6 The role of anthropogenic methane emissions in bridging the emissions gap

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6.1 Introduction

Methane emissions are the second largest contributor to global warming to date after carbon dioxide (CO_2), accounting for about one third of the warming impact of all well-mixed greenhouse gas (GHG) emissions and 45 per cent of the net warming impact of all anthropogenic activities in 2019 (Intergovernmental Panel on Climate Change [IPCC] 2021). Along with black carbon, tropospheric ozone and some hydrofluorocarbons (HFCs), methane is a short-lived climate pollutant (SLCP), a class that has much greater warming impacts per ton than CO_2, but a much shorter atmospheric residence time. Methane accounts for more than half of the warming of all SLCPs.

Atmospheric observations show that emission growth rates have accelerated over the past 15 years, with methane atmospheric concentrations reaching 1,879 parts per billion in 2020 on annual average, which was 6 per cent higher than in 2000 (Dlugokencky undated) and 260 per cent higher than during pre-industrial times (World Meteorological Organization [WMO] 2020). Anthropogenic emissions account for roughly 60 per cent of total methane fluxes to the atmosphere, amounting to around 365±30 megatons of methane ($MtCH_4$)/year. Approximately 35 per cent come from fossil fuels (two thirds from oil and gas and one third from coal), 40 per cent from agriculture (three quarters from enteric fermentation and manure management and one quarter from rice) and 20 per cent from waste (mostly landfills and solid waste), with the remaining ~5 per cent emitted through biofuel and biomass burning (Saunois *et al.* 2020).

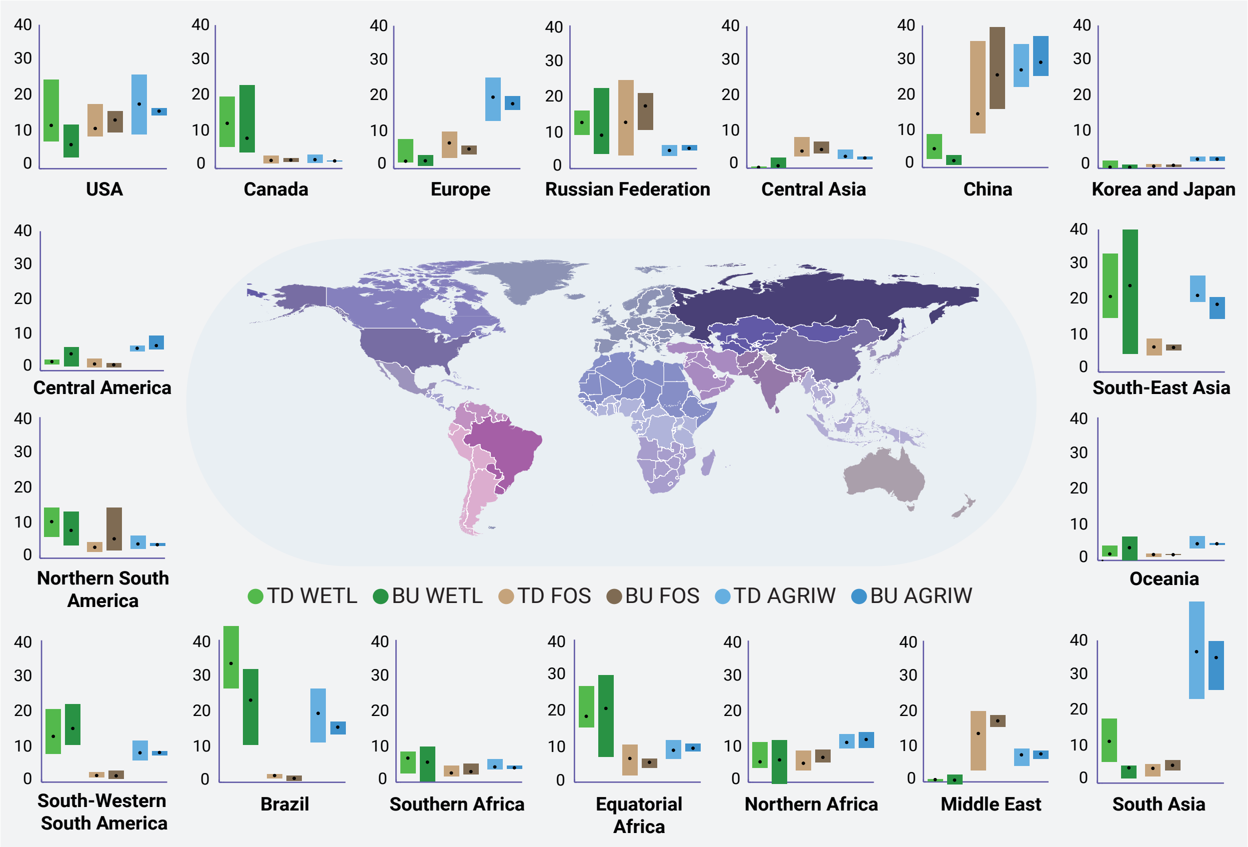
The remaining roughly 40 per cent of total methane emissions are generated by several natural sources: inland freshwaters (including wetlands, lakes, reservoirs and rivers), geological releases, wild animals, termites and permafrost. Sectoral partitioning of methane emissions varies greatly among countries/regions and large uncertainties remain in both anthropogenic and natural emissions (figure 6.1). Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws.

The size of methane sinks (mainly oxidation in the atmosphere), and how this varies over time, remain difficult to predict and study. Unlike CO_2, little attention has been given to capturing methane from the air, and further assessment of the feasibility of methane removal is therefore required (Jackson *et al.* 2019).

Although methane emission reductions are a necessary part of long-term mitigation strategies alongside CO_2 reductions (Rogelj *et al.* 2018), mitigating methane emissions would especially contribute to reducing climate change-related damages in the near term, while reducing the level of eventual temperature stabilization and decreasing peak warming during this century.

As a result, there has been increased focus in recent years on the immediate need and opportunity to reduce methane emissions. The United Nations Environment Programme (UNEP) and Climate and Clean Air Coalition (CCAC) released a Global Methane Assessment in May 2021, which analysed the benefits of reducing methane emissions, the policies and costs of mitigation actions and the reductions needed to meet Paris Agreement goals (United Nations Environment Programme [UNEP] and Climate and Clean Air Coalition [CCAC] 2021). Several groups have recently analysed abatement potentials for methane, while others have both examined mitigation and described the impacts of such mitigation on the ability to meet climate targets (Nisbet *et al.* 2020; Ocko *et al.* 2021; UNEP and CCAC 2021). The main findings of these studies are assessed below, with some elements highlighted and implications for nationally determined contributions (NDCs) explored.

Figure 6.1. Average methane emissions for 2008–2017 in $MtCH_4$/year for 18 continental regions



Note: Emissions are shown for three main emission categories: wetlands (WETL), fossil fuel-related (FOS) and agriculture and waste (AGRIW). Coloured bars represent the minimum and maximum range of available estimates from top-down (TD) and bottom-up (BU) approaches. Black dots show the average for each approach (based on Saunois *et al.* 2020 data sets). The colours in the map indicate regions only.

6.2 Optimizing methane emission reductions

The level of methane emissions (and other short-lived substances) at the time of reaching net zero for long-lived GHGs will play an important role in determining the level at which temperatures stabilize. Methane stabilization at a level greater than the pre-industrial level will mean a long-term commitment to warming relative to the pre-industrial level, whereas changes in methane emissions will contribute further to future temperature changes. As a GHG that does not accumulate semi-permanently in the atmosphere, achieving net-zero methane emissions is not required for climate stabilization, nor is it expected, in marked contrast to the sum of CO_2 and nitrous oxide (N_2O), for which net-zero emissions are required for stabilization (Rogelj *et al.* 2018; see also chapter 3).

Methane abatement would affect warming rates in the near term, resulting in benefits for ecosystems and the ability of humans to adapt. As a precursor of tropospheric ozone,[1] which can be toxic to both humans and plants, methane emissions affect public health and crop yields via air pollution. Defining the optimal path for methane emission reductions is therefore arguably more suited to a multiple-benefits analysis than other GHGs, rather than an analysis

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[1] The troposphere is the lowest level of the atmosphere, which includes surface air.

only defined by a climate metric (though other GHGs may also have co-benefits that affect air pollution and health). Captured methane has a clear use and market value as natural gas. As a result, many methane reduction measures have low or even negative costs, with many models examining least-cost pathways to meet low warming targets reducing methane sharply in the current decade (Harmsen *et al*. 2019a; UNEP and CCAC 2021), though such reductions are not yet occurring.

Depending on progress in mitigating emissions of long-lived GHGs, rapid reductions of methane are also likely to play a role in limiting peak warming (chapter 3). That role depends heavily on how quickly emissions of CO_2 are reduced, how much CO_2 removal is deployed, and on the emissions trajectories of other short-lived climate forcers.

6.3 Short- and long-term mitigation potentials

The UNEP and CCAC Global Methane Assessment assessed the methane mitigation potential and cost estimates produced by several teams. This assessment included sector-specific assumptions about technology turnover times, estimates for improvements in technology over time and the achievable pace of regulations. Costs include estimates for the future value of recovered gas as well as the discounting of future returns with rates of 4–10 per cent.

Implementation of readily available methane-targeted abatement measures alongside broader structural and behavioural measures could reduce methane emissions by approximately 180 Mt/year by 2030, which is equal to nearly 50 per cent of current methane emissions. Implementation of readily available methane-targeted measures alone (i.e. excluding structural and behavioural measures) could reduce 2030 methane emissions by around 30 per cent.

The fossil fuel sector shows the largest all-cost (i.e. not restricting the analysis to low or negative net emission control costs) absolute 2030 abatement potential in analyses by three teams (Harmsen *et al.* 2019b; United States Environmental Protection Agency [U.S. EPA] 2019; Höglund-Isaksson *et al.* 2020). Methane emissions from this sector could be reduced by approximately 75 Mt/year (~2.2 gigatons of CO_2 equivalent ($GtCO_2e$)/year using global warming potential over 100 years – GWP100) in the short-term (2030) using methane-specific emission abatement measures relative to ~130 Mt/year in projected 2030 business-as-usual (BAU) emissions. Within the sector, oil and gas has a substantially larger reduction potential than coal in two of the analyses and roughly equal potential in the third analysis. Based on the Global Methane Assessment, all-cost oil and gas emission mitigation potential is 25–58 Mt/year by 2030 and 35–95 Mt/year by 2050 (relative to projected BAU 2050 emissions of ~155 Mt/year). Averaged over all measures, abatement costs are quite similar for the coal subsector, but vary substantially for the oil and gas subsector. Restricting the analysis to low cost (< US\$600/tCH_4; < ~US\$20/tCO_2e using GWP100) measures only, ~17–32 Mt/year can be abated by 2030 in the oil and gas subsector, compared with ~8–24 Mt/year in the coal subsector. The largest and most cost-effective abatement potentials within the fossil fuel sector for 2030 are to prevent all venting of associated gas during oil and gas extraction (including from inefficient flaring), to install leak detection and repair programmes for natural gas infrastructure and to utilize ventilation air methane oxidation technology in coal mines (table 6.1).

Reducing methane emissions from waste and agriculture will be more challenging but is crucial to achieving low warming targets. For waste, the three analyses assessed in the Global Methane Assessment have very similar 2030 all-cost abatement potentials relative to projected 2030 BAU emissions (~28–32 Mt/year; ~30–35 per cent; ~0.9 $GtCO_2e$/year using GWP100), but with widely varying cost estimates (+US\$3 to -US\$200/tCO_2e using GWP100). The largest and most cost-effective abatement in the waste sector comes from municipal solid waste, typically either by diverting organic waste from the waste stream or capturing and utilizing landfill gas. More simply, covering landfills with soil is a very effective and low-cost measure, and reduces fires, odours and air pollution. This could be an attractive option for many tropical and subtropical megacities, which typically have extremely large and ill-managed landfills. Crop waste fires are widespread in the tropics, leading to significant air pollution and methane emissions from partial combustion. Such crop waste could instead be burned under controlled conditions to generate electricity or returned to the soil to provide nutrients.

All-cost abatement estimates for rice cultivation have similar abatement potentials (~7–10 Mt/year) but vary markedly in costs (roughly US\$3–100/tCO_2e using GWP100), whereas low-cost abatement potentials and costs are quite similar across analyses. Abatement within rice cultivation is possible through changes in agricultural production techniques, such as alternate wetting and drying of paddy fields, though the benefits can be undermined by increased N_2O emissions (table 6.1). In contrast, all-cost abatement potential estimates for the livestock sector have similar costs (~US\$13–30/tCO_2e using GWP100) but significantly varied abatement potentials (4 to > 40 Mt/year). These differences are largely attributable to assumptions about the feasibility of some countries being able to switch to higher-yielding livestock breeds. The average abatement potential is therefore smallest in the agriculture sector at ~20–25 per cent. Several less well-established abatement options are also under study for the livestock sector, including feed substitutes and methane inhibitors (UNEP and CCAC 2020; Ocko *et al.* 2021). At the same time, substantial mitigation of livestock-related methane could be achieved through widespread changes in human dietary choices, possibly reaching 30 Mt/year (~0.9 $GtCO_2e$/year using GWP100) by 2050, with additional CO_2 and N_2O reductions (Willett *et al.* 2019; UNEP and CCAC 2021).

For 2050, abatement potentials tend to increase moderately compared with 2030, with the exception of waste and oil and gas in one analysis that shows very large abatement increases. The average abatement potential for waste across the three estimates roughly doubles between 2030 and 2050. Similarly, the average all-cost abatement potential in oil and gas increases to ~80 per cent of the 2050 value, with roughly half of these emission controls available at low net cost. Targeted abatement estimates (without behavioural changes) increase only modestly in agriculture, which is expected to become the main anthropogenic source of emissions in low warming scenarios (e.g. Rogelj *et al.* 2018). Abatement costs also change, with some of the most noticeable shifts being that oil and gas abatement will become more expensive on average. Changes in livestock abatement costs vary significantly among analyses.

There are additional opportunities to reduce methane beyond methane-targeted abatement measures. These include fuel switching from natural gas to renewables in electricity generation and in buildings, and behavioural changes such as reduced consumption of cattle-based foods and reduced food waste and loss. Integrated assessment models show large ranges in potential methane mitigation due to these processes. On average, these models indicate that such actions could reduce methane emissions by another 15 per cent beyond the targeted measures, for a total 2030 reduction under 1.5°C scenarios of 45 per cent relative to BAU (UNEP and CCAC 2021). Both the Global Methane Assessment and Ocko *et al.* (2021) emphasize that fast methane action, as opposed to slower or delayed action, can contribute greatly to reducing midterm (2050) temperatures, i.e. peak warming if long-lived GHG emissions are also controlled. Fast action to reduce methane to a trajectory consistent with 1.5°C scenarios was found to be able to reduce both 2050 and 2100 global mean temperatures, by 0.2–0.4°C and 0.4–0.8°C, respectively, compared with a broad set of potential baseline scenarios (UNEP and CCAC 2021).

Table 6.1. Global annual abatement potential in 2030 and 2050 ($MtCH_4$ and $MtCO_2e$)

Sector	Technical abatement measure	2030 $MtCH_4$	2030 $MtCO_2e$	2050 $MtCH_4$	2050 $MtCO_2e$
Livestock	Manure anaerobic digestion with biogas recovery on large farms >100 livestock units	1.2	35	2.6	77
	Breeding for improved productivity, longevity and reproduction	1.2	36	12.2	354
	Feed management and feed additives	1.8	54	9.5	274
Rice cultivation	Improved water management, use of alternative hybrids and soil amendments	6.1	177	3.9	112
Burning of agricultural waste residuals	Ban and enforcement of bans	1.8	52	3.1	89
Coal mining	Pre-mining degasification	4.4	128	17.7	513
	Ventilation air methane oxidation	6.0	173	16.8	488
	Flooding of abandoned coal mines	1.7	50	8.0	231
Oil production	Increased recovery of associated petroleum gas	14.8	429	12.6	366
	Leak detection and repair programmes	4.7	136	17.5	507
Gas production	Leak detection and repair programmes	9.4	274	14.4	416
Gas transmission pipelines	Leak detection and repair programmes	2.7	79	10.6	308
Gas distribution networks	Replacement of grey cast iron pipes and leak detection and repair	6.7	195	18.0	522
Food industry waste	Anaerobic digestion with biogas recovery	3.2	93	21.3	617
Paper, textile and wood industry waste	Recycling and incineration with energy recovery	1.8	53	5.1	147
Municipal solid waste	Source separation and anaerobic digestion with biogas recovery	6.1	177	11.8	341
	Source separation and recycling	5.9	170	14.1	410
	Source separation and incineration with energy recovery	3.7	109	13.3	385
Wastewater – industry	Two-stage anaerobic and aerobic treatment with biogas recovery	6.7	195	23.1	671
Wastewater – municipal	Upgrade of primary to secondary/tertiary with biogas recovery	1.2	35	5.8	169
All sectors		91	2,650	241	7,000

Source: Höglund-Isaksson *et al.* (2020)

6.4 Link between methane mitigation and paths to net-zero CO_2

There are important links between methane emissions and the path to net-zero CO_2. Scenarios with strong climate change mitigation policies include decarbonizing the economy, which would reduce methane leakage from fossil fuel systems due to reduced demand. However, decarbonization will lead to more abandoned oil and gas wells and coal mines, which would need targeted actions to reduce methane emissions that are distinct from direct decarbonization policies (e.g. Kholod *et al.* 2020). By 2050, methane abatement associated with decarbonization alone is only about 30 per cent of the methane abatement seen under a broad multi-pollutant, multi-policy 2°C scenario, emphasizing the large role played by methane-specific policies.

On a more fundamental physical level, the less methane is reduced, the smaller the available carbon budget will be that is consistent with a given target (e.g. Rogelj *et al.* 2018). Quantitatively, every ~100 Mt of methane emissions reduced and kept reduced increases the cumulative twenty-first century carbon budget by around 450 $GtCO_2$.

There are also many linkages between methane reduction actions and opportunities for decarbonization. For example, within land use, the abatement of livestock-related methane typically involves reduced demand for cattle, which then frees up pasture and feed lands for potential production of biofuels or afforestation. Methane-formed surface ozone is known to reduce the growth rate of many plants, affecting both crops (and therefore land use, as a greater area would be required to produce the same yield) and decreasing CO_2 uptake by forests (e.g. Sitch *et al.* 2007). Finally, using organic material from landfills as plastic substitutes could reduce the need for petroleum-based plastics, which could play a role in the transition away from fossil fuels (though likely a modest role), while reducing landfill-related methane emissions. As shown, several methane mitigation pathways also have the potential to contribute to CO_2 mitigation.

6.5 Methane mitigation in the first NDCs

Many countries present their mitigation pledges for GHG emission reductions in various ways in their NDCs.[2] Some emissions targets are not quantitative, while most that are quantitative tend to be provided as aggregated GHGs, which makes it difficult to discern projections for individual gases (at present, individual gases are only reported in national communication submissions by Annex I countries for trajectories based on current policies). The emissions implications of many major emitters' first NDC commitments have been analysed as part of a large international research project. Using a suite of global and national models and informed by policy-specific input from national experts, the project developed a range of plausible implementation pathways to achieve the NDCs (Roelfsema *et al.* 2020). The project also examined a least-cost 2°C scenario (accounting for mitigation costs only, and excluding environmental costs), with reductions starting in 2020 and a 66 per cent chance of staying below 2°C.

According to those estimates, some countries have made pledges that would lead to substantial decreases in their methane emissions by 2030 (table 6.2). Extrapolating countries' NDCs reveals that most are projected to achieve substantially greater reductions by 2050 than 2030. Japan is the exception, showing a smaller reduction in 2050. A group of major emitting countries, including the United States of America, European Union nations, Japan and Canada, have NDCs that will likely result in reductions of ~80–88 per cent of those seen in 2°C least-cost pathways by 2030 compared with 2015, and ~69–77 per cent by 2050. However, most of the world is not yet as close to 2°C pathways, so at the global scale, NDCs are expected to deliver only about a third of 2030 methane reductions expected under 2°C scenarios. Among the major emitting countries analysed, China, the Russian Federation, India and Australia show the greatest emission gaps for methane, with their NDC reductions relative to their 2°C reductions less than the global mean for both 2030 and 2050. Methane reductions in 1.5°C least-cost pathways are 44 per cent at the global level by 2030 compared with 2015, rather than 34 per cent for 2°C. The NDCs are therefore projected to deliver only about one quarter of 2030 reductions in 1.5°C pathways. The International Institute for Applied Systems Analysis (IIASA) has also carried out analyses of the impact of NDCs on methane for the European Union, which show decreases of 21 per cent by 2030 and 34 per cent by 2050 (relative to 2015), results that are very similar to those shown in table 6.2.

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[2] The assessment in this chapter only considers the first round of NDCs. New or updated NDCs are not considered.

Table 6.2. Projected changes in methane emissions relative to 2015 under nationally determined contributions and under a 2°C scenario

	2030	2030	2030			2050	2050	2050
Country	**% decrease in NDC**	**% decrease in 2°C**	**NDC/2°C fraction**		**Country**	**% decrease in NDC**	**% decrease in 2°C**	**NDC/2°C fraction**
Republic of Korea	26	29	89		USA	44	57	77
USA	30	34	88		EU	37	50	74
Canada	44	51	87		Japan	39	55	71
Japan	46	54	86		Canada	50	72	69
EU	22	28	80		Indonesia	40	65	61
Indonesia	23	40	59		Brazil	21	38	56
Turkey	22	38	58		Republic of Korea	31	64	49
Brazil	11	23	48		Turkey	26	59	44
Global	11	34	34		Global	23	55	41
Rest of world	10	34	30		Rest of world	22	57	39
Australia	2	9	18		China	18	59	30
Russian Federation	5	35	16		Russian Federation	19	63	30
China	6	40	15		India	8	46	17
India	1	26	3		Australia	5	43	12

Note: Projections for both the NDCs and the 2°C scenario are based on Roelfsema *et al.* (2020) and PBL Netherlands Environmental Assessment Agency (undated). Although ranges across the models were not specified for methane alone, the tenth to ninetieth percentile range of the emissions gap between the NDCs and 2°C scenario for all GHGs was ~36 per cent at the global level and 30–55 per cent at the national level, indicating that a similar uncertainty range is appropriate for methane estimates. The assumptions and underlying data are described in Roelfsema *et al.* (2020).

Although there are signs that transformation is taking place in some parts of the world, more ambitious efforts are clearly needed if the world is to aim for 2°C or 1.5°C pathways. In countries or regions with large projected decreases in methane emissions, specific policies have been put into place to achieve such reductions. Examples include the 2016 North American Leaders' Summit agreement to reduce oil and gas methane emissions by 40–45 per cent by 2025 (relative to 2012) in Canada, Mexico and the United States of America, the European Union's 2020 strategy to reduce methane emissions (COM/2020/663 final) and the goals of Nigeria and Côte d'Ivoire to reduce oil and gas methane emissions by 60–75 per cent by 2030 as part of the UNEP and CCAC Global Methane Alliance. In September 2021, the United States of America and the European Union announced a Global Methane Pledge to reduce anthropogenic methane emissions by at least 30 per cent globally relative to 2020 levels by 2030. On 11 October 2021, they reported that more than 30 additional countries had committed to joining the Pledge, with coverage now including nine of the top 20 methane emitters globally, and urged others to sign on before the official launch at the twenty-sixth United Nations Climate Change Conference of the Parties (COP26). There is a clear need for increased ambition almost everywhere, with possible actions that policymakers could consider including increased efforts to build on growing momentum to monitor and address environmental impacts within the private investment community. More transparent data on sector-specific 'best practice' methane emissions would help support a market for both monitoring and mitigation services by facilitating the identification of the best-performing companies.

NDCs typically include more information about the energy sector than the agriculture or waste sectors. Every country emits GHGs from municipal waste, which is largely generated by the human population (Eggelston *et al.* 2006). In NDCs representing 174 countries, 137 included general waste sector mitigation commitments, with 67 citing specific mitigation actions (Powell *et al.* 2018). The most common mitigation action was improved landfilling, followed by converting waste into energy (e.g. incineration and conversion of landfill gas into energy). Improvements in waste management systems could provide public health co-benefits, such as reducing hazards associated with wastewater mismanagement, improving air quality and diminishing land and water contamination (Mittal *et al.* 2017; Cohen *et al.* 2021).

Agricultural methane emissions primarily derive from animal stocks and rice cultivation, as well as deliberate biomass burning, factors that vary widely from country to country (Food and Agriculture Organization of the United Nations [FAO] 2021). In their first NDCs, 32 countries referred to 'climate-smart agriculture', with aims to optimize agricultural systems to increase productivity and incomes, enhance resilience and reduce GHG emissions (Strohmaier *et al.* 2016). However, countries rarely included quantitative targets for reducing agricultural methane emissions (Hönle *et al.* 2019). In fact, of the top 46 countries that contribute to 90 per cent of global agricultural emissions, only a quarter included broadly-stated measures targeting emissions from ruminant livestock. This may be due to relatively high abatement costs and the impact such measures may have on economically important sectors such as beef and dairy. Mitigation measures such as sustainable intensification of rice cultivation were more likely to be included, in part because they present clear co-benefits for modernization or productivity (Hönle *et al.* 2019). The magnitude of agricultural methane emissions suggests that agriculture should receive more attention than it currently does in methane mitigation strategies, and that strategies that include changes in consumption through a food systems approach will need to be considered (Tubiello *et al.* 2021). Setting quantitative goals for cropland and livestock management, which could come in the form of targets for best practices, would help countries raise their ambition in this sector.

6.6 Measurement-based verification of uncertain emission reporting

In many cases, methane mitigation efforts are hampered by uncertainties relating to actual emission numbers, making it important to urgently improve approaches for measuring and reporting emissions. Improved monitoring at the facility level could serve to motivate action to reduce emissions and to verify the effectiveness of such action. This would open up opportunities for regulators to use flexible policy instruments that directly target measurable emission reductions compared with more prescriptive best available technology standards. Effectively prioritizing methane sources, reducing methane emissions and tracking mitigation progress necessitates a broad suite of measurement-based technologies that draw on the unique advantages of each.

Traditional bottom-up approaches, based on source-specific emission factors combined with statistical activity data (for example, livestock numbers, amount of oil and gas extracted), have inherent uncertainties that can be large at the national/sectoral scale (figure 6.1), especially for non-Annex 1 countries with limited institutional capacity and data availability (Solazzo *et al.* 2021). Even in countries such as Germany and the United Kingdom, which have well-established emission reporting systems, methane inventories have been revised by up to 60 per cent between subsequent submissions (Bergamaschi *et al.* 2010).

New top-down approaches have been developed that use atmospheric observations (at the surface, airborne or from satellites), which when combined with atmospheric transport models, can be applied to determine emissions for a specific facility, sector, region or other aggregation. These top-down approaches have proven effective in correcting emission factors and in revising sectoral methane emissions in multiple geographies (e.g. Alvarez *et al.* 2018; Zavala-Araiza *et al.* 2021), and in this way have provided opportunities for identifying specific sources and mitigation opportunities (Lyon *et al.* 2016; Johnson *et al.* 2017).

Top-down approaches can also support the transparency of reporting processes, with the updated IPCC reporting guidelines recommending the application of such approaches as additional quality control (Bartram *et al.* 2019). However, at present, only Switzerland and the United Kingdom include top-down methane estimates in an annex to their national inventory reports (Manning *et al.* 2011; Henne *et al.* 2016).

New observational capabilities are revealing emission hotspots and facility- or city-scale emissions through measurements from cars, drones and aircraft, and satellite remote sensing, especially in remote world regions, which in at least a few cases has led to industry action to eliminate major emission point sources (Nisbet *et al.* 2020). However, at a larger scale, top-down methods depend highly on the density of observations and are challenged by the difficulty in disentangling different sources and separating natural emissions from anthropogenic emissions, which is crucial for many countries with large natural emissions. Compared with high-frequency in situ surface measurements, satellite observations have a broader coverage but less sensitivity to methane sources, and are limited by cloud coverage. Further deployment of mobile measurements and fixed stations should therefore be supported to better monitor methane concentrations, especially over tropical and boreal regions.

In the near future, wider use of top-down approaches will be facilitated by a new International Methane Emissions Observatory (IMEO) hosted by UNEP. The International Energy Agency (IEA) Methane Tracker (2020) already includes data on leaked methane of super emitters, which is detected by the TROPOspheric Monitoring Instrument (TROPOMI), with a new generation of satellites, such as GHGSat (Varon *et al.* 2020), being specifically designed to map and quantify point sources.