.8
PL	1951	1962	2631	1774	1896	2442	-25.2	-9.3	-27.1	-1.3	-0.5	-1.0
SG	4	39	183	7	45	215	0.3	0.8	4.6	7.8	2.1	2.5
Total	**90134**	**99139**	**114344**	**92624**	**105410**	**119678**	**355.7**	**895.9**	**762.0**	**0.4**	**0.9**	**0.7**

Reflecting the variation in emission levels and trends between the national and independent estimates, aggregate sectoral emissions do vary between the different datasets. Nonetheless, in terms of relative contributions to levels and trends in overall Member and Observer emissions, the datasets agree rather well. For both the Member and Observer totals, the different datasets show that fuel combustion for energy generation and industrial production (1A+2) is the dominant contributor to both the level and trends in BC emissions. The next most important sectoral contributor to both Member and Observer total BC emissions appears to be Agriculture (3), due predominately to the open burning of field residues. However, in the case of the Member BC emissions, the national and GAINS estimates show a significant contribution from fugitive BC emissions from fuels (1B). According to GAINS, these emissions, which are primarily the result of Gas Flaring, are in fact the second largest sectoral contributor ahead of Agriculture.

Fugitive emissions are the dominant sectoral source of total Member emissions of CH_4, which in the case of this GHG, include emissions from venting and flaring, as well as unintentional gas releases from the coal, oil and gas industries. In the case of GAINS, these sources of emissions are mostly responsible for the estimated increase in total CH_4 emissions over the last decade. The next largest sectoral contributors to total CH_4 emissions are the sectors Agriculture (mostly from enteric fermentation) and then Waste (mostly emissions from solid waste disposal). In the case of total CH_4 emissions from the Arctic Council Observer States, Agriculture is the largest sectoral contributor to total emissions, followed by fugitive emissions and emissions from Waste.

The following subchapters focus on Arctic Council Member emissions from priority sources according to national emission estimates. While these sources have been identified as priority sectors for mitigating black carbon, the subchapters describe national estimates of emissions of both BC and CH_4. Annex II furthermore summarizes the inventory methods used by the Arctic Council Member States to estimate emissions from these sources.

Road transport

Emissions of BC and CH_4 from road transport are those emissions resulting from fuel combustion in the motor engines of on-road vehicles. The emissions are included under the NFR and CRF category *1A3b Road transportation*.

According to national estimates, total Arctic Council Member emissions of BC and CH_4 from road transport in 2020 were 97.1 Gg BC and 97.4 Gg CH_4, respectively (Table 7). Relative to 2013 levels, these emissions have declined substantially over the last seven years (7.1% and 5.1 % per year for BC and CH_4). While road transport emissions contribute less than 0.2% of total CH_4 emissions in 2020, this sector constitutes 11% of the total 2020 BC budget of the Arctic Council Member States. Indeed, the reduced road transport emissions of BC (-6.90 Gg per year) are larger than the net decline in total Arctic Council Member emissions (-6.10 Gg per year).

Off-road transport

Emissions of BC and CH_4 from off-road transport are those emissions resulting from fuel combustion in the motor engines of off-road vehicles and mobile machinery. The emissions are included under the NFR and CRF categories:

- *1A2gvii Mobile combustion in manufacturing industries and construction*
- *1A3c Mobile combustion on Railways*

Table 7. Black carbon and methane emissions from road transport according to national estimates of Arctic Council Member States for the years 2013 and 2020.

Country	BC Emission levels and trends				CH_4 Emissions levels and trends			
	Emission levels		Change since 2013		Emission levels		Change since 2013	
	2013 (Gg)	2020 (Gg)	Gg per year	% per year	2013 (Gg)	2020 (Gg)	Gg per year	% per year
CA	7.66	6.22	-0.21	-2.69	9.43	8.29	-0.16	-1.74
DK	0.95	0.36	-0.08	-8.80	0.52	0.32	-0.03	-5.68
FI	0.94	0.56	-0.05	-5.81	0.56	0.32	-0.04	-6.24
IS	0.06	0.04	0.00	-4.94	0.07	0.04	0.00	-6.14
NO	0.83	0.38	-0.06	-7.73	1.07	0.92	-0.02	-1.96
RU	9.50	9.20	-0.04	-0.45	28.26	21.15	-1.02	-3.59
SE	0.98	0.39	-0.08	-8.55	1.00	0.83	-0.02	-2.43
US	76.20	31.67	-6.36	-8.35	56.44	30.50	-3.71	-6.57
Total	**97.12**	**48.83**	**-6.90**	**-7.10**	**97.37**	**62.37**	**-5.00**	**-5.14**

- *1A4aii Mobile combustion on Commercial/Institutional property*
- *1A4bii Mobile combustion on residential property e.g. household and gardening vehicles/machinery*
- *1A4cii Mobile combustion from off-road vehicles and other machinery in Agriculture, Forestry and Fishing*
- *1A5b Other off-road mobile combustion including military, land based and recreational boats*

According to national estimates, levels of and trends in BC and CH_4 emissions from off-road transport are of a similar order of magnitude to those emissions from road transport (Table 8). Therefore, the overall contribution of these sources to total CH_4 emissions of the Arctic Council Member States is minor, while the contribution to total BC levels and trends is significant. In fact the 2020 total off-road BC emissions of 62.3 Gg BC constitute 14% of total Arctic Council Member BC emissions. Moreover, due to substantial decreases in emissions (-7.6 Gg BC per year), changes in off-road emissions have also contributed substantially to the declining trend in total Arctic Council Member emissions of BC between 2013 and 2020.

Residential combustion

Emissions of BC and CH_4 from residential combustion are those emissions resulting from stationary fuel combustion in residual households for the purpose of heat generation (e.g. space-heating, warm water and cooking). The emissions are included under the NFR and CRF category *1A4bi Residential: Stationary combustion*.

In comparison to the previous mobile sectors, CH_4 emissions from residential combustion are approximately one order of magnitude higher (Table 9). Nevertheless, the 2020 emissions of 275.5 Gg CH_4 represent less than 1% of the total 2020 CH_4 budget of the Arctic Council Member States.

Table 8. Black carbon and methane emissions from off-road transport according to national estimates of Arctic Council Member States for the years 2013 and 2020

Country	BC Emission levels and trends				CH_4 Emissions levels and trends			
	Emission levels		Change since 2013		Emission levels		Change since 2013	
	2013 (Gg)	2020 (Gg)	Gg per year	% per year	2013 (Gg)	2020 (Gg)	Gg per year	% per year
CA	13.94	9.68	-0.61	-4.36	8.52	9.16	0.09	1.08
DK	0.71	0.35	-0.05	-7.18	0.17	0.13	-0.01	-3.60
FI	0.63	0.30	-0.05	-7.48	0.51	0.45	-0.01	-1.88
IS	0.00	0.01	0.00	n.a.	0.00	0.00	0.00	n.a.
NO	0.27	0.16	-0.02	-5.70	0.64	0.66	0.00	0.49
RU	4.00	4.90	0.13	3.21	5.93	2.42	-0.50	-8.46
SE	0.71	0.51	-0.03	-4.02	0.40	0.32	-0.01	-2.59
US	95.21	46.37	-6.98	-7.33	3.51	2.85	-0.10	-2.71
Total	**115.47**	**62.30**	**-7.60**	**-6.58**	**19.68**	**15.99**	**-0.53**	**-2.68**

Table 9. Black carbon and methane emissions from residential combustion according to national estimates of Arctic Council Member States for the years 2013 and 2020

Country	BC Emission levels and trends				CH_4 Emissions levels and trends			
	Emission levels		Change since 2013		Emission levels		Change since 2013	
	2013 (Gg)	2020 (Gg)	Gg per year	% per year	2013 (Gg)	2020 (Gg)	Gg per year	% per year
CA	8.18	6.94	-0.18	-2.16	60.90	53.36	-1.08	-1.77
DK	0.81	0.73	-0.01	-1.27	4.49	2.48	-0.29	-6.39
FI	2.66	2.05	-0.09	-3.28	7.61	6.21	-0.20	-2.63
IS	1.1E-05	7.9E-06	-4.4E-07	-4.00	7.1E-04	5.4E-04	-2.4E-05	-3.43
NO	0.93	0.86	-0.01	-1.11	9.74	8.66	-0.15	-1.59
RU	12.40	11.30	-0.16	-1.27	44.18	40.58	-0.51	-1.16
SE	0.90	0.65	-0.04	-4.07	2.66	1.97	-0.10	-3.72
US	16.39	25.07	1.24	7.57	195.88	162.20	-4.81	-2.46
Total	**42.27**	**47.61**	**0.76**	**1.80**	**325.47**	**275.46**	**-7.14**	**-2.19**

Total 2020 emissions of BC from residential combustion are at 47.6 Gg BC similar to the level of total road transport emissions and constitute ca. 11% of the collective 2020 BC emissions of the Arctic Council Member States. However, in contrast to the decline in total road transport emissions, total BC emissions from residential combustion have increased since 2013 by 1.8% per year. As the Table 9 shows, this overall trend has been driven by the US, whose increases in residential emissions (1.24 Gg BC per year) outweigh the collective declines of the other seven Arctic Council Member States. Of course, one should consider that residential emissions largely reflect the substantial annual variations in winter temperatures and subsequent heating demand. Thus, the comparison of two separate years may not be completely indicative of the general trend over time.

Fugitive emissions from oil and gas

Fugitive emissions of BC and CH_4 from oil and gas are those resulting from unintentional losses of CH_4 along the oil and gas exploration-, production- and supply chains, as well as the controlled venting and flaring of excess gas that builds-up in industrial oil and gas processes. The emissions are included under the NFR and CRF categories:

- *1B2a Emissions from exploration-, production-, transport-, refining/storage of oil, as well the distribution of oil products*
- *1B2b Emissions from exploration-, production-, processing-, transmission and storage-, and distribution of gas*
- *1B2c Venting and flaring of excess gas build-up resulting from industrial exploration-, production-, processing- and refining of oil and gas*

While all subcategories are relevant for CH_4 emissions, BC emissions result primarily from combustion that occurs during flaring (1B2c). In contrast to the previous sectors, fugitive emissions from oil and gas make a substantial contribution to total Arctic Council emissions of CH_4 (Table 10). Total fugitive emissions of CH_4 from oil and gas (13551 Gg CH_4) represent 32% of the 2020 total CH_4 budget of the Arctic Council Member States. Since 2013, CH_4 emissions from this sector have decreased on average by 295 Gg CH_4 per year, a decline that is larger than the 249 Gg CH_4 per year decrease in total Artic Council emissions of CH_4. Fugitive emissions, primarily from flaring, are also a significant contributor to the total BC emissions of the Arctic Council Member States. The 79.6 Gg BC emissions from the sector constitute 18% of total 2020 Arctic Council emissions of BC. While the US, Russia and Canada all contribute significant fugitive emissions of CH_4 from oil and gas, respective BC emissions from flaring are dominated by Russian emissions. Of the 79.6 Gg total Arctic Council Member fugitive BC emissions from oil and gas in 2020, Russia contributes 77.6 Gg BC. Russia's 1B2 emissions of BC have increased since 2013 by an average of 2.14 Gg BC per year and this increase essentially dictates the overall sector trend of the Arctic Council Member States.

Open burning of agricultural residues and waste

Emissions of BC and CH_4 from open burning of agricultural residues and waste are estimated separately under the respective NFR and CRF categories:

- *3F Field burning of agricultural residues*
- *5C2 Open burning of waste*

Table 10. Fugitive emissions of black carbon and methane from oil and gas according to national estimates of Arctic Council Member States for the years 2013 and 2020

Country	BC Emission levels and trends				CH_4 Emissions levels and trends			
	Emission levels		Change since 2013		Emission levels		Change since 2013	
	2013 (Gg)	2020 (Gg)	Gg per year	% per year	2013 (Gg)	2020 (Gg)	Gg per year	% per year
CA	1.49	1.23	-0.04	-2.46	2304.88	1298.63	-143.75	-6.24
DK	1.4E-04	1.0E-04	-6.1E-06	-4.28	5.25	2.13	-0.45	-8.49
FI	NK*	NK*	n.a.	n.a.	1.57	0.87	-0.10	-6.37
IS	NK*	NK*	n.a.	n.a.	2.1E-02	1.8E-02	-4.0E-04	-1.96
NO	0.39	0.19	-0.03	-7.41	22.89	18.05	-0.69	-3.02
RU	62.60	77.60	2.14	3.42	4403.67	3748.42	-93.61	-2.13
SE	2.8E-03	1.1E-03	-2.3E-04	-8.50	2.30	1.76	-0.08	-3.34
US	0.12	0.59	0.07	53.33	8875.09	8481.27	-56.26	-0.63
Total	**64.61**	**79.61**	**2.14**	**3.32**	**15615.66**	**13551.13**	**-294.93**	**-1.89**

*Refers to use of notation key (NK) in the UNECE/UNFCCC reporting tables indicating why quantitative emission estimates have not been reported for the sector(s).

At 19 Gg CH_4, emissions from field burning in agriculture contribute only a tiny fraction to the 42489 Gg total CH_4 emissions of the Arctic Council Member States in 2020 (Table 11). BC emissions from this sector are on the other hand a large source, contributing 114 Gg BC (26%) of the 431 Gg total Arctic Council Member emissions of BC in 2020. Emissions of BC from this sector have increased since 2013 by 0.5% per year, with the large decreases of US emissions (83.5 Gg in 2013; 41 Gg in 2020) not quite cancelling out the large increases of Russian emissions (26.5 Gg in 2013; 72 Gg in 2020). Iceland and Sweden indicate in their reporting tables under the UNFCCC and the UNECE that such activities and emissions are *not occurring* in their countries (notation key *NO*). Interestingly, Russia also reports under the UNFCCC that these CH_4 emissions are not occurring, yet the Ginzburg paper (Ginzburg et al., 2022) estimates substantial BC emission from this activity. In contrast, Canada reports these CH_4 emissions under the UNFCCC, but does not report corresponding BC emissions under the Air Convention (notation key *NR*, signaling that the emissions are *not reported*).

Regarding emissions from open burning of waste, only Iceland reports CH_4 emission from this activity under the UNFCCC. Iceland also reports respective BC emissions under the Air Convention and so does Sweden despite not reporting corresponding CH_4 emissions under the UNFCCC. The other Arctic Council Member States report neither emissions of BC under the Air Convention nor CH_4 emissions under the UNFCCC. Interestingly, of notation keys given in the respective UNFCCC reporting tables instead of quantitative estimates, only Denmark indicates explicitly that this activity and the subsequent CH_4 emissions are *not occurring* (*NO*). Canada, Finland, Norway, Russia and Sweden use the notation *not estimated* (*NE*), while the US reports *not applicable* (*NA*). Given the lack of quantitative data reported, a respective table on 2013 and 2020 emissions from open burning of waste is not provided here.

Black carbon and methane emissions from wildfires in the Arctic Council Member States and shipping in Arctic waters

The BC and CH_4 emissions at national and aggregate sector level described in the previous subchapters refer to sources of emissions that are targeted by the Arctic Council Framework, i.e., emissions from the aggregate Air Convention/UNFCCC sectors: *1A Fuel combustion*; *1B Fugitive emissions*; *2 Industrial Processes and Product Use*; *3 Agriculture* and *5 Waste*. This subchapter briefly covers two sources of emissions that are not (fully) included in these sectors, yet could be having a significant impact on the Arctic climate: emissions from wildfires and emissions from international shipping in Arctic waters.

As Annex I Parties, the Arctic Council Member States are obliged to report wildfire GHG emissions (including CH_4) under the UNFCCC, when these disturbances occur on *managed lands*. Wildfire emissions (together with emissions from *controlled burning* that are not included in emissions from prescribed burning of savannas (3E) or from field burning of agricultural residues (3F)) are included under the sector 4(V). The CH_4 emissions from 4(V) are included in Table 12. While these emissions are small compared to the 42489 Gg total CH_4 emissions of the Arctic Council Member States, it should be noted that not all wildfire emissions

Table 11. Black carbon and methane emissions from open burning of agricultural residues according to national estimates of Arctic Council Member States for the years 2013 and 2020

Country	**BC Emission levels and trends**				**CH_4 Emissions levels and trends**			
	Emission levels		**Change since 2013**		**Emission levels**		**Change since 2013**	
	2013 (Gg)	**2020 (Gg)**	**Gg per year**	**% per year**	**2013 (Gg)**	**2020 (Gg)**	**Gg per year**	**% per year**
CA	NK*	NK*	NK*	NK*	1.623	1.627	0.001	0.032
DK	0.023	0.028	0.001	3.654	0.122	0.154	0.004	3.654
FI	0.025	0.019	-0.001	-3.503	0.088	0.069	-0.003	-3.062
IS	NK*	NK*	NK*	NK*	NK*	NK*	NK*	NK*
NO	0.024	0.030	0.001	4.159	0.089	0.115	0.004	4.159
RU	26.50	72.20	6.529	24.64	NK*	NK*	NK*	NK*
SE	NK*	NK*	NK*	NK*	NK*	NK*	NK*	NK*
US	83.52	41.67	-5.98	-7.16	17.0	17.06	0.009	0.052
Total	**110.1**	**113.9**	**0.550**	**0.500**	**18.92**	**19.02**	**0.015**	**0.078**

*Refers to use of notation key (NK) in the UNECE/UNFCCC reporting tables indicating why quantitative emission estimates have not been reported for the sector(s).

Table 12. Black carbon and methane emissions from wildfires according to national estimates of Arctic Council Member States for the years 2013 and 2020.

Country	BC Emission levels and trends				CH_4 Emissions levels and trends			
	Emission levels		Change since 2013		Emission levels		Change since 2013	
	2013 (Gg)	2020 (Gg)	Gg per year	% per year	2013 (Gg)	2020 (Gg)	Gg per year	% per year
CA	NK	NK	NK	NK	30.89	19.72	-1.60	-5.16
DK	NK	NK	NK	NK	1.69E-03	4.96E-05	-2.35E-04	-13.87
FI	NK	NK	NK	NK	3.05E-02	9.82E-02	9.67E-03	31.73
IS	NK	NK	NK	NK	1.18E-03	1.09E-03	-1.39E-05	-1.18
NO	NK	NK	NK	NK	1.59E-03	9.75E-03	1.17E-03	73.11
RU	113.30	248.00	19.24	16.98	550.85	625.27	10.63	1.93
SE	NK	NK	NK	NK	0.12	0.06	-0.01	-6.42
US	86.80	135.64	6.98	8.04	210.68	557.03	49.48	23.48
Total	**200.10**	**383.64**	**26.22**	**13.10**	**792.58**	**1202.20**	**58.52**	**7.38**

*NK refers to use of notation key in the UNECE/UNFCCC reporting tables indicating why quantitative emission estimates have not been reported for the sector(s).

are included. Large areas of *Forest land* and *Grassland* in Canada, Russia and the US are categorized as unmanaged, and emissions (and removals) on these lands including those due to wildfires are not included in the anthropogenic GHG inventories submitted to the UNFCCC. Under the Air Convention, air pollutant emissions from wildfires can be reported voluntarily as a memo item under sector *11B*. Only the US has reported these emissions under the Air Convention (Table 12), and while Russia does not report a black carbon emission inventory under the Air Convention, the Ginzburg paper (Ginzburg et al., 2022) does provide estimates of BC emissions from wildfires. Note that despite the unavailability of national estimates from the other Member States, the sum of wildfire BC emissions from Russia and the US in 2020 amounts to 384 Gg BC. Wildfire emissions of these two, albeit large countries are equivalent to almost 90% of the total 2020 BC emissions from the Arctic Council Member States. Furthermore, the difference between 2020 and 2013 BC emissions from wildfire represent average annual increase of 26 Gg BC per year. Of course, wildfire disturbances and subsequent emissions are subject to high inter-annual variability. The comparison of two separate years (from only two Arctic States) may therefore not be indicative of a general collective trend over time. Nevertheless, the change in emissions between 2013 and 2020 is consistent with recent and expected future trends of increased wildfire frequency and severity in the Arctic (Paunu and McCarty et al., 2023).

Emissions of BC and CH_4 from shipping in Arctic waters are in comparison much smaller. For instance, according to the CAMS-GLOB-SHIP dataset, CH_4 emissions from all shipping activities in the geographic Arctic (latitudes at or above 58.95°) totaled 20.2 Gg CH_4 in 2020. Nonetheless, in the case of BC, the location of the emission sources and proximity to the Arctic heavily influence the regional climate effect of BC through deposition. While emissions from shipping in the Arctic may be included in national emission inventories of the Arctic Council Member States, these will only be so-called *national emissions* from shipping voyages that depart and return to national ports, without stopping at ports of other countries. Furthermore, without gridded emissions data at the sector level, it is difficult to quantify that portion of national shipping emissions that occur in Arctic waters.

The International Council on Clean Transportation (ICCT) estimated 2021 BC emissions from shipping in the geographic Arctic (latitudes at or above 58.95°) at ca. 1.5 Gg BC. Of these emissions, almost one-third (413 t BC) occur further north in the Arctic waters designated by the International Maritime Organization (IMO), as defined by the polar code. While this level of emissions is not particularly high in comparison with the total BC budget of the Arctic Council Member States, these shipping emissions are occurring deep within the Arctic Circle. Furthermore, the BC emissions within the IMO Arctic waters are increasing at a rapid rate according to the ICCT. Within a period of six years, the ICCT estimates that BC emissions in the IMO Arctic waters have more than doubled from 193 t BC in 2015 to 483 t BC in 2021. However, the level and trend in BC emissions from Arctic shipping according to ICCT appear to diverge from those of CAMS-SHIP-GLOB. Emissions from shipping in the geographic Arctic (latitudes at or above 58.95°) according to CAMS-SHIP-GLOB totaled only 0.22 Gg BC in 2021 and were in fact lower than respective totals in 2015 (0.29 Gg BC). These differences could reflect the different assumptions on the fuel types used before and after the global 2020 Sulfur cap, but this will require further research.

Summary and perspectives

4

In 2020, total BC and total CH_4 emissions of the Arctic Council Member States were, according to national estimates, 431 Gg BC and 42489 Gg CH_4, respectively. Corresponding 2020 totals of the Arctic Council Observer States were 1274 Gg BC and 92624 Gg CH_4 according to gap-filled national estimates. While total emission levels vary somewhat between the national estimates and those derived from the independent GAINS and EDGAR datasets, the estimates agree to a large extent on the direction of the trends in total Member and Observer emissions since 2013. All three sources of data agree that total BC emissions of the Arctic Council Member and Observer States have decreased between 2013 and 2020. While the datasets furthermore agree that total Arctic Council Observer emissions of CH_4 have increased since 2013, the datasets diverge on the direction of trends in total Arctic Council Member emissions of CH_4. The GAINS and EDGAR estimates indicate an average annual increase of Arctic Council Member emissions of CH_4 of 1.68 and 0.19% per year compared to 2013 levels, while national estimates indicate a contrasting decrease of 0.56% per year.

This synthesis therefore indicates that more action on sources of CH_4 is required if the Arctic Council Member and Observer States are to collectively realize a key goal of the Arctic Council Framework in significantly reducing overall methane emissions. Nevertheless, all three sources of data indicate that significant reductions in overall BC emissions of the Arctic Council Member and Observer States have been made. Compared to collective BC emission levels in 2013, the respective 2020 emissions constitute annual decreases in BC emissions that range from 1.7 to 2.5 % per year for the Arctic Council Member States and 3 to 4.7% per year for the Arctic Council Observer States. If such trends continued, Arctic Council Member and Observer States would collectively reduce BC emissions in 2025 by 20.4-30% and 36-56.4%, respectively, compared to 2013 levels. While the 2013-2020 trends indicate large reductions in BC emissions, it should be noted that it is only the national data that indicate an annual trend in collective Arctic Council Member emissions (2.5% per year), which is consistent with the aspirational goal of reducing overall emissions in 2025 by 25-33%. If the annual trends derived from the GAINS and EDGAR datasets (1.7 and 1.8% per year) were to continue, Arctic Council Member States would collectively reduce BC emissions in 2025 by 20.4-21.6%.

Analysis of the national emission estimates for selected priority sectors revealed that reductions in emissions from road and off-road transport have been important drivers of the overall reductions in Arctic Council Member emissions of BC. This of course adds additional uncertainty in extrapolating 2013-2020 trends, given that 2020 emissions from road transport were likely significantly impacted by the unprecedented mobility restrictions introduced in response to the COVID-19 pandemic (Guevara et al., 2022). Furthermore, this synthesis highlighted the significance of fugitive emissions. Fugitive emissions from oil and gas contribute significantly to the level and trends in the collective BC and CH_4 emissions of the Arctic Council Member States. However, while CH_4 emissions from the oil and gas have declined since 2013, BC emissions from gas flaring, predominantly from Russia, have increased between 2013 and 2020 by 2.14 Gg BC per year. Finally, while the collective emissions summarized above will determine if the Arctic Council Framework realizes its internal goals on reducing emissions, it is important to note that mitigating the impact of BC and CH_4 on the Arctic climate could be limited by other sources not (fully) included in emission inventories. According to independent estimates of the ICCT, BC emissions from shipping in the IMO Arctic waters have more than doubled between 2015 and 2021. However, the apparent divergence from respective emission level and trends according to the CAM-GLOB-SHIP dataset should investigated. Nonetheless, the synthesis highlights the regional importance of BC emissions from wildfires. Although national inventory estimates do not include wildfire emissions, national estimates of BC emissions from wildfires in Russia and the US were 200 Gg BC in 2013 and 384 Gg BC in 2020.

Considering the levels and trends in collective emissions described above, it is important to note the gaps in the respective national estimates that had to be filled for compiling this synthesis. As Non-Annex I Parties to the UNFCCC, China, India, South Korea and Singapore have not been obliged to annually report GHG emission inventories. As such, the completeness of CH_4 emission time series in BURs/NCs reported up to 2022 varies between these countries. Furthermore, in contrast to the Annex I Parties, the reported emissions and the respective national inventory systems have not undergone thorough review. In terms of BC, the above countries, as well as Japan, are not UNECE countries and thus do not report emission inventories of air pollutants under the Air Convention. Furthermore, BC is a voluntary pollutant under the Air Convention, and reflecting this status, gaps in the data exist. Considering submissions up to 2022, the US has reported BC emissions for the years 2011, 2014 and 2017 only, while Russia has yet to report BC emissions under the Air Convention.

This report therefore utilized other sources of data and gap-filling methods. In doing so it provides a timely indication on recent BC and CH_4 emission trends of the Arctic Council Member and Observer States, given the current pause on (and previous gaps in) emissions reporting under the Arctic Council Framework. Indeed, such a multi-source approach could be adopted for future such syntheses, where gaps remain. With respect to potential future syntheses of emission inventories of AC Member and Observer States, it is important to note developments in international climate and air pollution policy that will/could lead to enhanced reporting of national CH_4 and BC emission inventories. All Arctic Council Member and Observer States are Parties to Paris Agreement[1], and starting in 2024 will all be obliged to report GHG emission inventories under the enhanced transparency framework following the Paris Agreement reporting guidelines[2]. Mandatory annual reporting by the Annex I Parties under the UNFCCC will continue, while the Non-Annex I parties will be required to report at a bi-annual frequency at least. Regardless of the reporting frequency, the GHG inventories of all Parties will be subjected to thorough and regular reviews.

Under the UNECE Air Convention, BC remains a voluntary pollutant under the new reporting guidelines[3] for the submissions from 2024 onwards. However, in 2022 only five Parties that reported data for main pollutants did not report data on BC. While a hypothetical change to the status of mandatory pollutant could lead to enhanced reporting of BC emission inventories, the effect would be limited to the UNECE countries. Furthermore, under the Air Convention, Russia reports only air pollutant emissions that occur in the part of the country that is west of the Urals, i.e., not all emissions occurring over the whole territory. Therefore, an enhancement of reporting of BC emission inventories comparable to the enhanced reporting of CH_4 emission inventories under the Paris Agreement is, in the near to medium term, unlikely. Nevertheless, it is important to mention current international policy developments that could stimulate the sharing and exchange of emissions data on air pollutants (including BC) beyond the UNECE countries. The new Forum for International Cooperation on Air Pollution (FICAP) is a platform that aims to extend collaboration regarding work on air pollution to regions outside the UNECE (Engleryd et al. 2023). FICAP could be a new forum for enhanced international cooperation on inter alia the development and reporting of national emission inventories. Available data on black carbon emissions (e.g. from scientific studies) could be brought into a format comparable to the reporting format under the Air Convention through cooperation of national and independent experts from outside and within the EMEP region. In raising awareness and informing on black carbon emissions at the FICAP meetings, the EMEP/EEA Guidebook could be promoted as a source of information for emission factors and methodologies. In this regard, it is particularly important to note the very relevant work of the IPCC task force on national greenhouse gas inventories (TFI). A TFI expert group on short-lived climate forcers (SLCFs) is currently working on developing an inventory methodology report for SLCFs including BC and other climate relevant air pollutants. In contrast to the EMEP/EEA Guidebook, the TFI methodology report will have a global scope and could constitute an important technical support to FICAP and other international fora on climate change and air pollution.

1 https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

2 Decision 18/CMA.1: Modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement. https://unfccc.int/documents/193408

3 EB Decision 2022/1 (ECE/EB.AIR/150/Add.1). https://unece.org/sites/default/files/2023-06/Revised_Decision%202022_1%20%28E%29.pdf

References

Acosta Navarro, J., Varma, V., Riipinen, I. et al., 2016. Amplification of Arctic warming by past air pollution reductions in Europe. Nature Geosci 9, 277–281. https://doi.org/10.1038/ngeo2673

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling and Software, 26 (12), pp. 1489-1501. , https://doi.org/10.1016/j.envsoft.2011.07.012

AMAP, 2021. Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://www.amap.no/documents/doc/impacts-of-short-lived-climate-forcers-on-arctic-climate-air-quality-and-human-health.-summary-for-policy-makers/3512

AMAP, 2015a. AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 116 pp. https://www.amap.no/documents/doc/amap-assessment-2015-black-carbon-and-ozone-as-arctic-climate-forcers/1299

AMAP, 2015b. AMAP Assessment 2015: Methane as an Arctic climate forcer. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 139 pp. https://www.amap.no/documents/doc/amap-assessment-2015-methane-as-an-arctic-climate-forcer/1285

AMAP, 2021. Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø. Norway. https://www.amap.no/documents/doc/impacts-of-short-lived-climate-forcers-on-arctic-climate-air-quality-and-human-health.-summary-for-policy-makers/3512

Arctic Council, 2015. Annex 4. Iqaluit 2015 SAO report to Ministers. Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action. Arctic Council Secretariat. http://hdl.handle.net/11374/610

Arctic Council, 2017a. Declaration of the Foreign Ministers of the Arctic States at the 10th Ministerial meeting of the Arctic Council, held in Fairbanks, Alaska, 10-11 May, 2017. http://hdl.handle.net/11374/1910

Arctic Council, 2017b. Expert Group on Black Carbon and Methane: Summary of progress and recommendations 2017. 49 pp. http://hdl.handle.net/11374/1936

Arctic Council, 2021a. Expert Group on Black Carbon and Methane: 3rd Summary of Progress and Recommendations, Oslo, Norway. https://oaarchive.arctic-council.org/handle/11374/2610

Arctic Council, 2021b. Declaration of the Foreign Ministers of the Arctic States at the 12th Ministerial meeting of the Arctic Council, held in Reykjavik, Iceland, 20 May, 2021. http://hdl.handle.net/11374/2600

Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. Deangelo, M.G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren and C.S. Zender, 2013. Bounding the role of 105 black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres, 118:5380-5552.

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, https://doi.org/10.2760/953322, JRC134504.

Crippa, M., Guizzardi, D., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S., Morikawa, T., Pouliot, G., Racine, J., Moran, M. D., Klimont, Z., Manseau, P. M., Mashayekhi, R., Henderson, B. H., Smith, S. J., Suchyta, H., Muntean, M., Solazzo, E., Banja, M., Schaaf, E., Pagani, F., Woo, J.-H., Kim, J., Monforti-Ferrario, F., Pisoni, E., Zhang, J., Niemi, D., Sassi, M., Ansari, T., and Foley, K., 2023. The HTAP_v3 emission mosaic: merging regional and global monthly emissions (2000–2018) to support air quality modelling and policies, *Earth Syst. Sci. Data*, 15, 2667–2694, https://doi.org/10.5194/essd-15-2667-2023

Denier van der Gon, H., Gauss, M., and Granier, C., 2023. CAMS2_61 – Global and European emission inventories, Documentation of CAMS emission inventory products. https://doi.org/10.24380/q2si-ti6i

Engleryd, A., Åström, S., Grennfelt, P., Klemetz, V., Salter, J., Genberg, J., 2023. Air Pollution Management in a World under Pressure Saltsjöbaden VII Workshop; ISBN 978-92-893-7662-4 (ONLINE). http://dx.doi.org/10.6027/temanord2023-529

EMEP/EEA, 2019. EMEP/EEA air pollutant emission inventory guidebook 2019, EEA Report No. 13/2019, European Environment Agency, Copenhagen. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

Ginzburg, V.A., Zelenova, M.S., Korotkov, V.N. et al., 2022. Estimated Black Carbon Emissions from Priority Source Categories in Russia. Russ. Meteorol. Hydrol. 47, 781–790. https://doi.org/10.3103/S1068373922100065

Guevara, M., Petetin, H., Jorba, O., Denier van der Gon, H., Kuenen, J., Super, I., Jalkanen, J.-P., Majamäki, E., Johansson, L., Peuch, V.-H., and Pérez García-Pando, C., 2022. European primary emissions of criteria pollutants and greenhouse gases in 2020 modulated by the COVID-19 pandemic disruptions, *Earth Syst. Sci. Data*, 14, 2521–2552. https://doi.org/10.5194/essd-14-2521-2022

Höglund-Isaksson, Lena, et al, 2020. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe

–results from the GAINS model. Environ. Res. Commun. 2 025004. https://iopscience.iop.org/article/10.1088/2515-7620/ab7457

ICCT, 2017. Greenhouse Gas Emissions from Global Shipping, 2013–2015, Olmer, N., Comer, B., Roy, B., Mao, X. and Rutherford, D. https://theicct.org/publication/greenhouse-gas-emissions-from-global-shipping-2013-2015/

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Published: IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Jalkanen, J.-P., Johansson, L., and Kukkonen, J., 2016. A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011, Atmos. Chem. Phys., 16, 71-84, https://doi.org/10.5194/acp-16-71-2016

Johansson, L., J.-P. Jalkanen, and J. Kukkonen, 2017. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atm. Env., 167, 403-415, doi: https://doi.org/10.1016/j.atmosenv.2017.08.042

Kurokawa, J. and Ohara, T., 2020. Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3, Atmos. Chem. Phys., 20, 12761–12793. https://doi.org/10.5194/acp-20-12761-2020

Li, S., Wang, S., Wu, Q., Zhang, Y., Ouyang, D., Zheng, H., Han, L., Qiu, X., Wen, Y., Liu, M., Jiang, Y., Yin, D., Liu, K., Zhao, B., Zhang, S., Wu, Y., and Hao, J., 2023. Emission trends of air pollutants and CO2 in China from 2005 to 2021, Earth Syst. Sci. Data, 15, 2279–2294. https://doi.org/10.5194/essd-15-2279-2023

Nicely, J.M., R.J. Salawich, T. Canty, D.C. Anderson, S.R. Arnold, M.P. Chippereld, L.K. Emmons, J. Flemming, V. Huijnen, D.E. Kinnison, J.-F. Lamarque, J. Mao, S.A. Monks, S.D. Steenrod, S. Tilmes and S. Turquety, 2017. Quantifying the causes of differences in tropospheric OH within global models. Journal of Geophysical Research: Atmospheres, 122(3):1983–2007

Rantanen, M., Karpechko, A.Y., Lipponen, A. et al, 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168. https://doi.org/10.1038/s43247-022-00498-3

Saunois, M. et al, 2020. The Global Methane Budget 2000–2017, Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020.

Annex I – Synthesis of Arctic Council Member and Observer Country emissions of black carbon and methane according to national and independent estimates

Arctic Council Member States

Figure A 1. Total methane (top row) and black carbon (bottom row) emissions of Canada according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

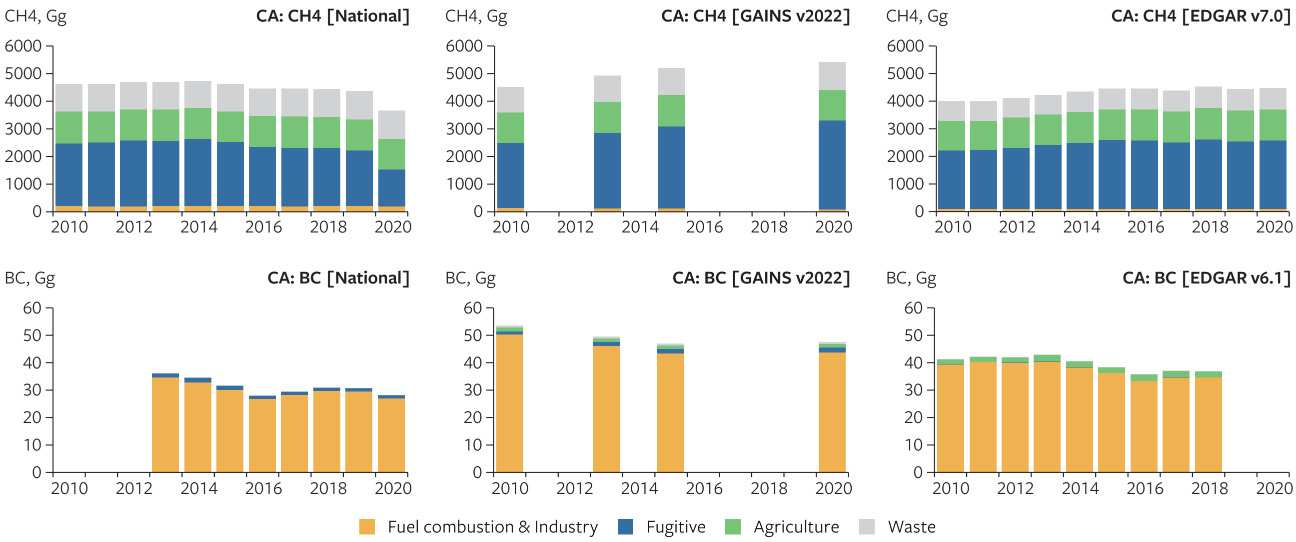


Figure A 2. Total methane (top row) and black carbon (bottom row) emissions of the United States of America according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

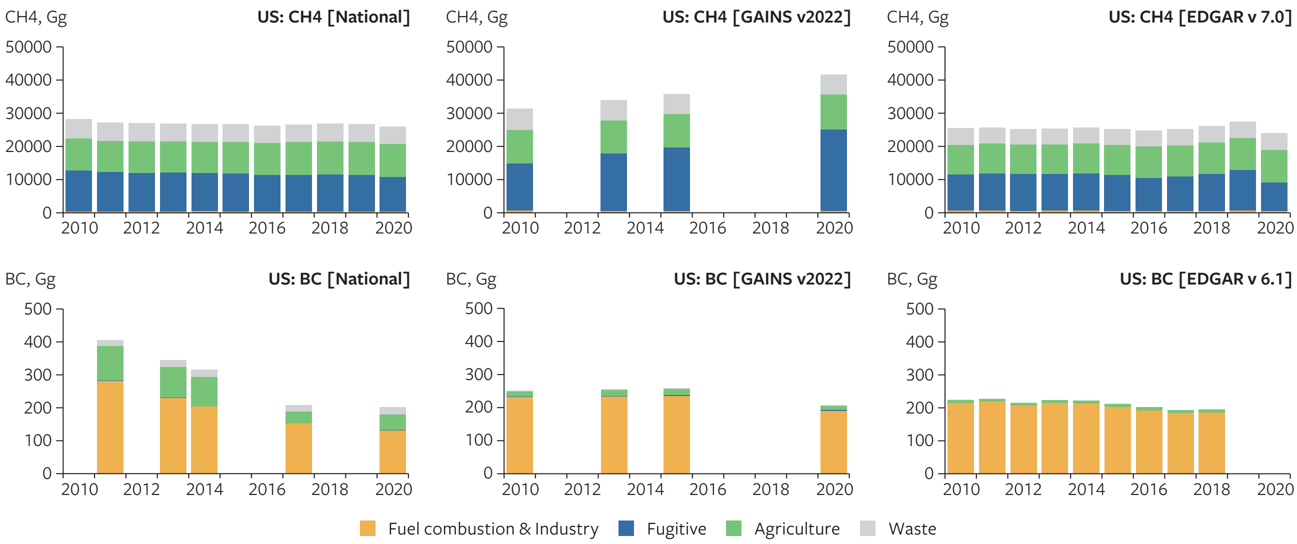


Figure A 3. Total methane (top row) and black carbon (bottom row) emissions of Denmark according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

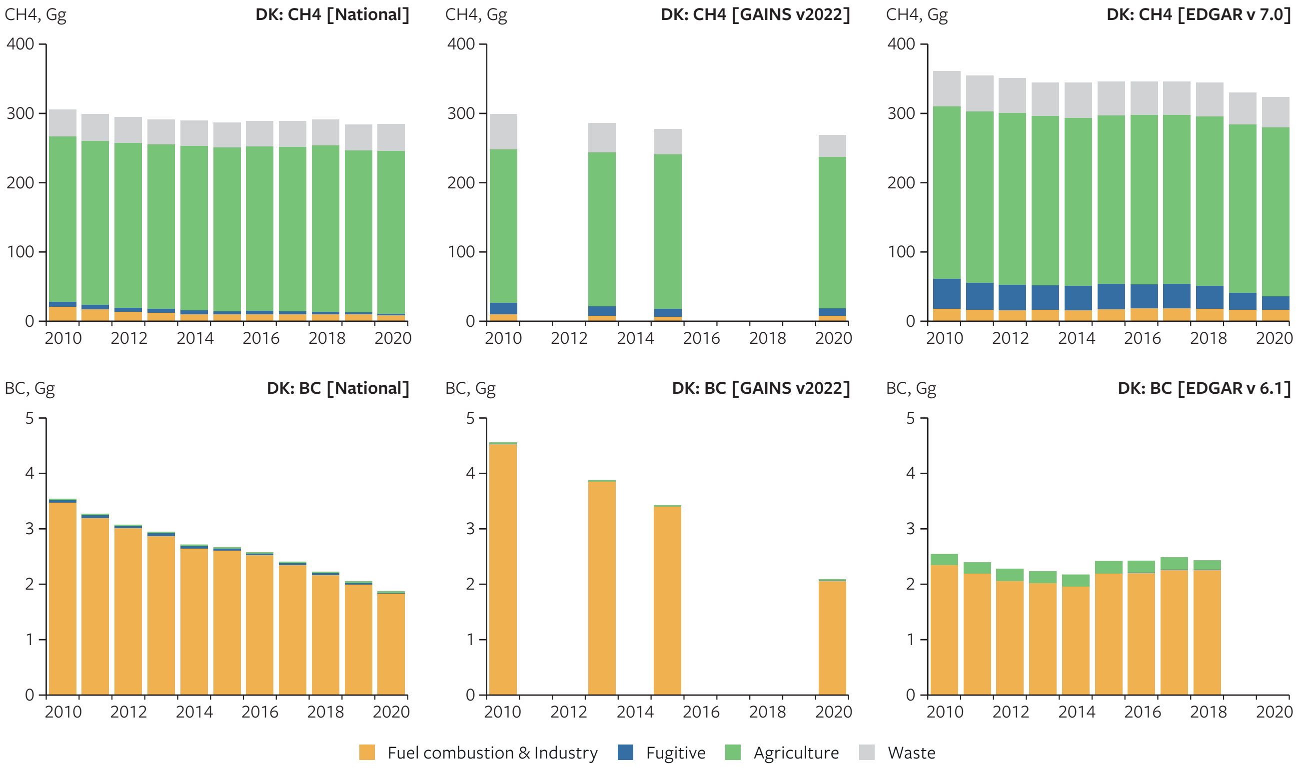


Figure A 4. Total methane (top row) and black carbon (bottom row) emissions of Finland according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

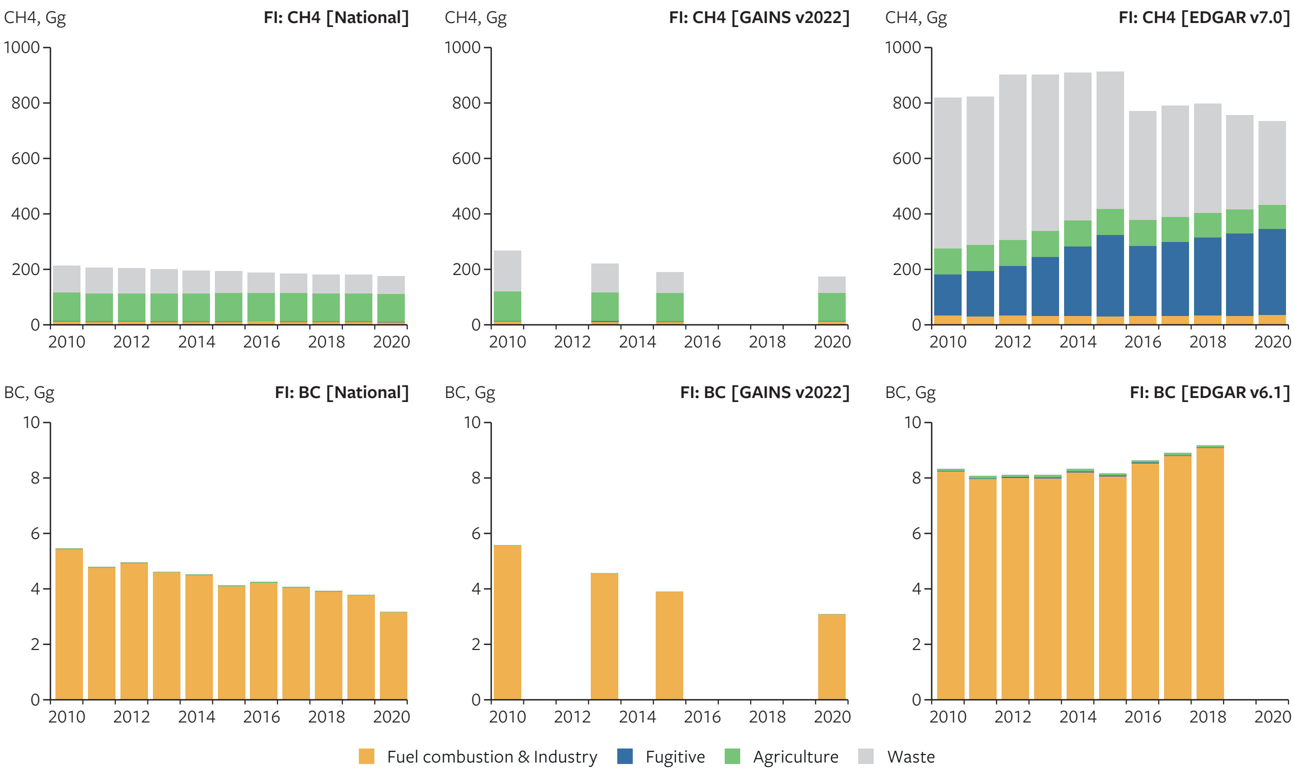


Figure A 5. Total methane (top row) and black carbon (bottom row) emissions of Iceland according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

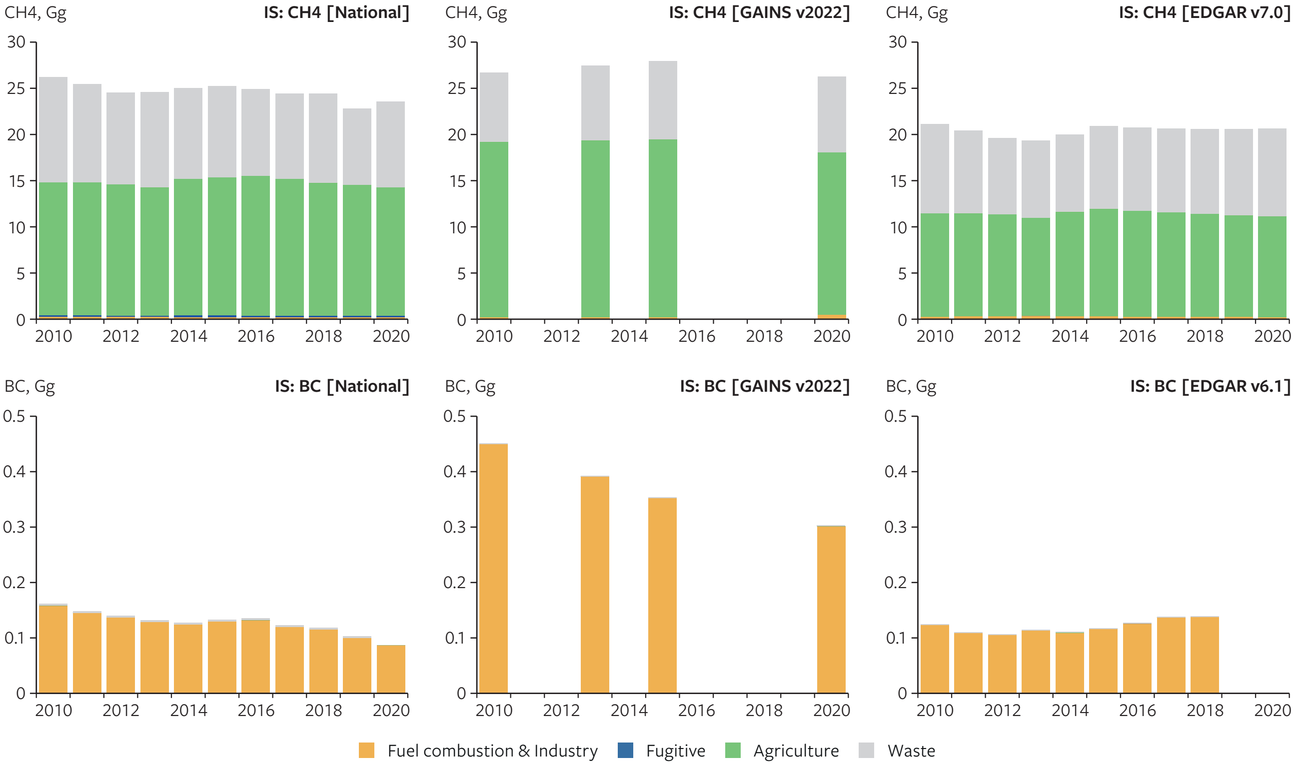


Figure A 6. Total methane (top row) and black carbon (bottom row) emissions of Norway according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

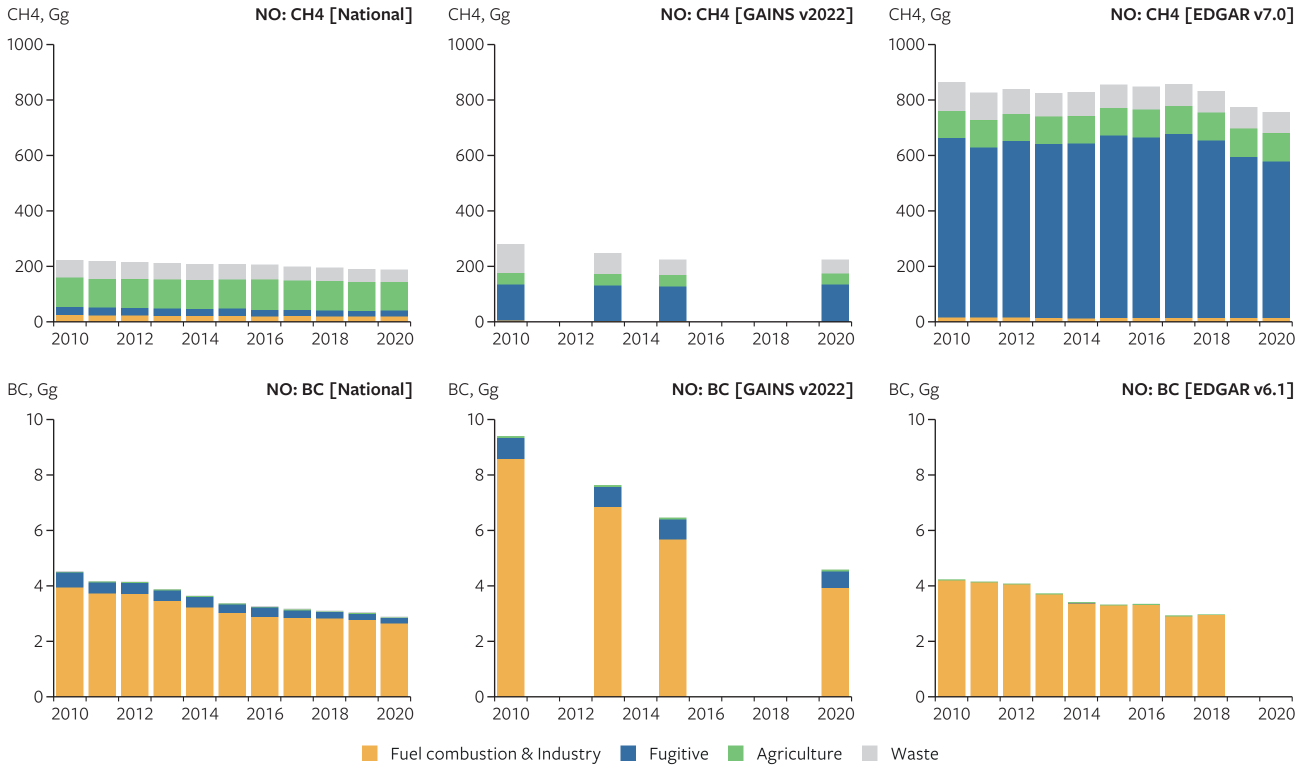


Figure A 7. Total methane (top row) and black carbon (bottom row) emissions of Russia according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

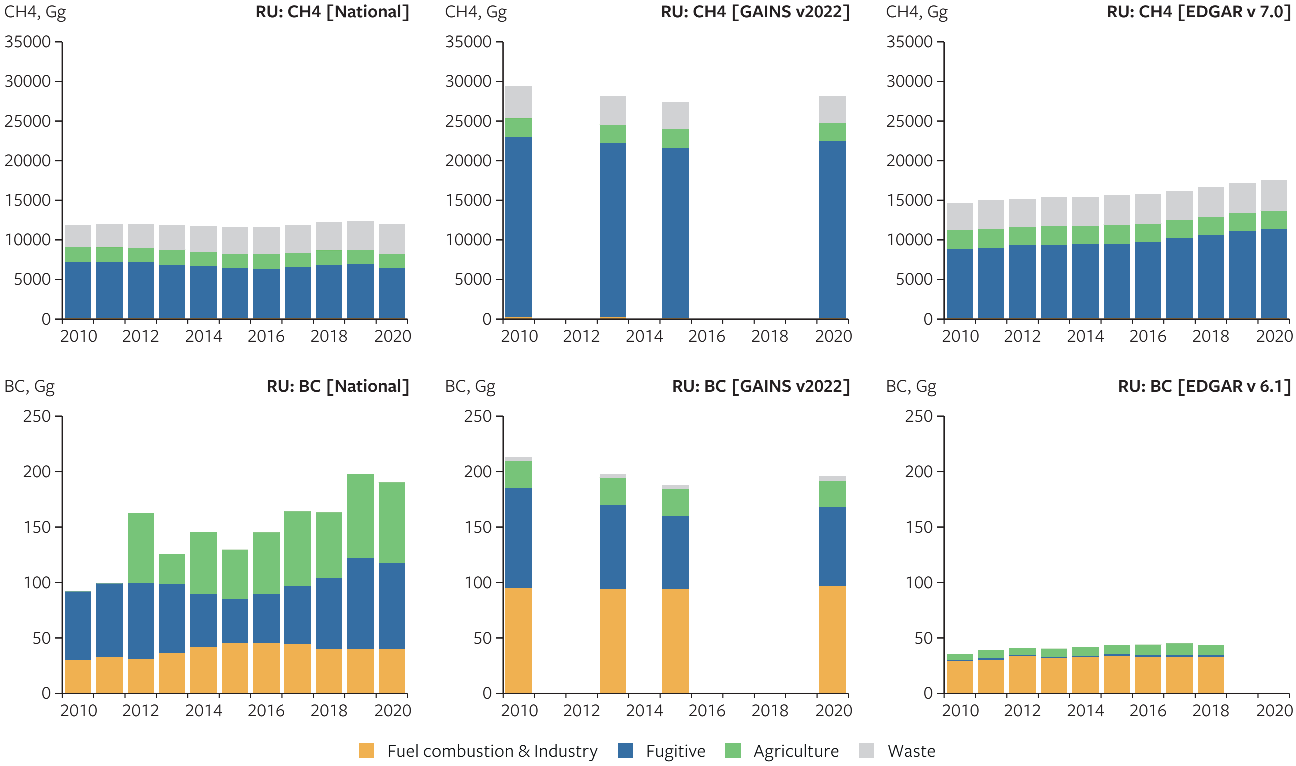
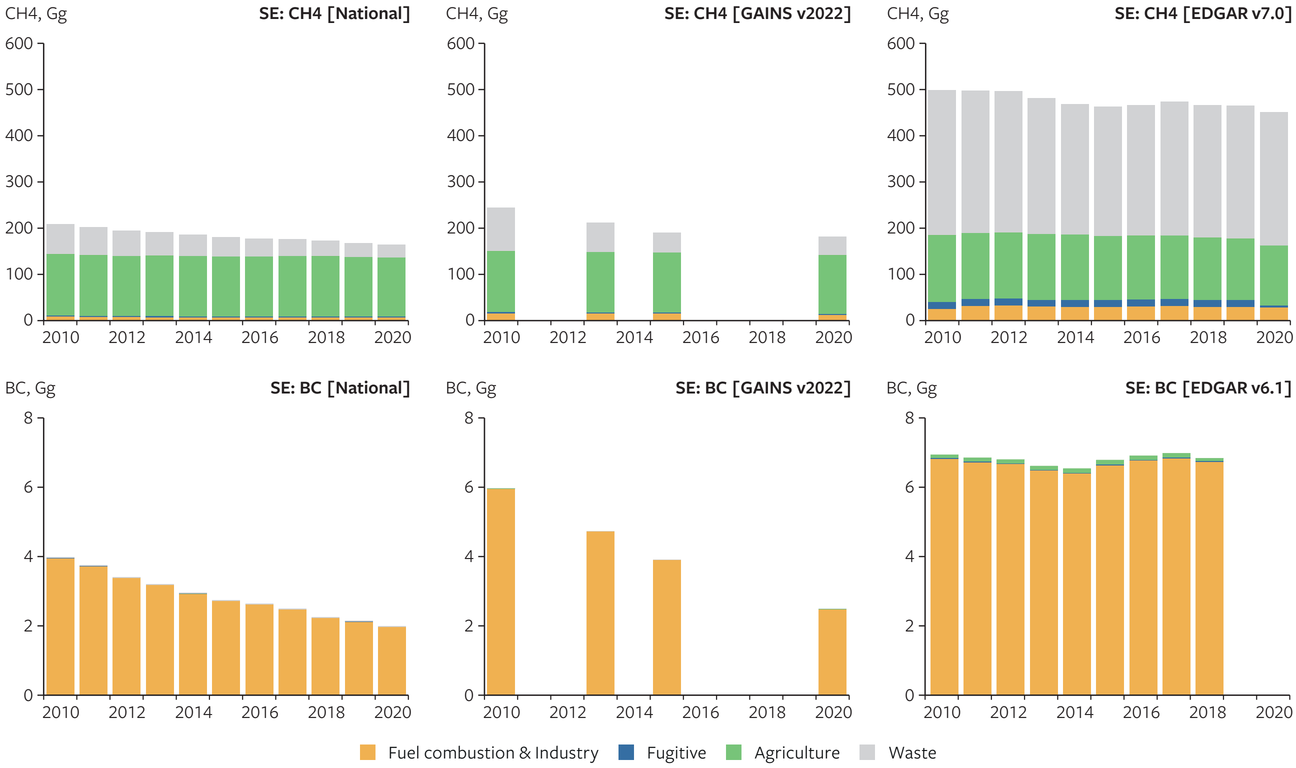


Figure A 8. Total methane (top row) and black carbon (bottom row) emissions of Sweden according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.



Arctic Council Observer States

Figure A 9. Total methane (top row) and black carbon (bottom row) emissions of Germany according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

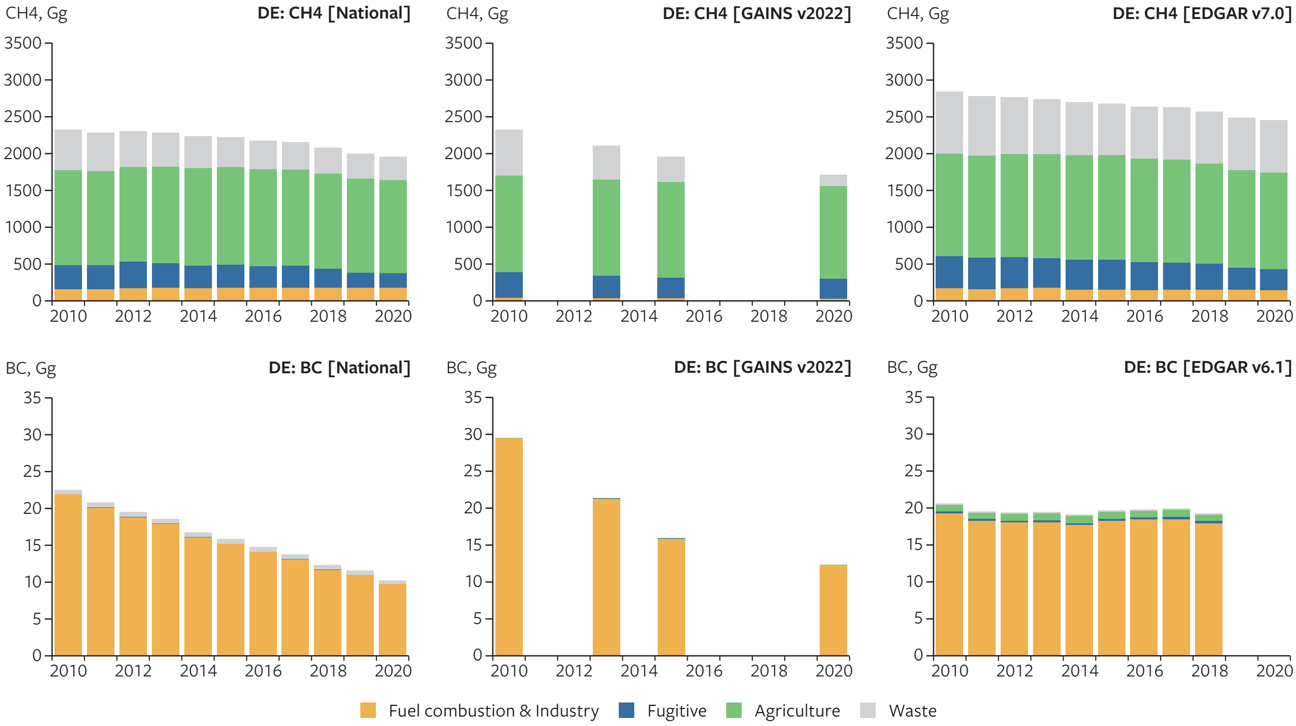


Figure A 10. Total methane (top row) and black carbon (bottom row) emissions of the Netherlands according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

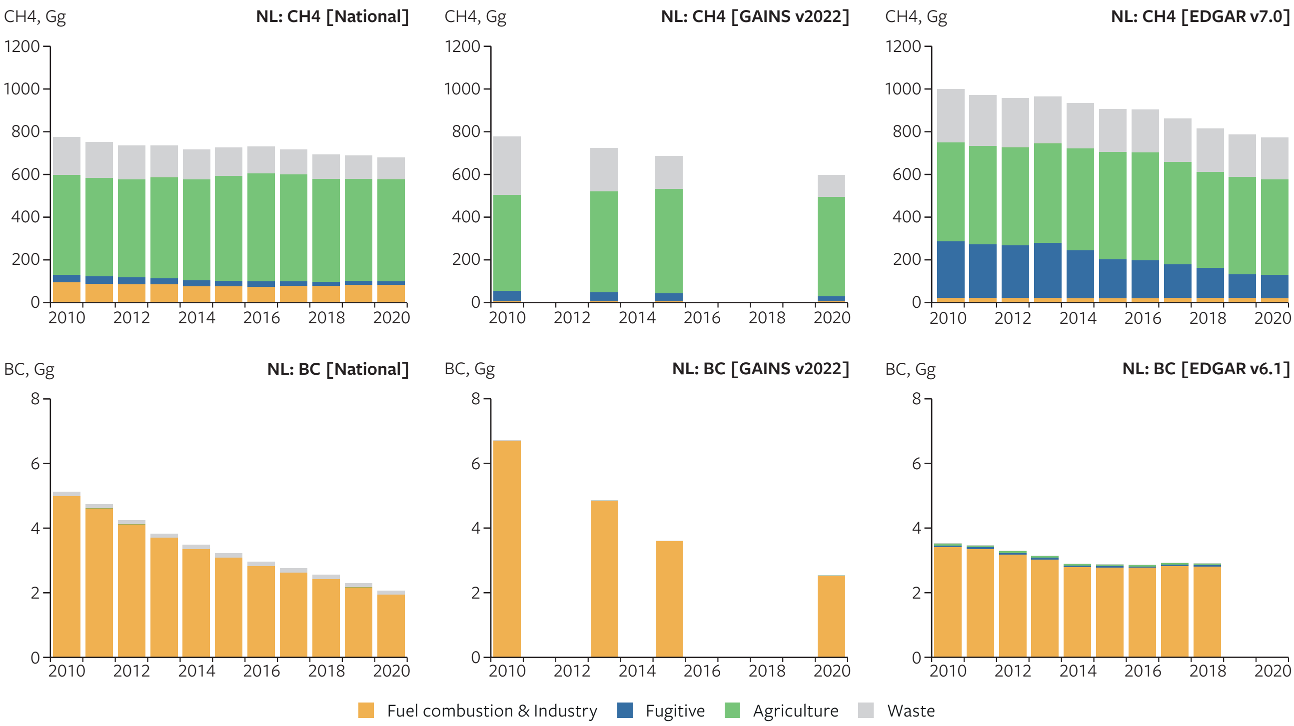


Figure A 11. Total methane (top row) and black carbon (bottom row) emissions of Poland according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

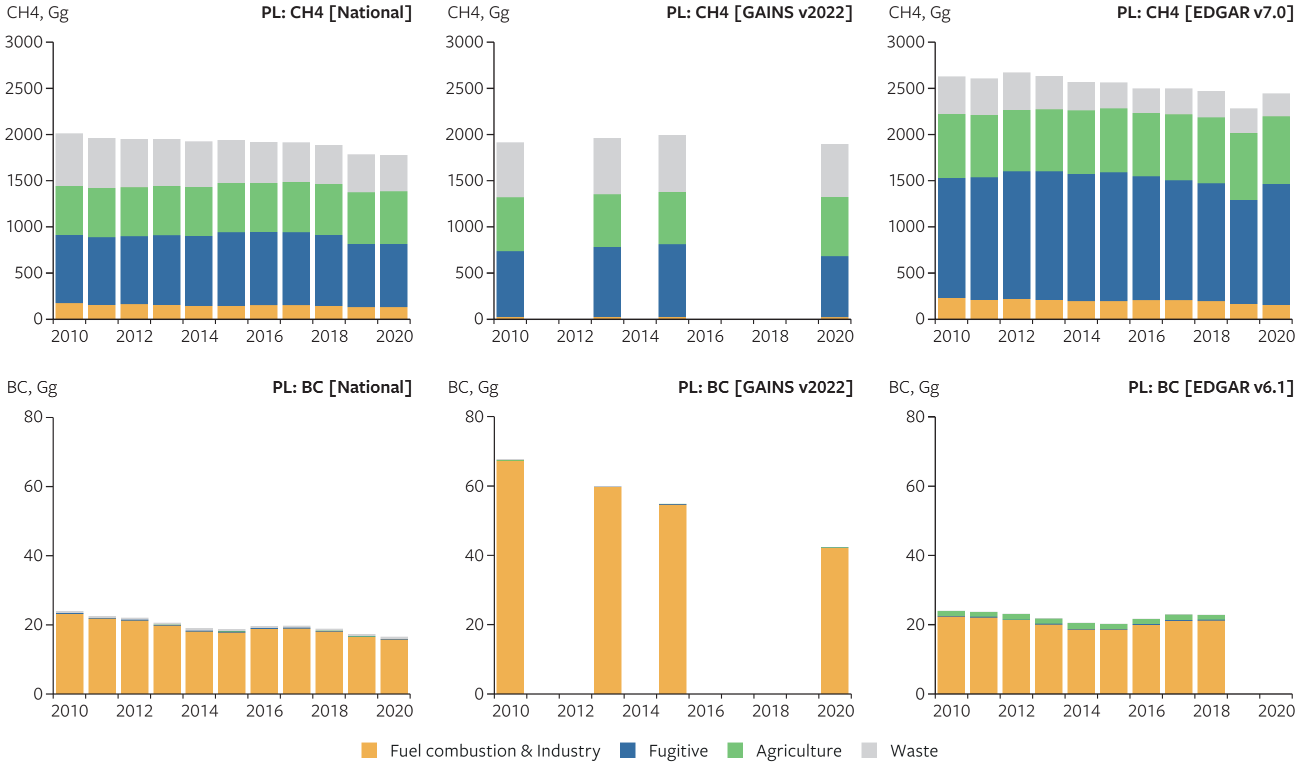


Figure A 12. Total methane (top row) and black carbon (bottom row) emissions of the United Kingdom according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

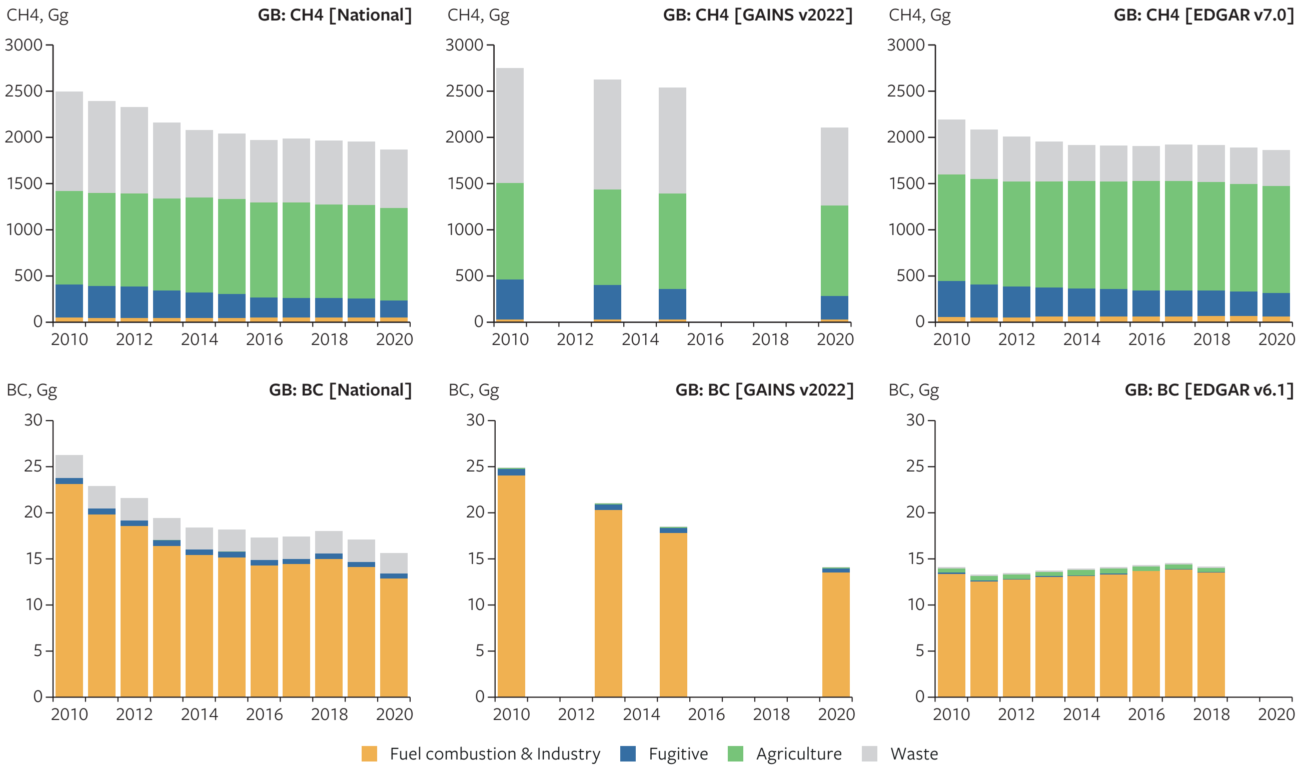


Figure A 13. Total methane (top row) and black carbon (bottom row) emissions of France according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

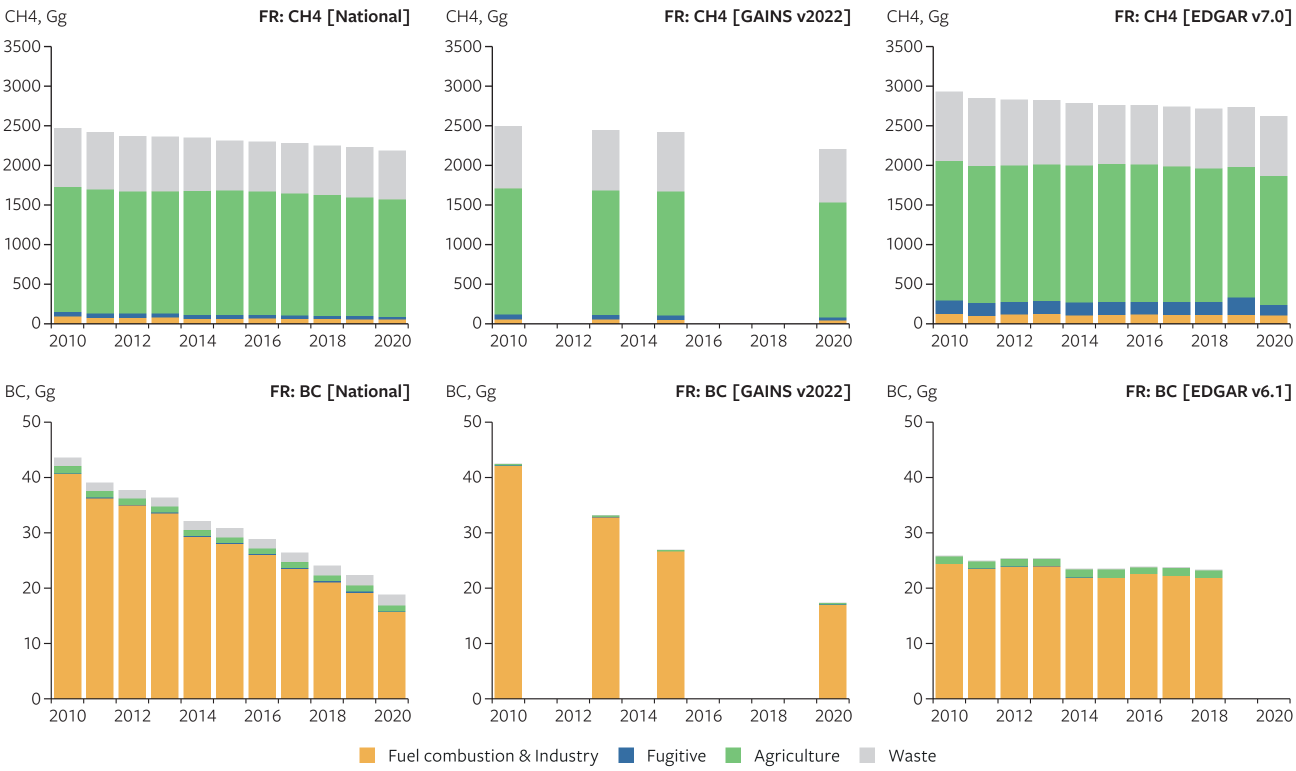


Figure A 14. Total methane (top row) and black carbon (bottom row) emissions of Spain according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

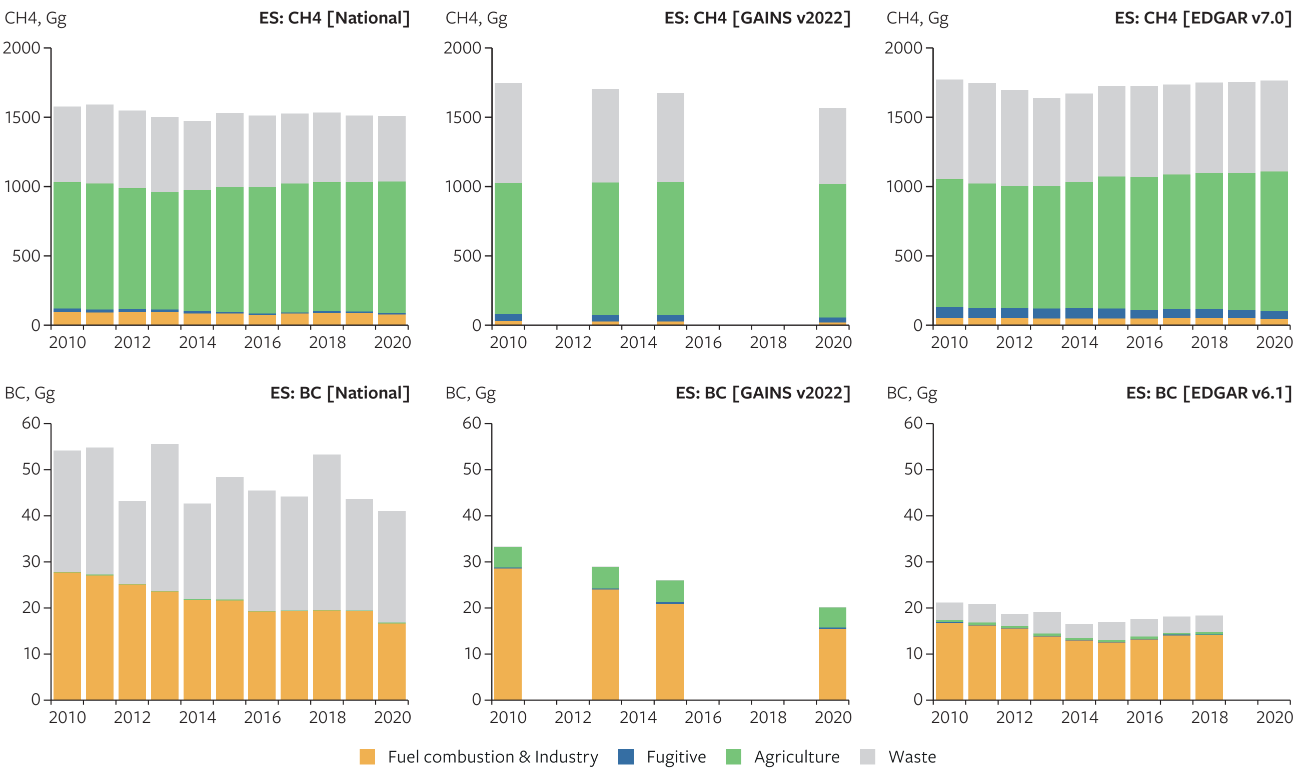


Figure A 15. Total methane (top row) and black carbon (bottom row) emissions of China according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

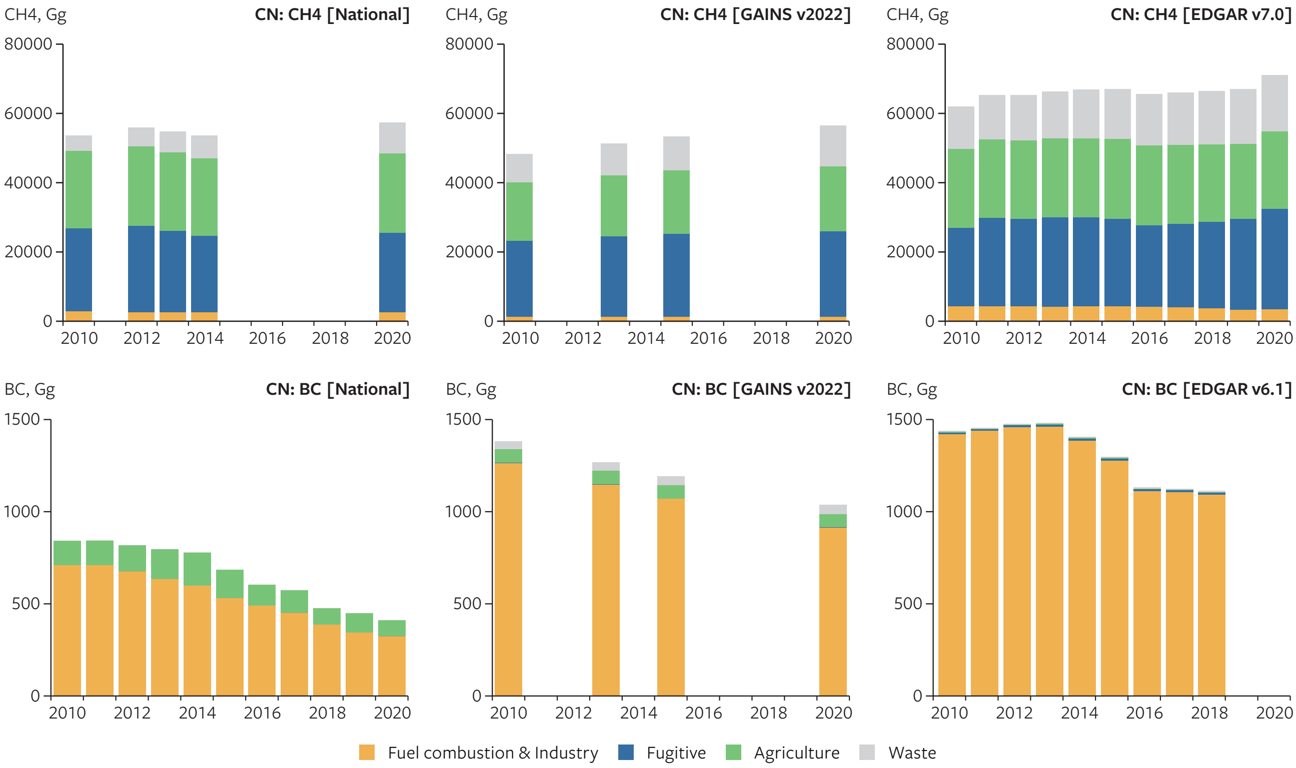


Figure A 16. Total methane (top row) and black carbon (bottom row) emissions of India according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

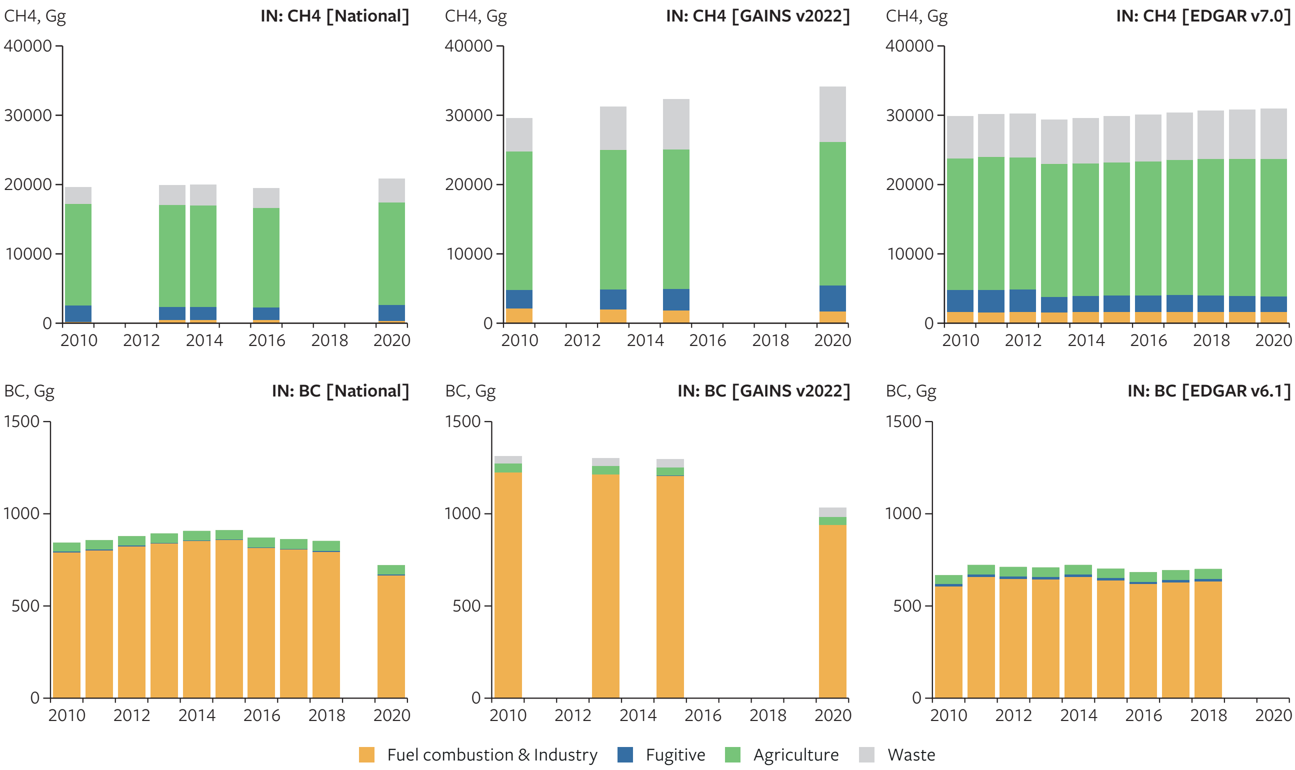


Figure A 17. Total methane (top row) and black carbon (bottom row) emissions of Italy according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

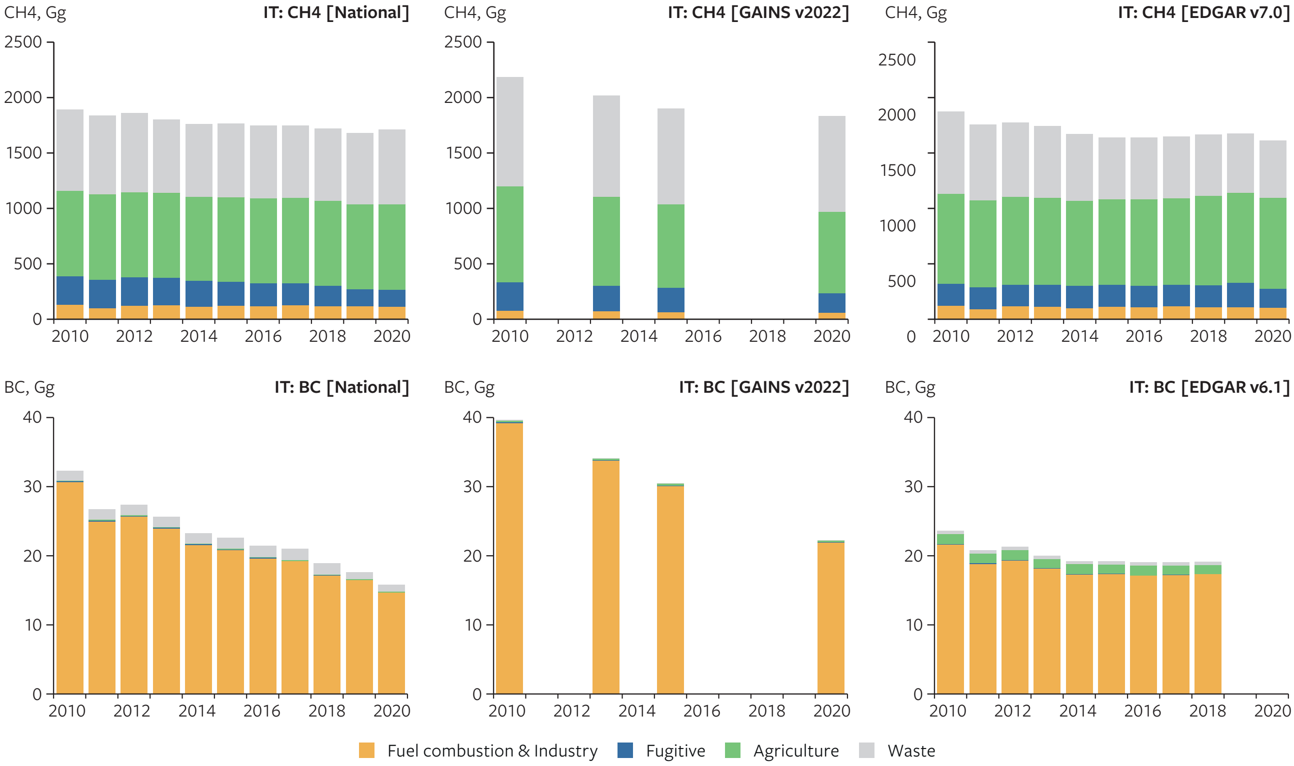


Figure A 18. Total methane (top row) and black carbon (bottom row) emissions of Japan according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

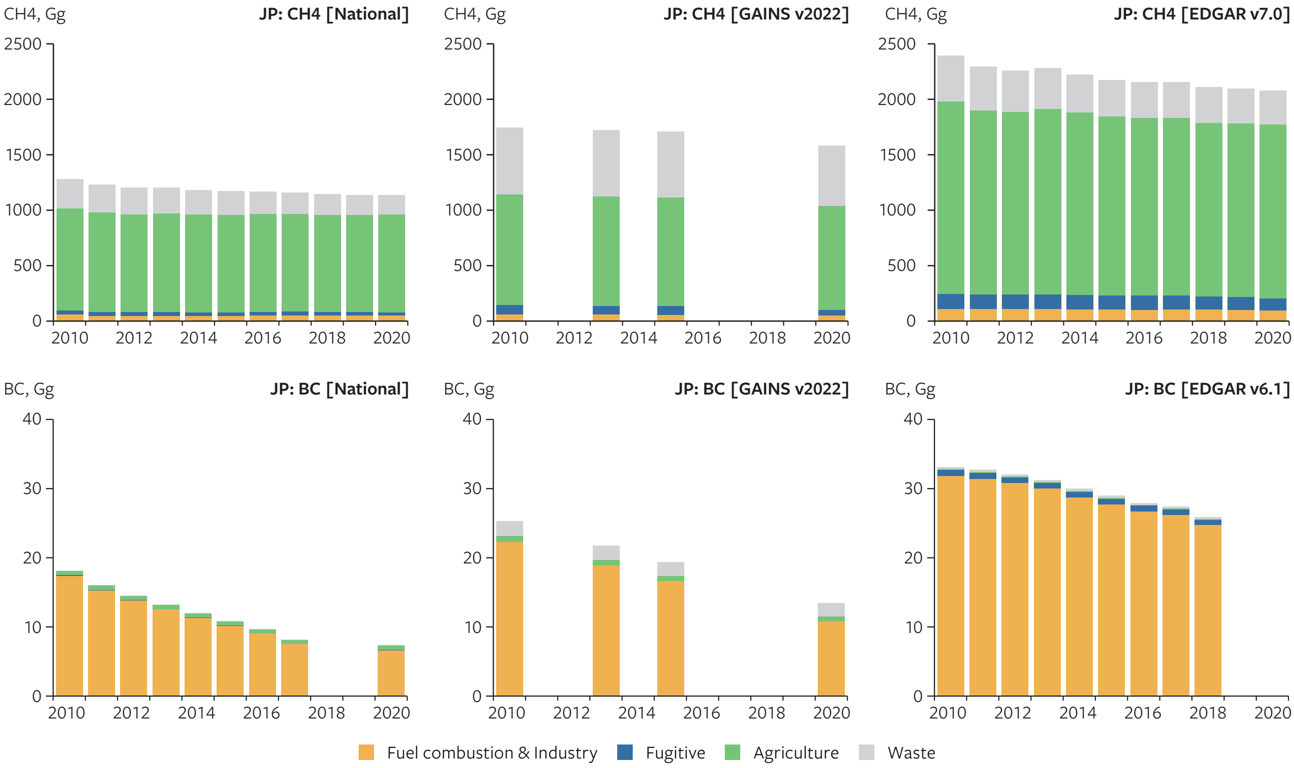


Figure A 19. Total methane (top row) and black carbon (bottom row) emissions of South Korea according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

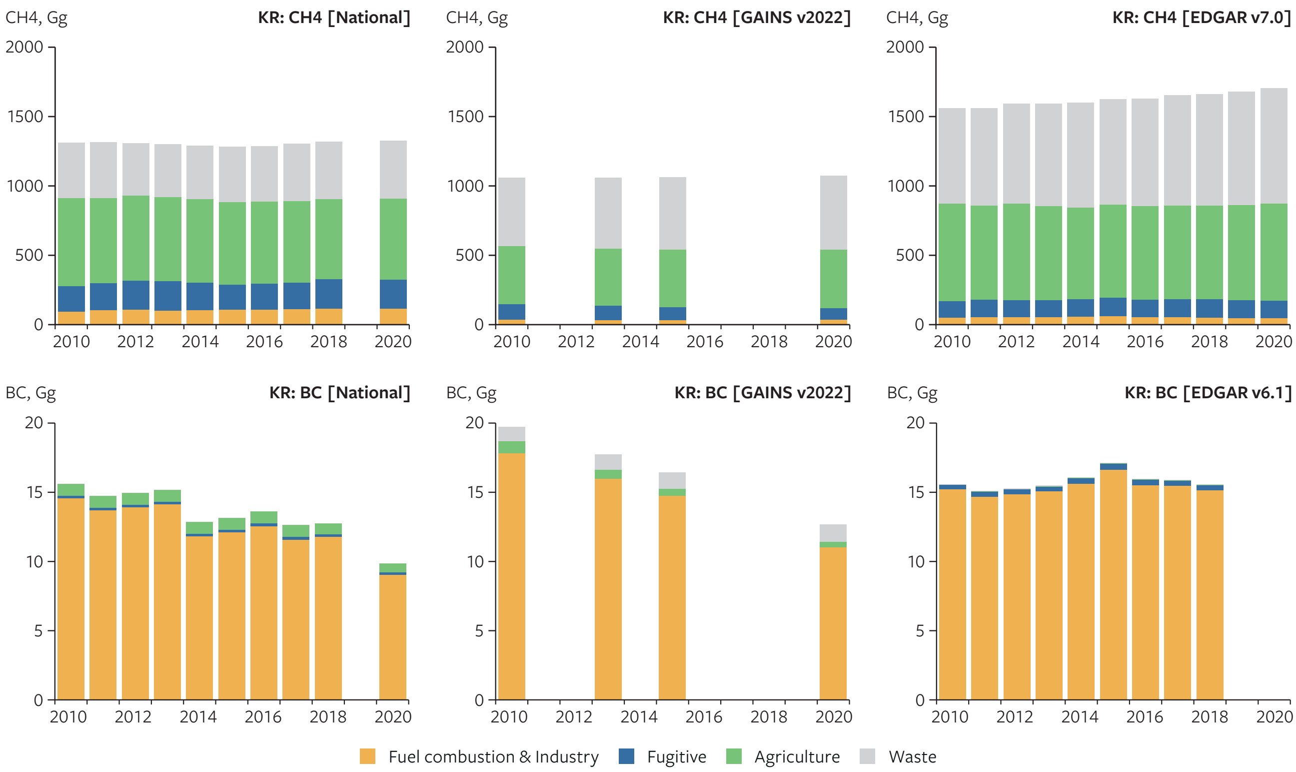


Figure A 20. Total methane (top row) and black carbon (bottom row) emissions of Singapore according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.

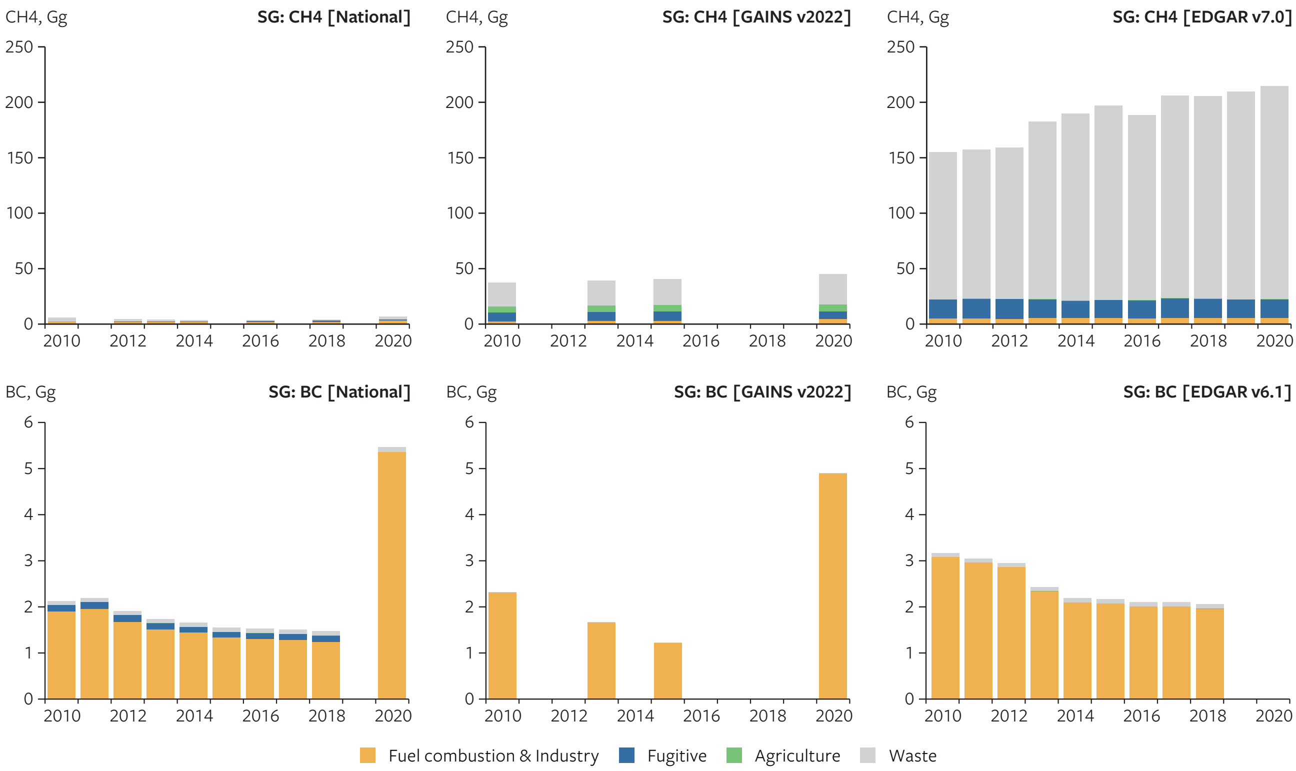
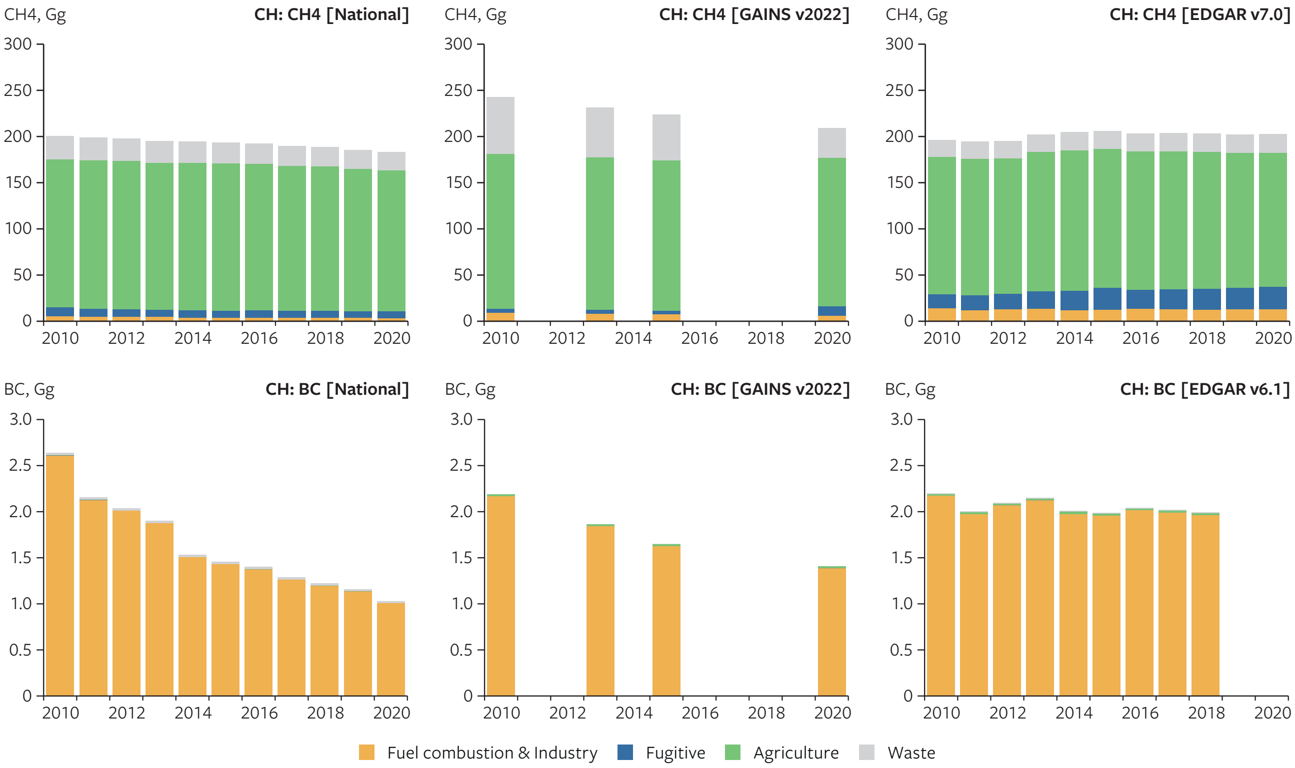


Figure A 21. Total methane (top row) and black carbon (bottom row) emissions of Switzerland according to national estimates (left) as well as independent estimates of GAINS (centre) and EDGAR (right). The bars show emissions only for the years where estimates are available and are stacked according to an aggregate sector split: Fossil fuel combustion for energy generation and industrial production, 1A+2; Fugitive emissions from fuels, 1B; Agriculture, 3; and Waste, 5. Emissions from Land use, land-use change and forestry (LULUCF) are not included.



Annex II – Review of inventory methods used by the Arctic Council Member States to estimate BC and CH4 emissions from selected sectors

This Annex summarizes the inventory methods used by the Arctic Council Member States to estimate BC and CH_4 emissions from priority sources. Sector-specific methods are briefly described in each of the respective subchapters. Despite sectoral specificities, the inventory methods for all sectoral BC and CH_4 emissions can be generalized. The EMEP/EEA Guidebook (EMEP/EEA, 2019) mostly recommends that black carbon emissions are calculated as a fraction of particulate matter emissions and also assumes that elemental carbon (EC) and black carbon (BC) are the same. Methane emissions are calculated using explicit methane emissions factors according to the 2006 IPCC Guidelines (IPCC, 2006) and the 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019).

Mostly, black carbon factors are given as a dimensionless proportion of $PM_{2.5}$ emissions (F_{BC}) rather than as an emission factor per se (EF_{BC}). As such, the inventory equation for black carbon emissions typically takes the form: $E_{BC} = AD \times EF_{PM2.5} \times F_{BC}$ (EMEP/EEA, 2019), where AD refers to activity data. For CH_4 emissions with explicit CH_4 emissions factors, the general equation takes the form: $E_{CH4} = AD \times EF_{CH4}$ (IPCC, 2006; IPCC, 2019). Of course, the general inventory approach can be applied within methodologies of varying complexity, so called *Tiers*, whereby it is assumed that the higher the Tier, the more accurate the emission estimate. While the differences between Tiers are source-specific, the three tier-levels can generally be differentiated as such

- Tier 1 method (T1): Activity data is derived from readily available national statistical information (e.g. energy statistics, statistics on industrial or agricultural production) and is applied at a national/aggregated resolution. Aggregate emission factors, applied at this resolution, are provided by the EMEP/EEA Guidebook, the IPCC Guidelines or other sources and are typically global factors or average factors representative of a region rather than of the specific countries.
- Tier 2 method (T2): The main difference to a T1 method is that the aforementioned national statistics are further resolved. For instance, consumption of certain fuels are further resolved by combustion technologies or statistics on e.g. burning of crop residues is resolved at the crop type level. Specific and more resolved T2 emission factors are applied at this level and can be sourced from the EMEP/EEA Guidebook, the IPCC Guidelines and/or scientific literature, and/or the emission factors are country-specific, i.e. have been derived from national research projects to best reflect national circumstances.
- Tier 3 methods: These methods are more sophisticated than the two Tiers above and typically involve a further resolution of the national activity data, e.g. subnational statistics and emission factors, facility level statistics, or even measurements. Tier 3 methods can furthermore involve the development and implementation of country-specific models that consider process-based understanding and more dynamic, non-linear relationships between activity and emissions.

Often the difference between Tier 2 and Tier 3 methods can be difficult to assess and consequently the analysis below focused on differentiating between Tier 1 and Higher Tier (T2/T3) methods. Furthermore, in the case of BC, the analysis evaluated both the underlying methodology for particulate emissions and the corresponding complexity of the applied BC fraction(s). If a single BC fraction was applied to sectoral PM emissions, these fractions were categories as Tier 1. Cases where more resolved fractions or a country-specific fraction were applied were categorised as Higher Tier BC fractions. To categorise the inventory methods applied, the following analysis evaluated the BC/CH_4 data and methods reported in the respective Informative Inventory Reports (IIRs) and National Inventory Reports (NIRs) reported in 2022 to the UNECE Air Convention[1] and the UNFCCC[2]. While the US reported national total- and sectoral BC emissions to the Air Convention, the US did not report an accompanying IIR document. The analysis of the US inventory methods therefore assessed the information provided in its National Report to the Arctic Council (US, 2021). While Russia has yet to report BC emissions under the Air Convention, the analysis does evaluate the methods used in the national BC emission inventory published in Ginzburg et al (2022).

1 https://www.ceip.at/status-of-reporting-and-review-results/2022-submission

2 https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-inventory-submissions-2022

Road transport (1A3b)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the sectors road transport (1A3b) and off-road transport the EMEP/EEA Guidebook suggests the use of activity data sources that include vehicle fleet numbers and statistics. Higher Tier methods require activity data such as vehicle kilometers and the distribution of the vehicle fleet. For these sectors, BC is calculated as a fraction of $PM_{2.5}$.

The Tier 1 method (T1) uses the formula emission of the pollutant equals the fuel consumption of the vehicle category times the fuel consumption specific emission factor of the pollutant. Tier 1 emission factors for PM and BC fractions can be found in the EMEP/EEA Guidebook, while the IPCC Guidelines provide respective Tier 1 emission factors for CH_4. There are different EFs for different car types (e.g. passenger cars, light duty vehicles) and fuel types, namely Diesel and Petrol.

The main difference of the Tier 2 method (T2) is that it requires detailed technology information. Tier 2 introduces fuels used by different vehicle categories, as well as their emission standards.

The Tier 3 method (T3) introduces several additional factors, such as vehicle kilometers, driving conditions and others in order to calculate emissions with a more sophisticated calculation model. The Tier 3 approach proposed in the EMEP/EEA Guidebook, for example, is implemented within the COPERT model[3].

Reporting of emissions and methods used by the AC Member States

Table A 1 shows that seven out of eight AC Member States provided values for road transport. All except one also included activity data in their submission under the Air Convention. Most countries that provided BC emissions used a Higher Tier method to calculate BC emissions and implemented road transport models like COPERT or HBEFA[4]. While Russia does not report BC under the Air

Table A 1: Overview of BC emission data reporting for road transport under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	$PM_{2.5}$ Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	1A3b	values	„NR“	-	Higher Tier	Higher Tier	US SPECIATE 4.4 Database	
DK	1A3b	values	values	Liquid fuels, Gaseous fuels, Biomass, Other (Mkm)	Higher Tier	Higher Tier	COPERT v5 / EEA (2019)	
FI	1A3b	values	values	Liquid fuels, Gaseous fuels, Biomass	Higher Tier	T1	EEA (2019)	
IS	1A3b	values	values	Liquid fuels, Biomass, Other activity (Mileage [10^6km])	Higher Tier	Higher Tier	COPERT v5 / EEA (2019)	
NO	1A3b	values	values	Liquid fuels, Gaseous fuels, Biomass, Other (10^6km)	Higher Tier	Higher Tier	HBEFA model/ Kupiainen and Klimont (2004)	
RU	1A3b	„NE“	„NE“, „NA“, „NO“	-	-	-	-	Ginzburg et al (2022) paper refers to the use of the COPERT model.
SE	1A3b	values	values	Liquid fuels, Gaseous fuels, Biomass, Other activity (Mileage [10^6km])	Higher Tier	Insufficient information	HBEFA model	
US	Mobile Onroad	values	-	-	Higher Tier	Higher Tier	Model-inherent speciation profile	values for 2017, 2014, 2011

3 https://www.emisia.com/utilities/copert/

4 https://www.hbefa.net/

Convention, the BC road transport emissions reported in Ginzburg et al (2022) refer to the use of the COPERT model and thus a Higher Tier approach.

Table A 2 illustrates that for CH_4 emissions reported under the UNFCCC, all AC Member States provided values and activity data for Road transport. It was evident for all countries that a Higher Tier approach was used to calculate emissions.

Off-road transport (1A2gvii, 1A3c,1A4aii, 1A4bii, 1A4cii, 1A5b)

Reporting of emissions and methods used by the AC Member States

Table A 4 illustrates that all Arctic Council Members except Russia reported emission values for at least one of the categories listed in Table A 3. For off-road transport, BC

Table A 2: Overview of CH_4 emission data reporting for road transport under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology
CA	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
DK	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
FI	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
IS	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
NO	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
RU	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
SE	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier
US	1A3b	values	values	Gasoline, Diesel Oil	Higher Tier

Table A 3: Off-road NFR subsectors analysed for this report

NFR Code	Long Name
1A2gvii	Mobile Combustion in manufacturing industries and construction: (please specify in the IIR)
1A3c	Railways
1A4aii	Commercial/institutional: Mobile
1A4bii	Residential: Household and gardening (mobile)
1A4cii	Agriculture/Forestry/Fishing: Off-road vehicles and other machinery
1A5b	Other, Mobile (including military, land based and recreational boats)

Table A 4: Overview of BC emission data reporting for off-road transport under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	$PM_{2.5}$ Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	Off-road transport	values	„NR“	-	Higher Tier	Higher Tier	US SPECIATE 4.4 Database	
DK	Off-road transport	values	values	Liquid fuels, Biomass	Higher Tier	T1	EEA (2019)	
FI	Off-road transport	values*	values*	Liquid fuels, Biomass	Higher Tier	T1	EEA (2019)	*no 1A5b reported, AD „IE“
IS	Off-road transport	„IE“, „NO“, values*	values	Liquid fuels	Higher Tier	T1	EEA (2019)	*“IE“ and „NO“ for emissions and AD, some values for some years reported for 1Agvii & 1A4cii
NO	Off-road transport	values	values	Liquid fuels, Gaseous fuels, Biomass	Higher Tier	Higher Tier	HBEFA model/ Kupiainen and Klimont (2004)	
RU	Off-road transport	„NE“	values	Liquid fuels				Ginzburg et al (2022) paper refers to the use of a T1 method.
SE	Off-road transport	values	values*	Liquid fuels, Biomass	Higher Tier	T1	EEA (2019)	*For 1A5b AD „IE“
US	Off-road transport	values	-	-	Higher Tier	Higher Tier	Model-inherent speciation profile	values for 2017, 2014, 2011

emissions are calculated as a fraction of $PM_{2.5}$ emissions. Most countries use the proposed from Tier 1 emission factor from the EMEP/EEA Guidebook. While Russia does not report BC under the Air Convention, the information provided in Ginzburg et al (2022) indicates that a Tier 1 method was applied to produce the off-road transport emissions of BC in the paper.

Table A 5 shows that all countries provided emissions values for CH_4 from at least one off-road transport source under the UNFCCC, as well as respective activity data for those. Information on the specific methodology was available in the NIR for all countries. Five countries were categorized as using Higher Tier methods to calculate off-road transport emissions of CH_4.

Residential combustion (1A4bi)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the sector residential combustion (1A4bi) the EMEP/EEA Guidebook suggests using activity data sources that range from statistics provided by national statistics institutes to energy balances from Eurostat and the International Energy Agency (IEA). For this sector, BC is calculated as percentage of $PM_{2.5}$.

The Tier 1 method (T1) uses the formula $E = AR_{fuelconsumption} \times EF$, whereas T1 EFs are provided in the EMEP/EEA Guidebook.

The main difference for the Tier 2 method (T2) is that the detailed methodology requires more fuel, technology and country-specific information. T2 emission factors take different appliances into account, such as boilers, fireplaces and stoves that use different fuel types.

A Tier 3 method (T3) takes into account facility level information as well as mitigation measures and other factors in order to enable a more sophisticated calculation model.

Reporting of emissions and methods used by the AC Member Countries

Eight Arctic Council Member States, six (Canada, Denmark, Finland, Iceland, Norway and Sweden) provided emission values in their reported submissions, whilst two countries provided either notation keys (“NE”, The Russian Federation) or no information at all (the United States). All countries except Canada (“NR”) and the United States (no information for this subsector provided) reported activity data (AD) in their Annex I submissions.

Two countries (Iceland and Sweden) calculated their black carbon emissions using Tier 1 BC fractions, with Iceland also applying a Tier 1 approach to the required PM emissions estimates. While Russia does not report BC under the Air Convention, the information provided in Ginzburg et al (2022) indicates that a Tier 1 method was applied to produce the residential emissions of BC in the paper. All other countries that provided emission values used a Higher Tier method to calculate their emissions (Table A 6).

As can be seen from Table A 7, all AC Member States provided CH_4 emission and activity data for residential combustion under the UNFCCC. Three countries (Iceland, Russia and Norway) used a Tier 1 method to calculate the emissions, whilst the other countries used a higher Tier method.

Fugitive emissions from the oil and gas industry (1B2a, 1B2b, 1B2c)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the categories 1B2a and 1B2c the EMEP/EEA Guidebook suggests using activity data, such as crude oil throughput for refineries, volume of gas flared, which can be measured instrumentally or calculated, as well as information from facility-level reports to model the process in more detail. BC is calculated as a fraction of $PM_{2.5}$.

Table A 5: Overview of CH_4 emission data reporting for off-road transport under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology
CA	Off-road transport	values	values	Liquid fuels, Biomass ...	Higher Tier
DK	Off-road transport	values	values	Liquid fuels, Biomass ...	Higher Tier
FI	Off-road transport	values	values	Liquid fuels, Biomass ...	Higher Tier
IS	Off-road transport	values	values	Liquid fuels, Biomass ...	T1
NO	Off-road transport	values	values	Liquid fuels, Solid fuels ...	Higher Tier
RU	Off-road transport	values	values	Liquid fuels, Solid fuels ...	T1
SE	Off-road transport	values	values	Liquid fuels, Solid fuels ...	Higher Tier
US	Off-road transport	values	values	Liquid fuels, Solid fuels ...	T1

Table A 6: Overview of BC emission data reporting for residential combustion under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	PM2.5 Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	1A4bi	values	„NR“	-	Higher Tier	Higher Tier	US SPECIATE 4.4 Database	
DK	1A4bi	values	values	Liquid fuels, Gaseous Fuels, Biomass	Higher Tier	Higher Tier	EEA (2019)	
FI	1A4bi	values	values	Liquid fuels, Solid fuels, Gaseous fuels, Biomass, Other fuels	Higher Tier	Higher Tier	National emission factors; but, no citation	
IS	1A4bi	values	values	Liquid fuels	T1	T1	EEA (2019)	
NO	1A4bi	values	values	Liquid fuels, Gaseous Fuels, Biomass	Higher Tier	Higher Tier	National emission factors; SINTEF (2013)	
RU	1A4bi	„NE“	values	Liquid fuels, Solid fuels, Gaseous fuels, Biomass	-	-		Ginzburg et al (2022) paper refers to the use of a T1 method.
SE	1A4bi	values	values	Liquid fuels, Solid fuels (0), Gaseous fuels, Biomass	Higher Tier	T1	EEA (2019)	
US	-	-	-	-	-	-	-	

Table A 7: Overview of CH_4 emission data reporting for residential combustion under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology	Note
CA	1A4bi	values	values	fuels (Liquid, gaseous, ...)	Higher Tier	
DK	1A4bi	values	values	fuels (Liquid, gaseous, ...)	Higher Tier	
FI	1A4bi	values	values	fuels (Liquid, solid, gaseous, ...)	Higher Tier	
IS	1A4bi	values	values	fuels (Liquid, solid, gaseous, ...)	T1	
NO	1A4bi	values	values	fuels (Liquid, gaseous, ...)	Higher Tier	
RU	1A4bi	values	values	fuels (Liquid, solid, gaseous, ...)	T1	
SE	1A4bi	values	values	fuels (Liquid, gaseous, ...)	Higher Tier	
US	1A4bi	values*	values*	fuels (Liquid, gaseous, ...)	T1	values for 2013, 2020

The Tier 1 method (T1) uses the formula $E = AR_{production} \times EF$, whereas there are no T1 EFs provided for BC in the EMEP/EEA Guidebook.

The main difference of the Tier 2 method (T2) is that it requires technology information. For calculating emissions from this source the production rate (AR) is multiplied with the Emission Factor (EF) for the technology used and then the results for all technologies are summed up. T2 emission factors consider specific appliances (for BC just “Refining, storage, fluid catalytic cracking – CO boiler”).

An example of a Tier 3 method (T3) would be to introduce separate estimates for each process as well as to add the impact of abatement systems installed to the equation in order to develop a more sophisticated calculation model.

The difference in Tiers for the calculation of CH_4 emissions follows the same principles described above.

Reporting of emissions and methods used by the AC Member States

Table A 8 lists the subsectors that are included in this sector. For the category 1B2b none of the AC Members provided emission data. A reason for this might be that there is no methodology for calculations described in the EMEP/EEA Guidebook. On the other hand, three countries (namely Denmark, Norway and Sweden) provided emission data for the categories 1B2a and 1B2c. Countries used a Tier 1 or Higher Tier methods to calculate the emissions, while for some countries insufficient information was available to assess the Tier used (Table A 9). While Russia does

Table A 8: NFR subsectors that contribute to fugitive emissions from the oil and gas industry

NFR Code	Long Name
1B2ai	Fugitive emissions oil: Exploration, production, transport
1B2aiv	Fugitive emissions oil: Refining / storage
1B2av	Distribution of oil products
1B2b	Fugitive emissions from natural gas (exploration, production, processing, transmission, storage, distribution and other)
1B2c	Venting and flaring (oil, gas, combined oil and gas)

Table A 9: Overview of BC emission data reporting for fugitive emissions under the Air Convention

AC Member	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	PM2.5 Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	1B2a	„NA“	„NR“	-				
CA	1B2b	„NA“	„NR“	-				
CA	1B2c	values	„NR“	-	Higher Tier	T1	McEwen (2013)	
DK	1B2a	„NA“	values	Other Activity (Mm3, Gg)	Insufficient information	Insufficient information	Insufficient information	1B2ai: 1990-2000, 2002, 2005, 2009, 2014, 2015; „NA“ for the other years/ categories
DK	1B2b	„NA“	values					1990-2000, 2002, 2005, 2009, 2014, 2015; „NA“ for the other years
DK	1B2c	values	values	Liquid fuels, Gaseous fuels, other activity (TJ)	T1	T1	EEA (2016)	
FI	1B2a	„NA“	„NA“	-				
FI	1B2b	„NA“	„NA“	-				
FI	1B2c	„IE“	„NA“	-				
IS	1B2a	„NO“, „NA“	„NO“, „NA“, Other fuels for 1B2av	-				
IS	1B2b	„NO“	„NO“	-				
IS	1B2c	„NO“	„NO“	-				
NO	1B2a	value (1B2aiv), „NA“	values	Other (Oil loaded (Mt), Crude Oil Refined (Mt), Oil Consumed (Mt)				
NO	1B2b	„NA“	„NA“					
NO	1B2c	values	values	Liquid fuels, Gaseous fuels, Biomass	Higher Tier	Higher Tier	McEwen and Johnson (2012)	
RU	1B2a	„NA“, „NE“	„NA“	-				
RU	1B2b	„NA“	„NA“	-				
RU	1B2c	„NE“	„NA“	-				Ginzburg et al (2022) paper refers to the use of a higher Tier method.
SE	1B2a	values, „C“, „NA“	values, „C“, „NA“, „NE“	Liquid fuels				
SE	1B2b	„NO“	„NA“	-				
SE	1B2c	values	values	Liquid fuels, Gaseous fuels	T1	Insufficient information	Insufficient information	
US	-	-	-	-				
US	-	-	-	-				
US	-	-	-	-				

not report BC under the Air Convention, the information provided in Ginzburg et al. (2022) indicates that a Higher Tier method was applied to estimate the BC emissions from gas flaring that are reported in the paper.

All AC Members States provided emissions and activity data for at least one of the categories responsible for fugitive CH_4 emissions. Most countries used a Higher Tier method to estimate emissions from this sector (Table A 10).

Table A 10: Overview of CH_4 emission data reporting for fugitive emissions under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology
CA	1B2a	values	values	Total crude production (m^3), number of oil wells + spills …	Higher Tier
CA	1B2b	values	values	Natural gas production (m^3), number of gas wells + spills …	Higher Tier
CA	1B2c	values	values	Total crude production, Natural gas production (m^3), number of wells drilled …	Higher Tier
DK	1B2a	values	values	Oil explored (m^3), Oil loaded, Oil refined …	Higher Tier
DK	1B2b	values	values	Gas explored (m^3), Gas produced, Gas distributed …	Higher Tier
DK	1B2c	values	values	Venting in gas terminals (GJ), Gas consumption (GJ) …	Higher Tier
FI	1B2a	values	values	kt oil refined	Insufficient information
FI	1B2b	values	values	PJ gas consumed, PJ gas distributed	Insufficient information
FI	1B2c	values	values	used fuels (TJ), kt oil refined, PJ gas consumed	Insufficient information
IS	1B2a	values	values	oil distributed (TJ)	T1
IS	1B2b	„NO“	„NO“	-	-
IS	1B2c	„NO“	„NO“	-	-
NO	1B2a	values	values	Exploration wells, Oil produced (m^3), Oil loaded in tankers (PJ), …	Higher Tier
NO	1B2b	values	values	Exploration wells, gas produced (m^3), Gas processed (PJ), …	Higher Tier
NO	1B2c	values	values	Oil and gas produced (PJ), Oil / Gas flared (PJ) …	Higher Tier
RU	1B2a	values	values	Oil produced (m^3), Oil transported by pipeline, oil refined …	Insufficient information
RU	1B2b	values	values	Natural gas produced (m^3), Marketable gas, Gas consumend	Insufficient information
RU	1B2c	values	values	Oil and Condensate produced (m^3), Associated gas flaring, …	Insufficient information
SE	1B2a	values	values	Consumption of feedstock (TJ), Transported amount of oil (m3), …	Higher Tier
SE	1B2b	values	„NO“, „NA“	-	Higher Tier
SE	1B2c	values	values	Venting of gas products (m3), Venting of oil products (TJ), …	Higher Tier
US	1B2a	values	values	Annual domestic production (Bbl), Refinery Feed, Abandoned wells	Higher Tier
US	1B2b	values	values	Annual production (ft^3), Consumption	Higher Tier
US	1B2c	„IE“	„NA“	-	-

Open burning of agricultural residues (3F)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the open burning of agricultural residues (3F) the EMEP/EEA Guidebook suggests using the mass of residue burnt (in kg dry matter) as activity rate ($AR_{residue\_burnt}$). As opposed to the other categories, BC emissions are not calculated as a fraction of $PM_{2.5}$ emissions for this sector.

The Tier 1 method (T1) uses the formula $E = AR_{residue\_burnt} \times EF$, whereas T1 EFs are provided in the EMEP/EEA Guidebook.

The main difference of the more detailed Tier 2 method (T2) is that it requires technology information. T2 emission factors consider specific crop types (e.g.: burning wheat, maize, barley, rice) and are equal to those for elemental carbon.

There is no Tier 3 method (T3) described in the EMEP/EEA Guidebook.

The difference in Tiers for the calculation of CH_4 emissions follows the same principles described above.

Reporting of emissions and methods used by the AC Members

Out of eight AC Member States, four (Denmark, Finland, Norway and the US) provided BC emission values for the sector 3F. Only the US used a Higher Tier method to calculate the emissions. While Russia does not report BC under the Air Convention, the information provided in Ginzburg et al (2022) indicates that a mix of default (tier) and country-specific parameters and emission factors were applied to estimate the BC emissions from open burning of agricultural residues that are reported in the paper (Table A 11).

Five AC Members provided CH_4 emissions values, most using a Tier 1 method to calculate the emissions. The United States use a Higher Tier method for the calculation. Finland's NIR did not clarify which tier method was used for the calculation of CH_4 emissions for the open burning of agricultural residues (Table A 12).

Table A 11: Overview of BC emission data reporting for the open burning of agricultural residues under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	PM2.5 Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	3F	„NA“	„NR“	-	-	-	-	
DK	3F	values	values	Other activity (Amount burned ton/yr)	T1	T1	EEA (2019)	
FI	3F	values	values	Other activity (kt dm3)	T1	T1	EEA (2019)	
IS	3F	„NO“	„NO“	-	-	-	-	
NO	3F	values	values	Other activity (Dry matter burned (tons))	T1	T1	EEA (2019)	
RU	3F	„NE“	„NA“	-	-	-	-	Ginzburg et al (2022) paper refers to the use of a default method mixed with country specific parameters and emission factors.
SE	3F	„NO“	„NA“	-	-	-	-	
US	Agricultural field burning	values	-	-	Higher Tier	Higher Tier	US SPECIATE Database	values for 2017, 2014, 2011

Table A 12: Overview of CH_4 emission data reporting for the open burning of agricultural residues under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	CH_4 Tier methodology	Note
CA	3F	values	values	Biomass available (t dm/ha), Combustion Factor, Total biomass burned (kt dm)	T1	-
DK	3F	values	values	Total biomass burned (kt dm), Other: grass seed fields (kt dm)	T1	-
FI	3F	values	values	Total biomass burned (kt dm)	Insufficient Information	Tier: CS („Country specific“) according to CRF
IS	3F	„NO,NE,NA“	„NO“	-	-	-
NO	3F	values	values	Total biomass burned (kt dm)	T1	-
RU	3F	„NO“	„NO“	-	-	-
SE	3F	„NO“	„NO“	-	-	-
US	3F	values	values	Area Burned, Biomass available (t dm/ha), Combustion Factor, Total biomass burned (kt dm)	Higher Tier	-

Open burning of waste (5C2)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the open burning of waste (5C2) the EMEP/EEA Guidebook suggests the use of activity data sources that include national statistics of areas of forestry and orchard, as well as the quantity of waste incinerated for different crops and the weight of waste produced per hectare for different types of farming for higher Tier levels. The EMEP/EEA Guidebook methods thus consider the burning of agricultural and forestry waste/residues that are not included under the category 3F. EMEP/EEA Guidebook does not provide emission factors for open burning of other waste materials (e.g. rubber tyres), likely reflecting the assumption that such activities are prohibited/not occurring in most of the EMEP countries. The IPCC guidelines, on the other hand, define open burning of waste as the combustion of unwanted combustible materials including paper, wood, plastics, textiles and rubber, which are burned in nature or open dumps.

For this sector, BC is calculated as a fraction of $PM_{2.5}$.

The Tier 1 method (T1) uses the formula $E = AR_{production} \times EF$, whereas T1 EFs are provided in the EMEP/EEA Guidebook, and are equal to those for elemental carbon.

The main difference of the detailed Tier 2 method (T2) is that the above equation is applied to different types of waste separately and with the emissions from the different waste types subsequently summed up. Tier 2 emission factors consider specific residues (e.g.: forest residues, orchard crops) and different types of waste.

An example of a Tier 3 method (T3) would be to introduce an estimation of the weight of waste produced per hectare for different types of farming in order to develop a more sophisticated calculation model.

The difference in Tiers for the calculation of CH_4 emissions follows the same principles described above.

Reporting of emissions and methods used by the AC Members

For open burning of waste the only AC Member State that reports BC emission data is Sweden. Russia does not report BC under the Air Convention. Furthermore, the Ginzburg et al (2022) paper does not provide estimates of BC emissions from this source (Table A 13).

None of the AC Member States reported CH_4 emissions for open burning of waste (Table A 14).

Table A 13: Overview of BC emission data reporting for the open burning of waste under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	PM2.5 Tier methodology	Tier of black carbon fraction	Source of BC fraction
CA	5C2	„NA“	„NR“	-	-	-	-
DK	5C2	„NE“	„NA“	-	-	-	-
FI	5C2	„NO“	„NO“	-	-	-	-
IS	5C2	„NO“	„NA“	-	-	-	-
NO	5C2	„NE“	„NA“	-	-	-	-
RU	5C2	„NE“	„NA“	-	-	-	Ginzburg et al (2022) paper does not provide estimates.
SE	5C2	values	„NA“	IIR	Higher Tier	Higher Tier	Johansson & Silvergren, (2021)
US	-	-	-	-	-	-	-

Table A 14: Overview of CH_4 emission data reporting for the open burning of waste under the UNFCCC

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology
CA	5C2	„NO,NE“	„NE,NA“	-	-
DK	5C2	„NO“	„NO“	-	-
FI	5C2	„NO,NE“	„NO,NE“	-	-
IS	5C2	„NO“	„NO“	-	-
NO	5C2	„NE,NO“	„NO,NE“	-	-
RU	5C2	„NO,NE“	„NO,NE“	-	-
SE	5C2	„NE“	„‘NO,NE“	-	-
US	5C2	„NA“	„NA“	-	-

Wildfires (4V / 11B)

Inventory methods according to the EMEP/EEA Guidebook and IPCC Guidelines

To calculate BC emissions for the sector wildfires (11B) the EMEP/EEA Guidebook suggests using activity data sources that include national statistics of areas of land burned. For this sector, BC is calculated as a fraction of PM2.5.

The Tier 1 method (T1) uses the formula $E = AR_{burnt} \times EF$, whereas T1 EFs are provided in the EMEP/EEA Guidebook.

For the Tier 2 method (T2) additional factors are added to the equation. In addition to the area of land burnt, the average fraction of carbon in fuel wood (0.45) as well as the average total biomass in the fuel material (B) are added to the equation. T2 emission factors take different forest types, such as boreal forests, into account.

A Tier 3 method (T3) would distinguish between the types of wood burnt in order to develop a more sophisticated calculation model.

The calculation of CH_4 emissions uses the same principle and is therefore not further described within this report.

Reporting of emissions and methods used by the AC Members

Only the United States reported emission values for wildfires within their submissions under the Air Convention. The United States provided emission values for the years 2011, 2014 and 2017 and stated in a technical support document that the values for BC are calculated as a fraction of PM2.5. While Russia does not report BC under the Air Convention, the information provided in Ginzburg et al (2022) indicates that a mix of default (tier) and country-specific parameters and emission factors were applied to estimate the BC emissions from wildfires that are reported in the paper (Table A 15).

On the other hand, all AC Member States reported emission values for CH_4 for the sector *4(V) – Biomass Burning*. Two countries use a Higher Tier to calculate emissions for this sector, namely Finland and Sweden, while three countries were assessed as using Tier 1 methods. For the remaining three countries, a categorisation of the inventory approach could not be made due to insufficient information (Table A 16).

Table A 15: Overview of BC emission data reporting for wildfires under the Air Convention

AC Member State	Subsector	Emissions reported (value/NK)	Activity data reported (blank/ value/NK)	Activity data type	PM2.5 Tier methodology	Tier of black carbon fraction	Source of BC fraction	Note
CA	11B	„NR“	„NR“	-	-	-	-	
DK	11B	„NE“	„NA“	-	-	-	-	
FI	11B	„NA“	„NA“	-	-	-	-	
IS	11B	„NR“	„NA“	-	-	-	-	
NO	11B	„NE“	„NA“	-	-	-	-	
RU	11B	„NE“	„NA“	-	-	-	-	Ginzburg et al (2022) paper refers to the use of a default method mixed with country specific parameters and emission factors.
SE	11B	„NE“	„NA“	-	-	-	-	-
US	Wildfires	values	-	-	Higher Tier	Tier 1	EPA (2020)	values for 2017, 2014, 2011

Table A 16: Overview of CH_4 emission data reporting for wildfires under the UNFCCC

AC Member	Subsector	Emissions reported (value/NK)	Activity data reported (blank/value/NK)	Activity data type	CH_4 Tier methodology
CA	4(V)	values	values	ha	Insufficient Information
DK	4(V)	values	values	ha	Insufficient Information
FI	4(V)	values	values	ha	Higher Tier
IS	4(V)	values	values	ha	T1
NO	4(V)	values	values	ha	T1
RU	4(V)	values	values	ha	Insufficient Information
SE	4(V)	values	values	ha	Higher Tier
US	4(V)	values	values	ha	T1

References

EMEP/EEA, 2019. EMEP/EEA air pollutant emission inventory guidebook 2019, EEA Report No. 13/2019, European Environment Agency, Copenhagen. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

Ginzburg, V.A., Zelenova, M.S., Korotkov, V.N. et al., 2022. Estimated Black Carbon Emissions from Priority Source Categories in Russia. Russ. Meteorol. Hydrol. 47, 781–790. https://doi.org/10.3103/S1068373922100065

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Published: IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

Johannson & Silvergren. 2021. Beräkningar av emissionerna av olika ämnen från sopbranden vid Kagghamra. SLB 54:2021

Paunu, V.-V. and J.L. McCarty et al., 2023. Fire in the Arctic: Current Trends and Future Pathways. Arctic Black Carbon impacting on Climate and Air Pollution (ABC-iCAP) Project Technical Report 1. November 2023 vi+20pp.

United States, 2021. U.S. National Black Carbon and Methane Emissions. Report to the Arctic Council, March 2021. https://oaarchive.arctic-council.org/server/api/core/bitstreams/0087bb56-d73a-41f5-a77d-c5828e6666c0/content

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Funded by the
European Union