# If It Matters, Measure It: A Review of Methane Sources and Mitigation Policy in Canada*

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*Abstract*

Methane, a potent greenhouse gas, is critically under-regulated in Canada. We review the sources of methane emissions in Canada, policies in place, policy overage, and mitigation options for each source. Three sectors account for 96 per cent of Canada's methane emissions: oil and gas, agriculture, and waste. The oil and gas sector is the largest contributor to national methane emissions, as well as the only sector with methane mitigation regulations and a methane reduction target. Agriculture is the largest source of unregulated and unpriced methane, mainly because livestock is the largest single source of methane emissions in Canada. In a best case scenario, direct regulatory coverage is approximately 54 per cent of methane emissions, with indirect regulatory coverage via offset markets accounting for 18 per cent. However, data gaps and policy exemptions and gaps make this measure of potential coverage an overestimate. Emissions measurement challenges hinder methane emissions management for all sectors. Due largely to these challenges, 28 per cent of Canada's methane emissions are unregulated and policy options are limited. Better methane management, relying on better measurement, is crucial to achieving Canada's 2030 and 2050 emissions reduction goals. Key short-term policy actions are improving and standardizing current emissions estimates, matching emissions to policy coverage, and identifying unregulated sources. Longer-term actions require further study of cost-effective regulatory options across all sources, to support stricter regulations or well-defined market-based approaches with measurable outcomes.

**Key words:** methane emissions, mitigation options, emissions regulation

**JEL Codes:** Q15, Q52, Q54, Q58

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## Introduction

Methane is a short-lived climate pollutant with a more powerful warming effect than carbon dioxide. Accordingly, methane mitigation is viewed as one of the most effective options to limit near-term global warming (IPCC 2021; The White House 2021). Despite this, methane mitigation has not been a policy or regulatory focus in most countries until recently. Canada, as part of a growing suite of climate policies, has recently expanded its policy attention to methane mitigation in oil and gas, agriculture, and waste. Crucially, this policy development is both national and subnational: economic activities are regulated by provinces, whilst the environment (and emissions) are shared federal and provincial jurisdiction. As one of the few countries aggressively developing policies for methane mitigation, Canada's actions can inform policy development in other countries. We explore Canada's current methane mitigation challenge using a policy lens, outlining methane sources and mitigation opportunities. We identify measurement challenges and their interaction with mitigation opportunities, the current state of mitigation policy, and policy gaps. Our guiding research question is what are Canada's methane sources and opportunities for policy-driven mitigation?

In what follows, we summarise and describe sources of methane emissions in Canada. Our goal is to identify methane emissions sources, challenges in measuring methane emissions, and opportunities for mitigation. We also highlight the sources of methane emissions that are currently subject to provincial or national emissions reduction policies and identify regulatory gaps where additional policies may be appropriate. We draw on extant literature, summarising key points and focus on methane emissions from a policy perspective. We provide the first comprehensive assessment of methane sources and potential policy coverage in Canada, relying on national methane inventories and our review of current legislation, regulations and programs. We find that while the majority of methane sources are *technically* regulated, exemptions and data gaps make *actual policy coverage* unquantifiable.

Starting in 2016, Canada's federal government advanced three major climate change plans: the *Pan-Canadian Framework on Clean Growth and Climate Change* (2016), *A Healthy Environment and a Healthy Economy* (2020a), and the *2030 Emissions Reduction Plan* (2022c). Mitigation policy in all three focuses primarily on carbon dioxide ($CO_2$), Canada's largest source of emissions. In 2017, the Government of Canada began targeting methane with release of draft oil and gas methane regulations (Environment and Climate Change Canada 2017a; 2017c). The primary federal approach to methane emissions is a commitment to reduce emissions from the oil and gas sector by 40 to 45 per cent by 2025 and 75 per cent by 2030 (Environment and Climate Change Canada 2016; 2020a). Secondary actions include the carbon price, which applies to methane emissions from incomplete fossil fuel combustion; an offset market to support methane reduction in landfills; a clean fuel regulation to incentivize switches to renewable fuels; and funding programs supporting reductions in food waste, clean fuel projects, use of waste biomass for low-carbon energy, and producer-led practices to reduce methane emissions in the agriculture and oil and gas sectors (Environment and Climate Change Canada 2022c). The *Healthy Environment* additionally proposes to establish methane regulations for "large landfills," with the *Emissions Reduction Plan* setting a target date of 2024 for publishing draft regulations (Environment and Climate Change Canada 2020a; 2022c). In October 2021, Canada announced its support for the Global Methane Pledge, which aims to reduce global anthropogenic methane emissions across all sectors by at least 30 per cent below 2020 levels by 2030 (Environment and Climate Change Canada 2021b).

Like most areas of joint policy jurisdiction, Canada uses a cooperative federalism approach to regulating methane emissions: federal regulations form a minimum standard and provinces can develop their own policies. These policies, when granted equivalency, stand in place of the federal regulations. Notably, granting equivalency is not the same as true equivalency in the regulated activity. The cooperative federalism approach creates significant differences in policy action, and in the case of methane, differences in allowable and penalized actions (van de Biezenbos 2022).

Canada's official greenhouse gas inventory estimates methane emissions of 3,667 kt in 2020, equal to 91,665 kt carbon dioxide equivalent ($CO_2e$) and 14 per cent of Canada's total greenhouse gas emissions.[1] This is greater than Canada's greenhouse gas emissions from the electricity sector (56,200 kt), the oil sands (80,900 kt) and passenger transport (79,600 kt) (Environment and Climate Change Canada 2022d). Three sectors account for the majority (96 per cent) of Canada's methane emissions: oil and gas, agriculture, and waste.

Oil and gas is the largest contributor to national methane emissions, and the only sector with an explicit emissions reduction target. There are opportunities for significant emissions reductions, as a large share of methane releases in oil and gas are avoidable through improved processes, and leak identification and repair. As a result, most existing research on methane emissions policy focusses on oil and gas. This literature includes the accuracy of Canada's current methane emissions estimates (Johnson et al. 2016; Atherton et al. 2017; Johnson et al. 2017; Werring 2018; Zavala-Araiza et al. 2018; Chan et al. 2020; MacKay et al. 2021); policy implications stemming from measurement difficulties and the lack of a reliable baseline estimate (Jordaan and Konschnik 2019; O'Connell et al. 2019; Schiffner, Kecinski, and Mohapatra 2021); options for methane abatement (ICF International 2015; Munnings and Krupnick 2017; Gorski et al. 2018; Tyner and Johnson 2018; Liu et al. 2021; Gorski et al. 2022; Mohlin et al. 2022; Connoy, McKenzie, and Gorski 2022); and evaluation of provincial and federal methane regulations and equivalency agreements (Gorski 2019; Johnson and Tyner 2020a; van de Biezenbos 2022).

In contrast, there it little extant research on methane emissions policy for the agriculture and waste sectors, particularly in Canada. Existing sector-specific research on methane emissions is generally technical in nature, focusing primarily on measurement methods or abatement options (Basarab et al. 2013; Vu, Ng, and Richter 2017; Desjardins et al. 2018; Duthie et al. 2018; Worden and Hailu 2020; Baray et al. 2021). Policy-focussed research has tended to treat methane emissions as one component of a broader discussion of the overall sustainability and clean growth opportunities for agriculture and solid waste management systems (Ragan et al. 2018; Yildirim, Bilyea, and Buckingham 2019).

We augment this literature by explicitly discussing methane sources, how measurement challenges translate to policy implementation challenges, mitigation options in the three aforementioned sectors, and our estimated coverage of current policy. We find current policy action appears to directly target up to 54 per cent of Canada's methane emissions, with indirect regulation accounting for an additional 18 per cent. This proportion is uncertain and an overestimate for three reasons. First, methane emissions are particularly difficult to measure and estimation methods tend to have large margins of error. Second, the policies in place are mostly threshold-based, targeting large emitters and exempt methane from some sources, creating gaps in policy coverage. Third, the aggregate nature of national inventory reporting makes apportioning policy actions to actual emissions an approximation exercise. Evaluating the efficacy of Canada's methane mitigation policies will depend on improving measurement and disaggregating data to enable matching policy to methane sources.

The remainder of this paper proceeds as follows. We start with a brief primer on methane and an overview of Canada's methane emissions from anthropogenic sources. We summarise methane's (estimated) contribution to Canada's total greenhouse gas emissions profile, the shares of methane emissions across sectors and provinces, and briefly discuss the uncertainty around current methane emissions estimates. Next, we provide a sectoral analysis, describing sources of methane within each sector, policy coverage and opportunities for methane reduction. We identify key existing policies or programs that encourage

[1] International conversion rates for methane to carbon dioxide are contested and, consequently, are regularly re-evaluated and updated in the Intergovernmental Panel on Climate Change assessment reports. The current recommended rate for methane reporting purposes is 25 and is from the fourth assessment report, released in 2012 (UNFCCC Secretariat 2014). We discuss conversion rates in more detail in the next section.

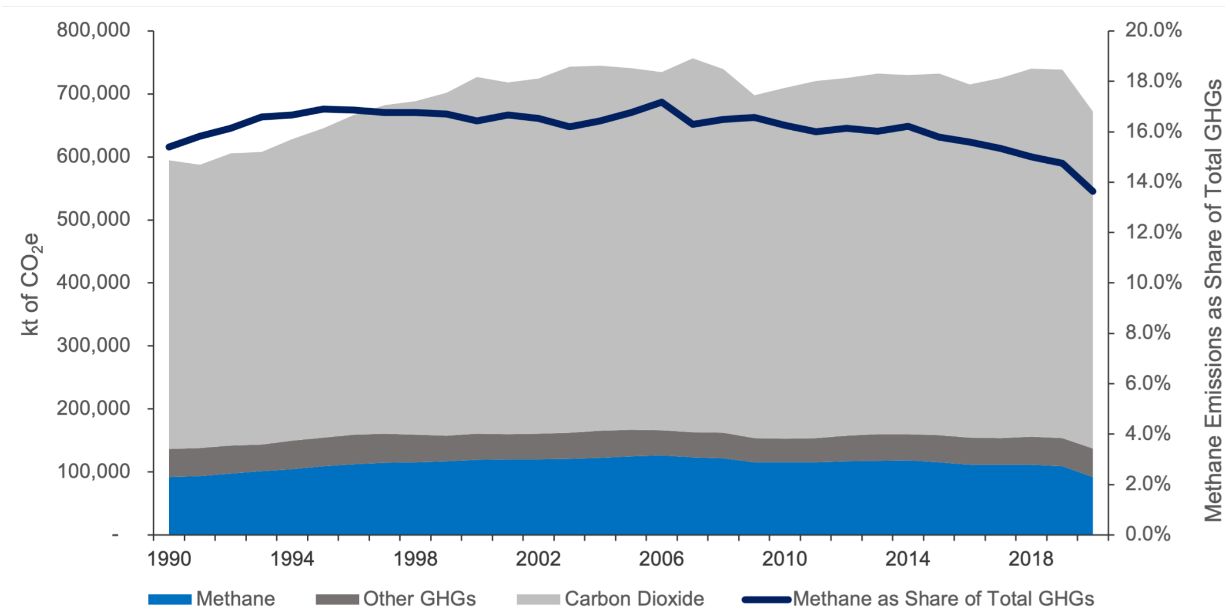
methane emissions reductions, and their gaps and flaws. We conclude with identifying future opportunities for methane emissions mitigation in Canada.

## Canada's Methane Emissions Inventory

Here, we briefly review Canadian methane emissions sources and trends. We rely on Canada's *National Inventory Report* (NIR) under the UN Framework Convention on Climate Change (UNFCCC). The NIR is the only comprehensive source of greenhouse gas emissions data, and it attributes emissions and specific greenhouse gasses to activity types. We present emissions by source, economic activity, and province. A caveat to our presentation is that the NIR underestimates the true methane emissions inventory, and we conclude this section with a discussion of the challenges with the NIR data in accurately accounting for methane emissions.

Relative to Canada's total greenhouse gas emissions, methane emissions are generally constant over time (Figure 1).[2] Methane emissions in 1990 were 91,555 kt $CO_2e$ (Environment and Climate Change Canada 2022d). They rose to a peak of 126,121 kt $CO_2e$ in 2006 and have since been largely declining, reaching 91,665 kt $CO_2e$ in 2020. Nearly half of this decline (-17,200 kt $CO_2e$) occurred from 2019 to 2020 and is attributable to new regulation of methane emissions from the oil and gas sector. Methane's share of Canada's total greenhouse gas emissions has declined from a high of 17 per cent in the mid-2000s to 14 per cent in 2020. In addition to the oil and gas regulations, rising greenhouse gas emissions in sectors that do not generate significant amounts of methane emissions contribute to this declining share. In particular, between 1990 and 2020 there were substantial increases in carbon dioxide emissions from the oil sands and freight transport.

**Figure 1: Canada's Historical Greenhouse Gas and Methane Emissions ($CO_2e$)**




Note: $CO_2e$ values are converted from tonnes of $CH_4$ using a 100-year GWP of 25, per the National Inventory Report methodology.
Source: Authors' calculations using Environment and Climate Change Canada (2022d).

[2] Per the National Inventory Report methodology, we report tonnes of $CH_4$ in $CO_2e$ using a 100-year GWP of 25.

Canada has three primary sources of methane emissions: direct releases of natural gas to the atmosphere, chemical reactions releasing methane as a byproduct, and organic decomposition releasing methane as a byproduct.

Direct releases of natural gas are the largest source of methane emissions, and take the form of venting and fugitive emissions. Venting emissions are deliberate and controlled natural gas releases. For example, venting is a common operational feature of equipment (e.g. pneumatic devices and compressors) that run on natural gas. Fugitive emissions, in contrast, are accidental releases of natural gas. Oil, natural gas and coal extraction, the oil and gas supply chain, and industrial processes with natural gas as an input are the primary sources of direct releases.

The most common chemical reaction releasing methane byproducts is incomplete hydrocarbon combustion, which occurs when combustion has insufficient oxygen. Complete hydrocarbon combustion results in the release of only water vapour and carbon dioxide. Incomplete combustion produces numerous by-products, including methane. Incomplete combustion is present across the Canadian economy, though major sources are onsite natural gas use in oil and gas extraction, residential heating, and transportation.

Organic decomposition releasing methane is from a type of microorganism classified as methanogenic archaea, or, more simply, methanogens. Methanogens generate methane as a metabolic byproduct when breaking down organic material in an anaerobic environment (an environment without oxygen). The two most common processes that result in methanogenic activity are degradation of organic landfill waste and ruminant animals' food digestion. In the former process, methane migrates to the landfill surface and escapes to the atmosphere; in the latter case methane is primarily from ruminant animals' belching. Methane generation depends on the specific characteristics of the organic material and the conditions it decomposes under. While optimal conditions for methanogenic activity will vary across subgroups of methanogens, two environmental conditions that typically increase activity — and thereby methane generation — are higher temperatures and moisture. Also key is that oxygen suppresses methanogen activity. Accordingly, methane generation will sharply decline when organic material decomposes in the presence of oxygen (an aerobic environment).

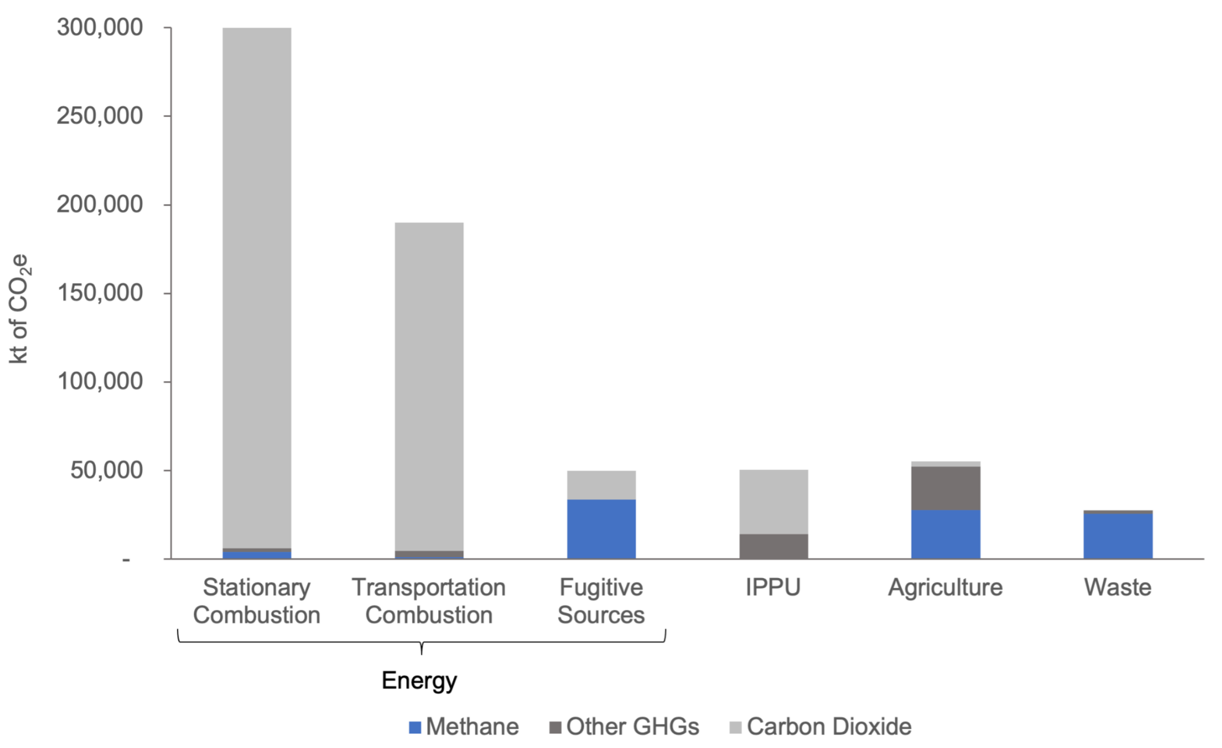
## Methane Emissions by Sector and Province

Canada's emissions reporting follows UNFCCC and Intergovernmental Panel on Climate Change (IPCC) guidelines in classifying emissions categories. These guidelines specify four main top-level GHG categories: energy; industrial processes and product use (IPPU); agriculture; and waste.[3] In what follows we translate IPCC sector emissions to economic sectors of interest.

The energy category is the largest source of total greenhouse gas emissions and encompasses three primary subcategories: stationary combustion, transportation combustion, and fugitive sources. Stationary and transportation combustion emissions are predominantly carbon dioxide (98 per cent), with a small proportion (1.3 per cent) of methane releases from incomplete combustion (Figure 2). Methane from incomplete combustion is mainly from the oil and gas sector (onsite natural gas use) and residential use (biomass burning). Fugitive sources are unintentional or waste fossil fuel emissions from coal mining and the oil and natural gas supply chains, and 67.5 per cent methane emissions. Fugitive sources include controlled processes (flaring and venting) and uncontrolled processes (unintentional emissions from coal mining and the oil and natural gas sector). Methane emissions from flaring are from incomplete combustion. Venting and uncontrolled emissions are direct releases to the atmosphere.

[3] The fifth emissions category is land use, land use change and forestry (LULUCF). UNFCCC guidelines only require countries to report national LULUCF emissions, and these emissions are not included in national inventory totals. Accordingly, we omit this source from our discussion.

**Figure 2: Greenhouse Gas and Methane Emissions by IPCC Reporting Category (2020)**



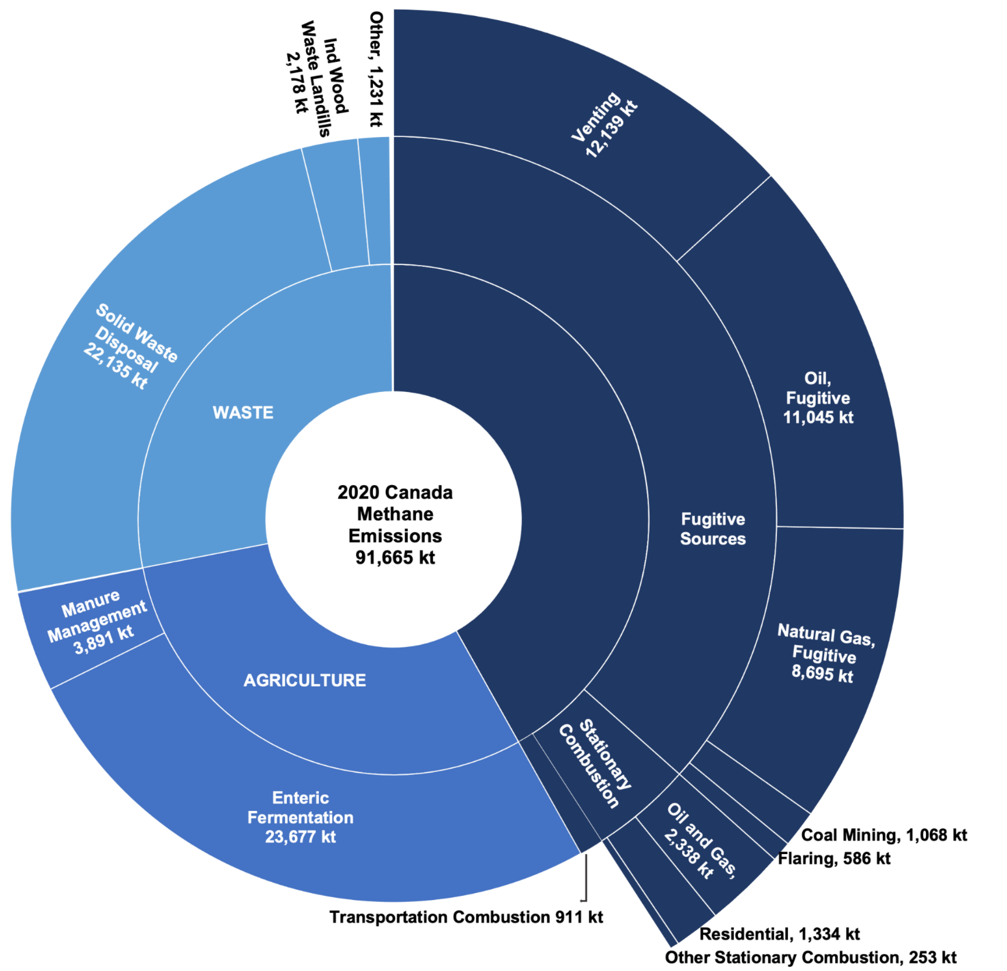

Note: IPPU is industrial processes and product use. Other GHGs include $N_2O$, HFCs, PFCs, $SF_6$ and $NF_3$.
Source: Authors' calculations using Environment and Climate Change Canada (2022d).

Together, incomplete combustion and fugitive sources in the oil and gas sector account for 38 per cent (34,985 kt $CO_2e$) of national methane emissions; the oil and gas sector is the largest contributor to Canada's total methane emissions (Figure 3). The largest sources of methane within the oil and gas sector are venting (13.2 per cent of national emissions/12,139 kt $CO_2e$) and uncontrolled fugitive emissions from oil production (12 per cent/11,045 kt $CO_2e$).

Agriculture accounts for 30 per cent of national methane emissions, almost entirely through non-combustion emissions. Enteric fermentation, the methane emissions produced by methanogens as a byproduct of cattle and other ruminant livestock's digestion, is the largest single source of methane emissions, at 26 per cent (23,677 kt $CO_2e$) of national emissions. The waste sector accounts for 27 per cent (25,544 kt $CO_2e$) of national emissions with most of that total attributable to solid waste disposal and methanogens' decomposition of solid organic waste (24 per cent/22,135 kt $CO_2e$). Methane emissions are dominant in both the agriculture and waste sectors where they account for 40 and 93 per cent of total sector emissions respectively.

IPPU methane emissions are minimal, accounting for only 0.3 per cent of total category emissions. Most methane emissions in this category are attributable to chemical reactions from petrochemical processing. Of note, however, is that any industrial facility that uses natural gas as a fuel source is susceptible to methane emissions as a result of leaks (fugitive emissions) and incomplete combustion. While an estimate of methane emissions from incomplete combustion is included in the energy sector category, the IPCC does not include fugitive emissions in its IPPU category. This suggests IPPU methane emissions may be an underestimate. For example, studying the U.S. fertilizer industry, Zhou et al. (2019) use airborne measurements to estimate an industry natural gas loss rate of 0.34 per cent, corresponding to annual industry methane emissions of 28 kt. In comparison, the U.S. fertilizer industry reported annual methane emissions of only 0.2 kt (Zhou et al. 2019).

**Figure 3: Canadian Methane Emissions (kt of $CO_2e$) by IPCC Subcategory (2020)**

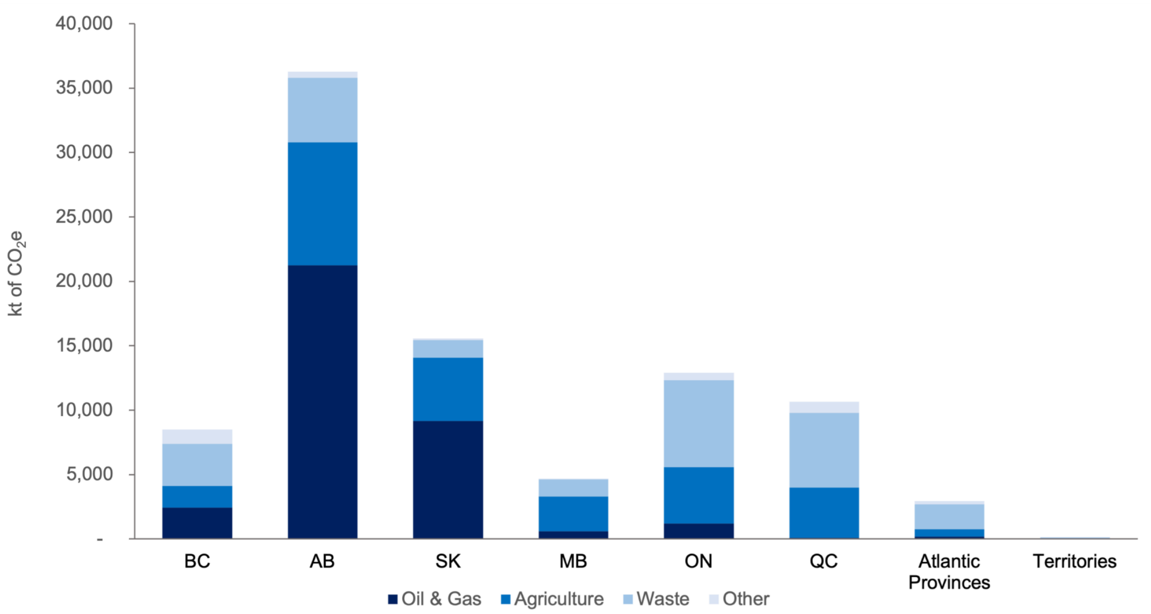



Note: The waste "other" subcategory includes biological treatment of solid waste (178 kt $CO_2e$), wastewater treatment and discharge (1,052 kt $CO_2e$) and waste incineration and open burning (1 kt $CO_2e$). The stationary combustion "other" subcategory includes public electricity and heat production (160 kt $CO_2e$), petroleum refining industries (8 kt $CO_2e$), mining (3 kt $CO_2e$), manufacturing industries (58 kt $CO_2e$), construction (0.6 kt $CO_2e$), commercial and institutional buildings (22 kt $CO_2e$), and agriculture and forestry (1 kt $CO_2e$). Last, transportation combustion includes aviation (4 kt $CO_2e$), road transportation (207 kt $CO_2e$), railways (9 kt $CO_2e$), marine (10 kt $CO_2e$) and other transportation (off-road vehicles and pipelines, 681 kt $CO_2e$). Not visible in the figure due to small quantities are IPPU methane emissions (143 kt $CO_2e$) and methane emissions from the agriculture subcategory of field burning of agricultural residues (41 kt $CO_2e$). Two additional agriculture subcategories — agricultural soils and liming, urea application and other carbon-containing fertilizers — have zero recorded methane emissions.
Source: Authors' calculations using data from Environment and Climate Change Canada (2022d).

Methane emissions differ across provinces (Figure 4), which speaks to differences in mitigation opportunities and policy priorities. Unsurprisingly, methane emissions are highest in Alberta (36,272 kt $CO_2e$), which accounts for the majority of Canada's oil and gas production and is home to the largest proportion (approximately 40 per cent) of Canada's cattle population (Canada Energy Regulator 2020; Statistics Canada 2020). Second in methane emissions is Saskatchewan (15,553 kt $CO_2e$), which correspondingly is second in Canada for both oil production and cattle population. Oil and gas and agriculture account for over 85 per cent of methane emissions in both provinces, with the majority of remaining emissions from the waste sector.

Third and fourth for methane emissions are Ontario (12,910 kt $CO_2e$) and Quebec (10,655 kt $CO_2e$) respectively, where waste and agriculture are the primary emissions sources. Ontario additionally has just under 10 per cent of its methane emissions from the oil and gas sector. This is despite negligible production volumes, and is most likely a result of fugitive emissions from natural gas transmission and distribution pipelines.

**Figure 4: Methane Emissions by Province and Sector (2020)**




Source: Authors' calculations using Environment and Climate Change Canada (2022d).

British Columbia's methane emissions (8,504 kt $CO_2e$) are fifth highest among the provinces; the waste sector is its largest source. This is somewhat unexpected as British Columbia is Canada's second largest producer of natural gas, with more than one-third of 2020 production (Canada Energy Regulator 2020). Despite this, the province accounted for less than 6 per cent of fugitive emissions from natural gas production (and only 7 per cent of total Canadian oil-and-gas-sector methane emissions). In comparison, Alberta accounted for 63 per cent of 2020 natural gas production and 77 per cent of fugitive methane emissions from natural gas production, while Saskatchewan accounted for only 2 per cent of production and 5 per cent of fugitive natural gas methane emissions. Much of this discrepancy can likely be explained by lower use of natural-gas-driven pneumatic devices at British Columbian production sites (Robinson et al. 2020). Also of note is higher volumes of natural gas — and correspondingly fugitive emissions — in transmission pipelines that start in Alberta and run through Saskatchewan, delivering natural gas to Eastern Canada and the United States. Fugitive natural gas emissions from distribution pipelines are also likely weighted towards Ontario and Alberta, which have the highest household use of natural gas (Natural Resources Canada 2018).

Manitoba (4,689 kt $CO_2e$) and the Atlantic provinces (2,958 kt $CO_2e$) have the lowest levels of methane emissions. In Manitoba, the agriculture sector accounts for 57 per cent of methane emissions, with a small amount of additional emissions from the waste sector. In the Atlantic provinces, the largest source of methane emissions is waste, with small amounts from agriculture and the residential sector. Last, at only 123 kt $CO_2e$, methane emissions in the territories are negligible.

Figure 4 shows that mitigating oil and gas methane emissions will primarily require policy incentivizing reductions in Alberta and Saskatchewan, and to a much lesser extent BC and Ontario. Similarly, waste mitigation relies on Ontario, Quebec, Alberta and BC. In contrast, mitigating agriculture emissions is much more equally spread across provinces. We now turn methane measurement issues before exploring in detail the policy environment and mitigation options for these three sectors.

## Challenges in Methane Measurement

There are two major issues in methane measurement that cause underestimation of methane inventories. The challenges are not specific to Canada, but are relevant when considering abatement opportunities and the scope and stringency of policy necessary to meet Canada's emissions reduction targets. Both issues stem from guidelines and approaches to constructing inventory estimates. The NIR forms the basis of Canada's emissions reduction targets (its nationally determined contribution under the Paris Agreement) and Canada's national and subnational policy choices to meet those targets. Underestimating methane emissions changes the target emissions level and underestimates the necessary abatement actions. Understanding these measurement challenges are key for critically evaluating policy driving abatement actions and the effectiveness of those policies.

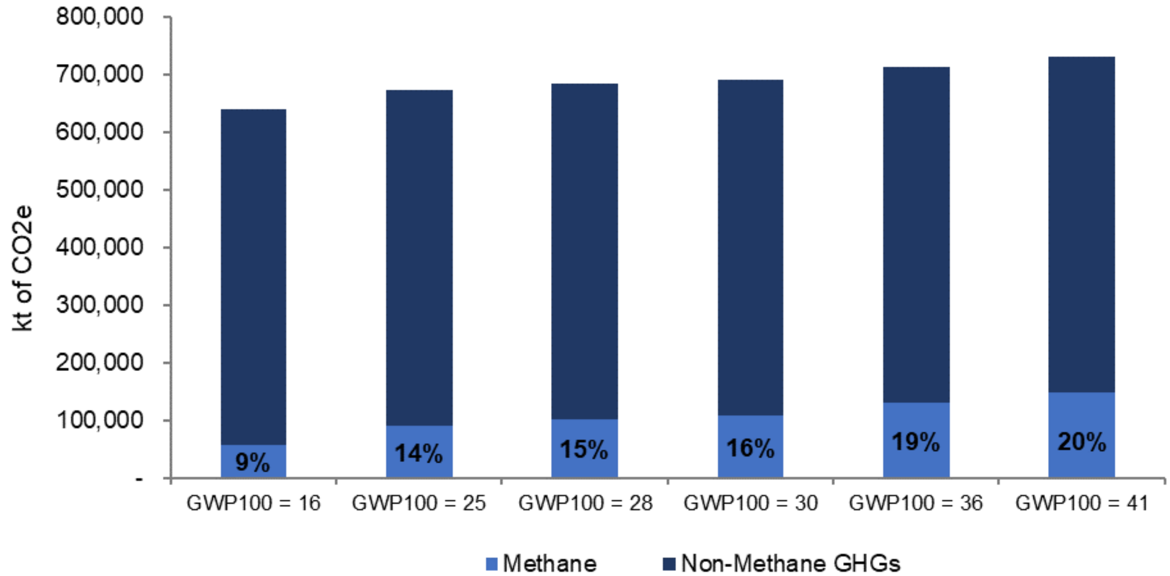
Canada's greenhouse gas inventory reports methane emissions in tonnes of $CH_4$ and tonnes of $CO_2e$. Canada converts methane into $CO_2e$ using a global warming potential (GWP) factor. The GWP factor approximates how many tonnes of $CO_2$ will result in the same global warming effect, over a specific period, as one tonne of methane. The use of $CO_2e$ creates a common unit of measurement for all greenhouse gases and facilitates comparison of the relative importance of these gases within Canada's overall emissions profile. Methane has a relatively short atmospheric life of approximately 12 years (IPCC 2013). Significantly, however, it has a much more powerful warming effect than carbon dioxide over this short period. The fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC) estimates the 20-year GWP for methane between 84 and 87 and the 100-year GWP between 28 and 36 (IPCC 2013). The most recent evaluation for the sixth assessment report places methane's 20-year GWP between 53.9 and 108.3 and 100-year GWP between 16 and 40.8, with a central estimate of 29.8 (IPCC 2021).[4] This means that, over two decades, the warming effect of one tonne of methane is 54 to 108 times greater than one tonne of $CO_2$. Over one century, the warming effect of methane falls between 16 and 41 times greater than one tonne of $CO_2$. The reduction in GWP over the 100-year time period reflects the short lifespan of methane in relation to $CO_2$.

Reporting guidelines for greenhouse gas emissions under the United Nations Framework Convention on Climate Change recommends converting methane to $CO_2e$ using a 100-year GWP of 25 from the IPCC fourth assessment report (UNFCCC Secretariat 2014). Canada follows the UNFCCC guidelines when preparing its annual national inventory report, the only source for a comprehensive estimate of national and provincial methane emissions. Using the GWPs from the fourth assessment report (potentially) significantly underestimates Canada's methane inventory. Using the most recent 100-year GWP central estimate, Canada's methane emissions estimate increases by 17,600 kt $CO_2e$ relative to the current NIR estimates (Figure 5), increasing Canada's total greenhouse gas emissions estimate by 2.6 per cent.[5] While Canada is compliant with the UNFCCC guidelines, following the guidelines rather than best-available science means the NIR underestimates its methane inventory. This creates a policy challenge, as the NIR understates both the baseline for reduction targets and the magnitude of required reductions.

[4] The ranges are due to uncertainty, as well as differing GWP estimates for fossil and non-fossil methane. The central estimate for fossil methane is a GWP-100 of 29.8; for non-fossil methane the GWP-20 is 27.

[5] If the high-end GWP-100 of 40.8 is the true GWP, then Canada's methane emissions are 8.6 per cent higher; in contrast, if 16 is the correct GWP-100, then Canada's methane emissions are 4.9 per cent lower.

**Figure 5: Effect of 100-year Methane GWP Assumptions on 2020 Methane Emissions Estimate**



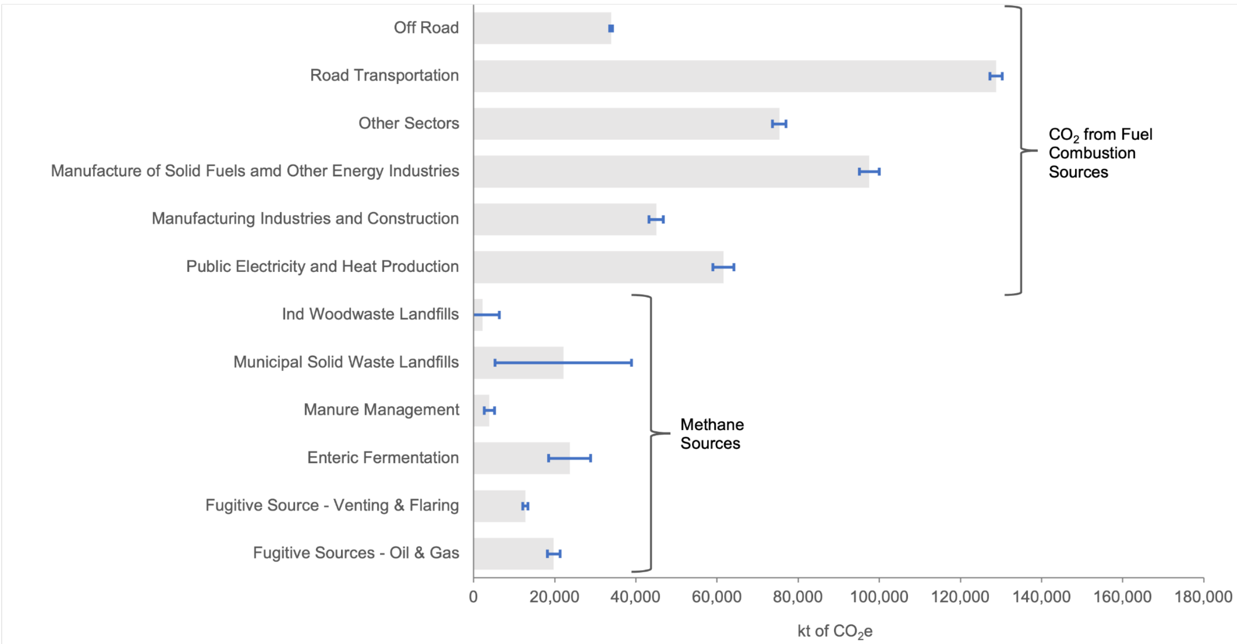

Source: Authors' calculations using Environment and Climate Change Canada (2022d).

The second issue with methane measurement is the three sources — direct releases of natural gas, chemical reactions and methanogenic activity — are challenging to track and quantify. There are two approaches for estimating methane emissions: top-down and bottom-up (National Academies of Sciences Engineering and Medicine 2018). The top-down approach starts by taking atmospheric measurements of methane concentrations. These concentrations are inputs to an atmospheric transport model that attributes them to a location and source. While top-down models can provide accurate and complete measurements of methane concentrations where the sampling occurs, it can be difficult to attribute these emissions to a specific point source. This is particularly a challenge in geographic areas with overlapping sources of methane (Baray et al. 2021; Scarpelli et al. 2022). For example, ranch lands in Alberta and Saskatchewan commonly have cattle grazing in close proximity to oil and gas wells. The bottom-up approach starts with sampling, measurements and modelling of methane emissions at individual point sources. This information is used to calculate an emission factor, which approximates average emissions per point source. Estimates of total regional emissions come from multiplying each emission factor by an activity factor that approximates the total number of individual point sources in a region.

In producing the NIR, Environment and Climate Change Canada predominantly relies on bottom-up methods to estimate greenhouse gas emissions. The NIR includes an uncertainty assessment to provide insight on the precision of its emissions estimates. The uncertainty values are not measures of the accuracy of the NIR's estimates, which ". . . can only be quantified by measuring departure from the truth" (Environment and Climate Change Canada 2022g, 10). Instead, the uncertainty values give a likely range for repeated emissions measurements.

Estimating $CO_2$ combustion emissions, the most common source of greenhouse gas emissions, is straightforward. The activity factor is quantity of fuel consumed and the emission factor is quantity of $CO_2$ per unit of fuel. While the emission factor will vary with specific fuel and engine characteristics, both measures are known with reasonable precision. For the six largest sources of $CO_2$ combustion emissions in the 2022 NIR, the relative uncertainties range from 1.1 to 4.2 per cent (Figure 6). In contrast, there is much more uncertainty around the precision of the NIR methane estimates. The six largest methane sources in the 2022 NIR have relative uncertainty estimates ranging from 5 to 190 per cent. Further, despite emissions from methane sources being much smaller than combustion emissions, the absolute uncertainty — the full range of emissions in which repeated measurements are likely to fall — is typically much larger. For three of the six methane emissions categories — municipal solid waste landfills, industrial wood waste landfills and enteric fermentation — the absolute uncertainty exceeds all six of the largest sources of combustion emissions. These three sources are the first, third and fifth largest contributors to the overall uncertainty in estimation of Canada's total greenhouse gas emissions (when excluding land use, land use change and forestry emissions).

**Figure 6: Uncertainty in NIR Emissions Estimates**




Note: The x-axis reports NIR sectoral total emissions estimates, and the blue error bars show the range of uncertainty. The uncertainty ranges are not a measure of accuracy (how close the emissions estimates are to their true value) but rather precision (the range of estimates that is likely to result from repeated measurements). For each emissions category, the NIR provides an uncertainty estimate for the activity data, the emission factor and the overall emissions estimate. For most emissions categories, emission factor uncertainty is the primary cause of overall uncertainty.
Source: Authors' calculations using Environment and Climate Change Canada (2022g).

Several factors contribute to the high uncertainty in methane emissions estimates. Methane emissions from direct releases of natural gas, for example, are primarily attributable to the oil and gas sector, which tends to be characterized by super emitters: a small number of facilities that are responsible for the majority of emissions (Zavala-Araiza et al. 2015; 2018; Vollrath 2022). Further, emissions are frequently a result of uncontrolled and disparate events — including human error, equipment failure, pipeline ruptures, unlit flares and well blowouts — that may or may not be detected (Vollrath 2022). As methane emissions associated with these events are colourless, odorless and tasteless, they have a high probability of going undetected. These characteristics are in stark contrast to the underlying assumption of the bottom-up estimation approach, which is a static and homogenous relationship between the activity factor and the emission factor.

Methane emissions attributable to methanogens are mostly found in the agriculture and waste sectors. The level of these emissions is highly dependent on site-specific environmental conditions; temperature, moisture and oxygen availability, and the management systems in place at individual farms and landfills. As it is not practical to obtain emission factors at individual farms and landfills, much of this information is missing when using the bottom-up approach. In the waste sector, lack of detailed data on the volumes and types of waste sent to landfill each year also contributes to uncertainty.

There is a growing literature on the accuracy of methane emissions measurement, primarily focusing on oil and gas (Vollrath 2022). Several studies of the oil and gas sector compare top-down estimates of methane emissions to inventory estimates (both the NIR and provincial inventories), consistently finding that inventory estimates of methane emissions are substantially less than provincial top-down measurements. The range of estimated discrepancies is large, however, varying from 25 to 50 per cent (Johnson et al. 2017), to more than 200 per cent (Atherton et al. 2017; Chan et al. 2020). There are two potential reasons for the discrepancy. First, emissions and activity factors are outdated and do not account for super-emitters, and second, inventories do not fully inventory all emissions sources (Vollrath 2022). The International Energy Agency compares several national methane emissions estimates for Canada's oil and gas sector. Of the eight estimates reported, Canada's official estimate from the NIR is the smallest, by factors ranging from approximately 25 to 100 per cent (International Energy Agency 2022b). This result underscores the challenges in measuring methane emissions from oil and gas and emphasizes policymakers need to view and interpret current estimates with caution due to significant uncertainty about the true magnitude of emissions.

Partly in response to these discrepancies, the 2022 NIR introduces a new methodology for estimating methane emissions from the oil and gas sector, which significantly changes the inventory estimates. These changes include a more direct method for estimating methane emissions from reported venting and flaring in Saskatchewan, and a new facility-based, upstream oil and gas emissions model to estimate key categories of fugitive emissions in British Columbia, Alberta and Saskatchewan. Annual methane emissions estimates for the oil and gas sector increased on average by 18 percent between the 2021 and 2022 reports. Moreover, 2022 estimates are 30 to 40 per cent higher than 2021 estimates between 2006 and 2020. While these changes reduce the discrepancy between top-down and inventory estimates, it also underscores the value of additional research and monitoring to address persistent uncertainty and inaccuracy in oil and gas methane emissions.

There is little research comparing inventory estimates of methane emissions with top-down measurements for Canadian agriculture and waste sectors (Baray et al. 2021; Scarpelli et al. 2022). Research on the agriculture sector generally finds estimates calculated through bottom-up and top-down approaches align reasonably well (Desjardins et al. 2018; Chan et al. 2020). One confounding factor is the spatial overlap in agriculture and oil and gas operations, which may mask agricultural methane emissions (Wecht et al. 2014; Baray et al. 2021; Scarpelli et al. 2022). In the waste sector, in contrast, there tends to be a significant discrepancy between top-down and bottom-up estimates (Vu, Ng, and Richter 2017; Chan et al. 2020).

Uncertainty about accuracy and precision of NIR estimates, in conjunction with underestimating methane's contribution to total greenhouse gasses, creates policy and regulatory challenges. Specifically, it creates uncertainty in the position and slope of the abatement supply curve. Canada's policy objective is to lower anthropogenic methane emissions at least 30 per cent below 2020 levels by 2030, and to achieve net zero total greenhouse gas emissions by 2050. Evaluating whether Canada is meeting its targets and if policy is effective and sufficiently stringent requires more accurate methane measurement. Moreover, Canada risks misallocating policy attention and resources away from methane abatement and to other GHGs based on an incorrect assessment of the relative importance of methane in national inventories. Relatedly, uncertainty in measurement and the relative importance of different methane sources can influence the most effective policy choices in incentivizing low-cost abatement (e.g. market-based versus command and control). Finally, underestimating methane inventories and uncertainty in methane measurement means policy action will likely be insufficiently stringent. With these challenges in mind, we next discuss the implications of these measurement challenges and sources of uncertainty on methane mitigation policy for each sector.

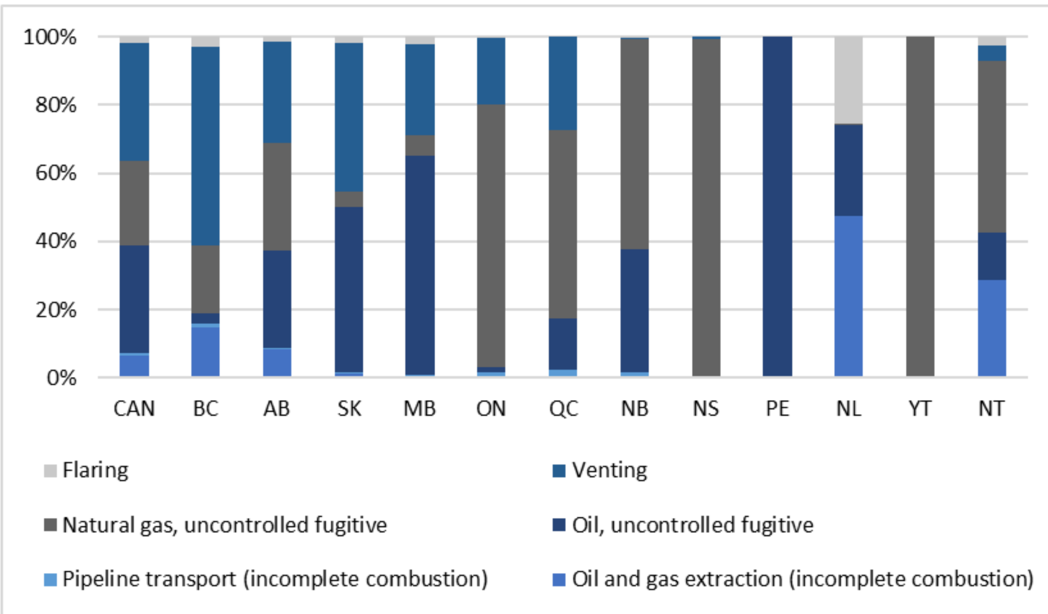
## Sector-Specific Sources and Mitigation Opportunities for Methane Emissions

### Oil and Gas

*Sources*

The oil and gas sector emitted 34,985 kt $CO_2e$ of methane in 2020 (Environment and Climate Change Canada 2022a). The large majority of these emissions are from direct releases of natural gas; specifically venting (12,139 kt $CO_2e$/35 per cent of total oil and gas methane emissions), unintentional natural gas fugitive emissions (8,695 kt $CO_2e$/25 per cent), and unintentional oil fugitive emissions (11,045 kt $CO_2e$/32 per cent). The remaining emissions in the sector come from incomplete combustion attributable to stationary combustion processes and pipelines (2,519 kt $CO_2e$/7 per cent), and flaring (586 kt $CO_2e$/2 per cent). The distribution of these emissions is quite variable across provinces (Figure 7), with oil and gas producing provinces showing more variation in source.

**Figure 7: 2020 Oil and Gas Methane Emissions Shares by Emissions Source and Jurisdiction**




Note: Nunavut has no reported methane emissions from oil and gas.
Source: Authors' calculations from Environment and Climate Change Canada (2022d; 2022e).

Venting is used for operational, safety and economic reasons to dispose of excess or waste gases along the entire oil and gas supply chain (including exploration, production, processing, transmission, refining and distribution). In 2020, total venting emissions in Canada (from all greenhouse gases) were 21,748 kt $CO_2e$, with methane emissions accounting for 56 per cent of this total (Environment and Climate Change Canada 2022d).

The largest source of vented methane emissions is solution (or associated) gas that accompanies conventional oil production.[6] With the recent introduction of methane reduction targets for the oil and gas sector in 2018, producers are facing increasingly stricter limits on solution gas venting in large quantities.

[6] The composition of venting emissions by source is unavailable nationally. However, in Alberta — which drives the national numbers due to its large share of oil and gas production — solution gas venting accounts for 43 per cent of all reported vented gases (methane and other) from the upstream oil and gas sector in 2020 (Alberta Energy Regulator 2022a).

However, under specific conditions — mainly if the quantity of solution gas is small enough and it is not economic to capture — then limited venting is allowed. Another significant source of vented emissions in the upstream oil and gas sector is pneumatic devices that run on natural gas and vent small amounts at a specified rate as part of their normal operations. Vented emissions also occur at glycol dehydrators, which remove water vapours from produced natural gas before it enters a pipeline and, in the oil sands, at upgraders and liquid extraction plants.

Similar to venting, unintentional fugitive emissions in the oil and natural gas sector capture direct, non-combusted releases of gas to the atmosphere. What distinguishes these emissions from venting, however, is that they are uncontrolled. Unintentional fugitive emissions occur along the entire gas supply chain, while along the oil supply chain they occur primarily at the production and processing stages.[7] There are multiple sources of these emissions including equipment and pipeline leaks; accidents and equipment failures; evaporative losses from storage tanks; losses during the transfer of liquid products (loading and unloading); and surface-casing vent flows[8] and gas migration[9] from active, inactive and reclaimed[10] oil and gas wells. There are two additional fugitive emissions sources in oil sands mining. First, methane trapped in the oil sands ore is emitted from the faces of open-pit mines, and during transport and processing of the mined ore (Johnson et al. 2016). Second, tailings ponds emit methane via methanogens decomposing residual hydrocarbons (Siddique et al. 2012). Fugitive emissions are almost entirely attributable to direct atmospheric releases of non-combusted natural gas; methane comprises most of this category. In 2020, total unintentional fugitive emissions from oil and natural gas production in Canada were 20,463 kt $CO_2$e, with methane emissions accounting for 96 per cent of the total (Environment and Climate Change Canada 2022d).

### *Mitigation Options and Costs*

As with most pollutants, the two overarching regulatory options for mitigating methane in the oil and gas sector are financial penalties and command-and-control regulation. Methane emissions from the oil and gas sector are unique in that most methane emissions are from natural gas releases, which is a marketable product with a distinct value. Correspondingly, marginal abatement cost curves suggest that significant quantities of methane can be abated at a net negative cost (ICF International 2015; International Energy Agency 2022b). That is, for certain technologies, the cost of investing in abatement to reduce methane emissions is more than offset by the revenues from increased marketable natural gas production. At first glance, this suggests that financial penalties should be effective in achieving methane emissions reductions. The challenge in recent years, however, is that persistent low natural gas prices decrease the returns from an increase in marketable natural gas production and shrink the negative portion of the marginal abatement cost curve.[11] The uncertainties around sources of methane emissions, and the challenges in obtaining

[7] Unintentional fugitive emissions are largely limited to the production and processing stages of the oil supply chain; any unvented or unflared solution gas remains mixed with oil following production and is removed during processing. As unintentional fugitive emissions are primarily uncontrolled releases of natural gas, once solution gas is removed there is limited opportunity for further emissions.

[8] The release of gas, liquid or both from the surface casing of an oil or gas well (Alberta Energy Regulator 2022a).

[9] Where gas flows away from the casing of a well and becomes detectable at the surface (Alberta Energy Regulator 2022a).

[10] Abandoned is the term for wells that reach the end of their productive life; they are generally permanently plugged and the land reclaimed.

[11] For example, ICF International (2015) finds negative marginal abatement costs for approximately 6,650 kt $CO_2$e of methane emissions. This result relies on a 2020 natural gas price of $5.00 CAD per thousand cubic feet (Mcf). The actual average 2020 AECO natural gas price (the Western Canadian benchmark) was $2.32 CAD per Mcf. A lower natural gas price decreases the value of conserved gas and moves a share of emissions from the negative to the positive section of the marginal-abatement-cost curve.

accurate measurements, also pose a significant hurdle to regulation through financial penalties. As a result, command and control regulation tends to be the primary mechanism to regulate methane emissions.

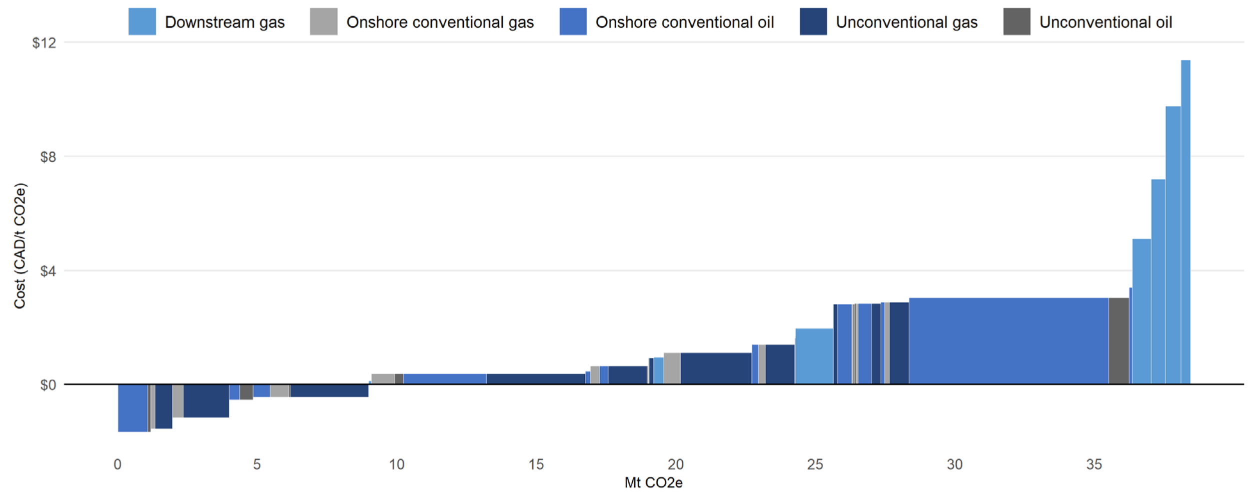
Command and control regulation for methane emissions from the oil and gas sector can be divided into three general categories: technology-based standards for processes and equipment; performance-based standards for processes and equipment; and leak detection and repair (LDAR) requirements (Munnings and Krupnick 2017; Mohlin et al. 2022). Technology- and performance-based standards typically target methane emissions from venting while LDAR programs target fugitive sources. With technology-based standards, operators are required to use a specific type of equipment or process that minimizes (or eliminates) methane emissions. With performance-based standards, operators have flexibility on the types of equipment or process they use but are required to keep methane emissions (or natural gas releases) below a certain rate or level. Last, LDAR requirements prescribe the activities operators must undertake to monitor their sites for natural gas leaks, as well as repair any leaks they find. In some cases, LDAR requirements may also prescribe a specific leak-detection technology or combination of technologies (e.g. an LDAR "program") for an operator to use.

Abatement options fall into three categories. First, replacing or retro-fitting existing devices that emit methane with lower-bleed equivalents or devices with electric instead of natural gas motors. Second, installing new devices to prevent venting, either via methane capture or flaring. Third, LDAR programs. The first two categories reflect abatement opportunities where methane emissions are known to occur, are gas-conservation actions (with the exception of flaring), and may have overall savings. Figure 8 presents a marginal abatement cost curve for the Canadian oil and gas sector using International Energy Agency (IEA) data. The IEA estimates 68 per cent of oil and gas methane emissions can be abated and 16 per cent can be abated at no net cost. The costs range from -\$1.66/t $CO_2e$ (-\$1.33 USD/t $CO_2e$) to \$3/t $CO_2e$ (\$2.43 USD/t $CO_2e$) for replacing devices, -\$1.51/t $CO_2e$ (-\$1.21 USD/t $CO_2e$) to \$4.78/t $CO_2e$ (\$3.83 USD/t $CO_2e$) for installing new devices, and -\$0.44/t $CO_2e$ (-\$0.36 USD/t $CO_2e$) to \$11.37/t $CO_2e$ (\$9.10 USD/t $CO_2e$) for LDAR activities. In contrast, the U.S. EPA estimates only 33 per cent of Canadian oil and gas methane emissions can be abated between 2020 and 2050, increasing to 36 per cent in 2050 (United States Environmental Protection Agency [EPA] n.d.). Between 7 and 16 per cent of emissions have abatement costs less than \$0 USD/t $CO_2e$, between 6 and 8 per cent have costs at \$50 USD/t$CO_2e$ or below and 14-15 per cent have costs above \$100 USD/t $CO_2e$ (EPA n.d.). Other estimates place abatement costs between -\$11 and \$41 CAD/t $CO_2e$ (ICF International 2015).

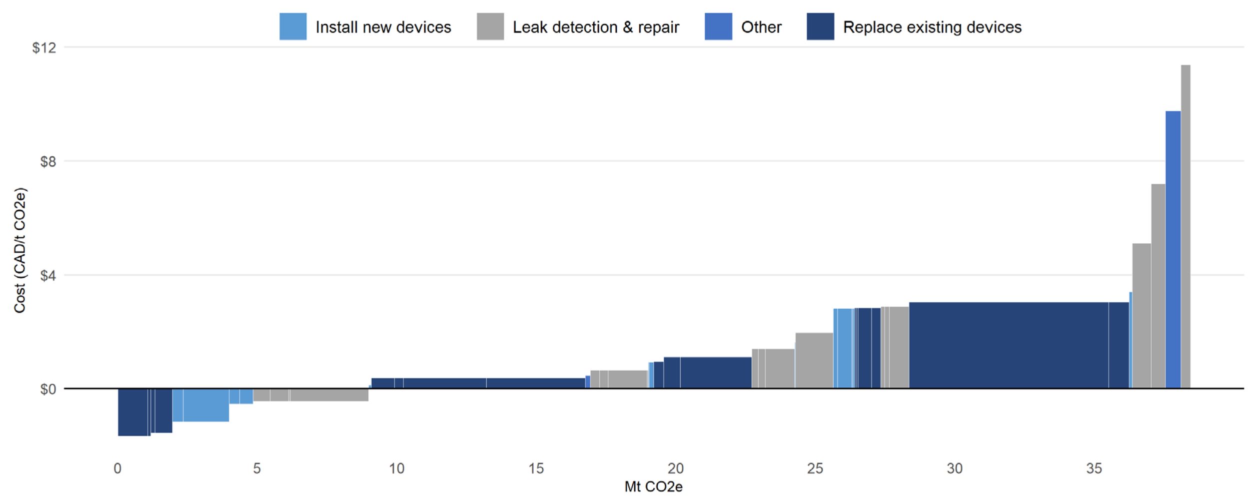
Specific to oil and heavy oil sites in Alberta, Tyner and Johnson (2018) find site-specific NPVs of -\$3.2 million to \$11.3 million CAD, with sites accounting for 97 per cent of abatement potential with NPVs between -\$360,000 and \$540,000 CAD. These estimates account for numerous abatement technologies, and have average costs ranging between -\$6.76 and \$14.91 per tonne $CO_2e$ at a methane GWP of 25. Similarly, Clearstone Engineering (2017) find average abatement costs between -\$6 and \$20 per tonne $CO_2e$ for gas conservation and combustion at a heavy oil site in Alberta. Finally, Umezor et al. (2019) estimate abatement costs in the Canadian natural gas supply chain. Abatement costs for pneumatic devices fall between -\$4 and \$5 per tonne $CO_2e$, upstream LDAR is between \$24 and \$42 per tonne $CO_2e$, abating midstream venting and fugitives between \$20 and \$35 per tonne $CO_2e$, and downstream fugitive abatement between \$60 and \$98 per tonne $CO_2e$. Umezor et al. (2019) is the most pessimistic assessment of abatement costs.

**Figure 8: Methane Abatement Potential and Costs in the Canadian Oil and Gas Sector**

*Panel A: Abatement Potential by Market Subsector*




*Panel B: Abatement Potential by Abatement Action*




Note: The IEA estimates of Canadian oil and gas emissions in the figure are 50 per cent higher than emissions reported in the 2021 NIR. Excludes savings with less than 1 kt $CO_2e$. Replace existing devices, in order of cost, includes early replacement of devices (high-bleed for low-bleed), replace pneumatic pumps with electric pumps, replace compressor seals or rods, replace pumps and controllers with instrument air systems, and replacing gas pneumatic devices with electric. Install new devices, in order of cost, includes vapour recovery units, blowdown capture, flares, and plunger lifts. Leak detection and repair includes upstream and downstream. Other includes methane-reducing catalysts, use of associated gas in remote locations, better maintenance practices, and "green" well completions.
Source: Authors' calculations from International Energy Agency (2022a).

## *Current Policy Approach and Gaps*

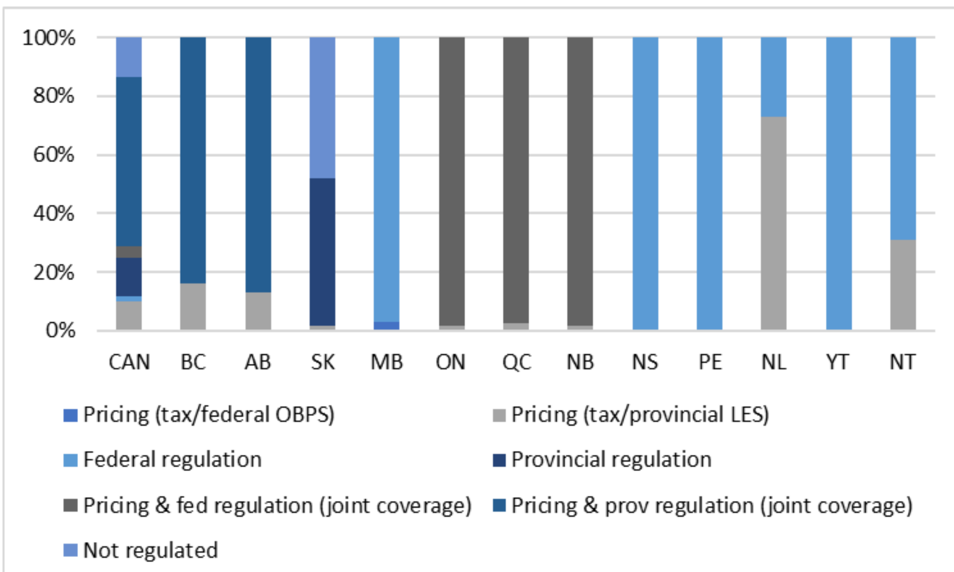
Oil and gas production, processing and transportation is provincial/territorial jurisdiction in Canada,[12] and prior to the recent federal push for methane mitigation, methane regulation targeted safety and conservation,

[12] The exception is pipelines crossing provincial or international boundaries, and the environmental assessment process for facilities of a certain size.

not explicit mitigation. In 2016, the Government of Canada announced a goal of reducing methane emissions from the oil and gas sector by 40 to 45 per cent below its 2012 baseline by 2025.

Canada presently has two major policy levers for addressing oil and gas methane emissions: direct methane-abatement regulations, focused on venting and fugitive emissions, and emissions pricing Emissions pricing generally takes two forms, a fuel charge for small emitters and a tradeable performance standard for large industrial emitters, though there is variation across provinces in large emitter systems.[13] The fuel charge indirectly regulates methane from incomplete combustion from small emitters through the pricing incentive. The tradeable performance standard, or output-based pricing system, directly regulates methane through its inclusion in total facility emissions. Importantly, all three approaches incompletely regulate methane via exemptions, excluded activities, and other gaps. In this section, we discuss policy coverage, overlaps and gaps including intuition on economic incentives from design choices, and where possible, quantify the emissions subject to the policy. Table 1 provides a high-level summary of the policy environment by province, and Figure 9 an approximation of the policy coverage by jurisdiction. Importantly, the not-regulated category in Figure 9 is an underestimate due to the gaps and exemptions Table 1 describes. In most cases, it is impossible to accurately quantify shares of emissions subject to a given policy, and so the figure describes a best-case scenario of coverage in the absence of exemptions.

**Figure 9: Approximate Policy Coverage of Oil and Gas Methane Emissions by Jurisdiction**




Note: The emissions shares are a best-case scenario in the absence of data on emissions by source cross-tabulated with the policy gaps in Table 1. The ‘not-regulated’ category is an underestimate of indeterminate size.
Source: Authors’ calculations from (2022d) and Table 1.

[13] Thresholds differ across provinces and Quebec and Nova Scotia have cap and trade systems.

*Table 1: Provincial and Territorial Oil and Gas Methane Regulation, Exemptions and Interactions*

| | Policies | Direct Regulation | | Large Emitter Treatment | |
|---|---|---|---|---|---|
| | | **Characteristics** | **Exemptions and Gaps** | **Characteristics** | **Exemptions and Gaps** |
| **BC** | Provincial carbon tax, provincial upstream methane regulations, provincial large emitter system. | General oil and gas methane reduction target rather than activity or source-specific.<br><br>Requirement to not vent or flare with some exceptions.<br><br>Flaring volume limits and component-specific venting limits.<br><br>Surface casing vent flow limit of 100 $m^3$/day (2.8 kg/h).<br><br>Leak defined as release equal or greater than 500 ppm or an unintentional release detected by a gas imaging camera.<br><br>Annual or triannual LDAR surveys depending on facility type.<br><br>Facility: Repair within 30 days or next turn-around.<br><br>Well: Repair within 30 days. | No minimum flare efficiency requirement.<br><br>Flaring limits are a recommendation, not a requirement.<br><br>No specific venting limits other than SCVF.<br><br>SCVF tests part of routine maintenance, not an LDAR program.<br><br>No requirement to conserve gas over flaring.<br><br>Fugitive emissions repair not required below threshold.<br><br>LDAR does not apply to all wells.<br><br>Does not apply to liquefied natural gas facilities.<br><br>Allows for extension of repair timeline.<br><br>LDAR frequency likely insufficient. | Performance standard for facilities with annual emissions above 10,000 t $CO_2$e.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Specific performance standard for liquefied natural gas facilities. | Priced emissions are only from incomplete combustion.<br><br>Direct rebates of incremental carbon tax above $30 CAD/tonne for emissions intensity below standard. Eligible facility emissions include venting, flaring and fugitives.<br><br>LNG: requirement to not vent or flare with some exceptions; no LDAR requirement. |

| | | | | | |
|---|---|---|---|---|---|
| **AB** | Federal fuel charge, provincial upstream methane regulations, provincial large emitter system. | Venting, flaring and fugitive emissions reduction requirements.<br><br>Some flaring volume limits.<br><br>Component-specific venting limits.<br><br>Facility vent gas limit of 15,000 $m^3$ per month.<br><br>Annual or triannual LDAR surveys depending on facility type.<br><br>Facility: Repair within 30 days or next turn-around if release greater than 10,000 ppm.<br><br>Well: Repair within 90 days if release greater than 300 $m^3$ per day (8.5 kg/h). | Exempts oil sands mining, oil sands processing and natural gas distribution pipelines.<br><br>No LDAR or SCVF test frequency requirement for wells.<br><br>No minimum flare efficiency requirement.<br><br>Venting limit excludes certain activities and facilities below a threshold.<br><br>Requirement to conserve gas over flaring threshold-based.<br><br>Excludes facilities that vent all received and produced gas from an LDAR program.<br><br>Fugitive emissions repair not required below threshold.<br><br>Allows for extension of repair timeline.<br><br>Repair only at well abandonment if SCVF below 300 $m^3$/day (8.5 kg/h). | Output-based pricing for facilities with annual emissions above 100,000 t $CO_2e$.<br><br>Opt-in above 10,000 t $CO_2e$.<br><br>Allows for aggregation and opt-in of conventional oil and gas facilities with emissions below threshold.<br><br>Includes all sources of methane in facility total GHG quantification. Venting and fugitive emissions are not included in priced emissions. Venting and fugitive emissions reductions eligible for offset credits. | Priced emissions are only from incomplete combustion.<br><br>Venting emissions unpriced except through offset market. |

| | | | | | |
|---|---|---|---|---|---|
| **SK** | Federal fuel charge, provincial large emitter system with federal top-up, provincial methane regulations. | Firm-level emissions-intensity limits for venting and flaring from oil facilities.<br><br>Venting limit for oil wells and facilities, above which flaring required.<br><br>Venting from a gas well or facility in emergencies only.<br><br>Semi-annual LDAR surveys for gas facilities producing or receiving more than 60,000 $m^3$ annually.<br><br>Leak defined as release equal or greater than 500 ppm.<br><br>Facility: Repair within 30 days or next turn-around. | No LDAR requirements for wells or oil facilities.<br><br>Combined flaring and venting from a well allowable up to 900 $m^3$/day (25.5 kg/h), with exceptions.<br><br>Fugitive emissions repair not required below threshold.<br><br>No component-specific venting requirements.<br><br>Does not cover surface-casing vent flow.<br><br>No minimum flare efficiency requirement.<br><br>Allows for extension of repair timeline. | Output-based pricing for facilities with annual emissions above 25,000 t $CO_2$e.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Only includes stationary fuel combustion for upstream oil and gas (including gas plants).<br><br>Allows for aggregation of oil and gas facilities with aggregate emissions below 25,000 t $CO_2$e. | Priced emissions are only from incomplete combustion.<br><br>Excludes flaring. |
| **ON** | Federal fuel charge, federal methane regulations, provincial large emitter system. | Venting and fugitive emissions reduction requirements.<br><br>Site vent limit of 15,000 $m^3$ per year (1.03 kg per hour).<br><br>Flaring efficiency requirement.<br><br>Triannual LDAR surveys. | Venting limit excludes certain activities and facilities below a threshold.<br><br>No requirement to conserve gas over flaring.<br><br>Does not cover surface-casing vent flow. | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2$e.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions. | |

| | | | | | |
|---|---|---|---|---|---|
| **QC** | Provincial cap and trade system, federal methane regulations. | Leak defined as release equal or greater than 500 ppmv.<br><br>Repair within 45 days or next turn-around.<br><br>Repair within 730 days if an offshore facility. | Fugitive emissions repair not required below threshold.<br><br>Allows for extension of repair timeline. | Cap and trade with free permit allocation for facilities with annual emissions above 25,000 t $CO_2e$ and fuel distributors.<br><br>Voluntary participation for facilities above 10,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions. | Facilities with annual emissions below 25,000 t $CO_2e$.<br><br>Fuel distributors with annual distribution below 200 litres. |
| **NB** | Provincial fuel charge and large emitter system, federal methane regulations. | | | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2e$.<br><br>Voluntary participation for facilities above 10,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions. | |

| | | | | | |
|---|---|---|---|---|---|
| **NS** | Provincial cap and trade system, federal methane regulations. | | | Cap and trade with free permit allocation for facilities with annual emissions above 50,000 t $CO_2$e. No voluntary participation.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions. | Facilities with annual emissions below 50,000 t $CO_2$e.<br><br>Fuel distributors with annual distribution below 200 litres.<br><br>GHGs from offshore oil and gas production.<br><br>Natural gas distributors with delivered combustion emissions below 10,000 t $CO_2$e/year.<br><br>Fugitive emissions from natural gas transmission, storage, and transportation. |
| **PEI** | Provincial fuel charge, federal large emitter system and methane regulations. | | | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2$e.<br><br>Only covers methane emissions from incomplete combustion. | Facilities with annual emissions below 50,000 t $CO_2$e.<br><br>Priced emissions are only from incomplete combustion. |
| **NL** | Provincial fuel charge and large emitter system, federal methane regulations. | | | Output-based pricing for facilities with annual emissions above 25,000 t $CO_2$e. Voluntary participation for facilities above 15,000 t $CO_2$e. | Facilities below threshold.<br><br>Priced emissions are only from incomplete combustion.<br><br>Explicitly excludes venting and fugitive emissions from petroleum and natural gas production and natural gas |

| | | | | | |
|---|---|---|---|---|---|
| | | | | Only covers methane emissions from incomplete combustion. | processing in facility GHG quantification. |
| **NT** | Territorial carbon tax, federal methane regulations | | | Carbon tax with rebates. | Priced emissions are only from incomplete combustion.<br><br>Direct rebates of 72% of carbon taxes paid.<br><br>Grant of up to 12 per cent of carbon tax paid for GHG reductions of at least 5 per cent relative to business-as-usual. |
| **MB, YK, NU** | Federal fuel charge, large emitter system and methane regulations. | | | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2$e.<br><br>Only covers methane emissions from incomplete combustion. | Facilities with annual emissions below 50,000 t $CO_2$e.<br><br>Priced emissions are only from incomplete combustion. |

Note: Analysis here is specific to oil and gas activities, e.g. does not include petroleum refining. Includes relevant conservation provisions from acts and regulations that do not specifically target methane reductions.

The federal regulation consists of six key requirements; four of these came into effect on January 1, 2020 and two come into effect on January 1, 2023. The regulation outlines an LDAR program that targets fugitive emissions, and a series of performance- and technology-based standards that target general facility venting,[14] venting from compressors and pneumatic devices, venting from well completions involving hydraulic fracturing, and methane emissions from other equipment (Environment and Climate Change Canada 2020e). The regulation covers all provinces and territories except for British Columbia, Alberta and Saskatchewan, and covers approximately 2–6 per cent of Canada's methane emissions. The Government of Canada is currently reviewing its oil and gas methane regulations with an objective to expand coverage and increase the stringency (Environment and Climate Change Canada 2022b). Some argue the federal regulations generally follow best practices (Gorski 2019); we find gaps still remain (Table 1).

First, facilities have a common venting limit of 15,000 m$^3$ (8.1 t $CH_4$) per year, regardless of facility size. Like with any threshold-based policy, there is limited incentive for emissions-reductions below the threshold. The benefit of threshold is it doesn't require continuous monitoring. However, the annual nature of the limit means that temporal volatility in venting is allowable even if the cost of preventing the vent is lower than the foregone revenue or estimated climate damages. Components all have flow-rate limits that are temporal, and are subject to the same criticism. Relatedly, repairs are time delimited rather than a function of leak severity and climate damages. Finally, the venting limits mean that emissions intensity will vary across regulated facilities (Mohlin et al. 2022).

Second, exemptions decrease the effective stringency of the regulation. The facility limit may seem stringent, as the site vent limit is equivalent to 1.03 kg $CH_4$ per hour. This compares to recent estimates of median rates of 13.7 kg/h for tanks, 8.3 kg/h for compressors, and 5.5 kg/h for unlit flares at (emitting) Alberta oil wells (Tyner and Johnson 2021). However, the regulation excludes some types of venting emissions from the annual threshold, such as emergency venting, well completion, blowdowns, and venting from pneumatic devices. It also exempts facilities with total venting, combustion and delivery of hydrocarbon gas below 40,000 m$^3$. Finally, the regulation is entirely silent on surface casing vent flow from wells. These exemptions mean some methane sources are unregulated, reducing the effective stringency of the regulation and creating incomplete incentives for emissions reductions. A better approach would be to include all sources of emissions within a site limit, and opt for increasingly stringent site limits over time.

Third, the regulation does not include direction to minimize flaring in favour of gas conservation. While flaring is preferable to venting, it still wastes the resource. There is a financial incentive to conserve gas, via avoided carbon tax payments and revenues from selling conservation gas. However, these incentives interact with large emitter systems, and as we note above, low natural gas prices undermine the abatement incentive for conserving gas. Relatedly, the regulation does not include flaring limits. Both gaps are inconsistent with Canada's endorsement of the World Bank zero routine flaring initiative (Environment and Climate Change Canada 2017b; World Bank n.d.).

British Columbia, Alberta and Saskatchewan — three main oil and gas producing provinces — have equivalency agreements for provincial methane regulations (Government of Canada 2020a; 2020b; 2020c). This appears to be largely motivated by each province's desire to implement regulations specific to unique provincial circumstances, and that will be less costly for oil and gas producers than the federal regulations (French 2020). Alberta, for example, estimates that it would cost industry $1.2 billion to meet the federal regulations and $650 million to meet its provincial regulations. The lower cost is likely due to less-stringent regulatory requirements. For example, Alberta's venting limit is 15,000 m$^3$ (8.1 t $CH_4$) per month (with

[14] General facility venting is venting from all sources at a facility apart from the following: (i) liquids unloading; (ii) a blowdown (temporary depressurization) of equipment or pipelines; (iii) glycol dehydration; (iv) use of a pneumatic controller, pneumatic pump or compressor; (v) start-up or shut-down of equipment; (vi) well completion; or (vii) venting in an emergency situation to prevent serious risk to human health or safety (Canada 2020).

fewer exemptions than the federal regulations), whereas the federal limit is the same volume per year. The provincial regulations suffer from similar issues as those we identify above, with additional gaps.

British Columbia and Alberta's regulations are similar to the federal regulation in that they largely target specific sources of vented emissions through technology- and performance-based standards, and fugitive emissions through LDAR requirements. Alberta also includes limits on solution-gas flaring (Alberta Energy Regulator 2022b). Saskatchewan's regulation, in contrast, takes a much more flexible approach. Its primary element requires that large oil licensees (emissions greater than 50,000 tonnes of $CO_2e$ per year) meet a single performance-based standard (emissions limit) across all their facilities (Saskatchewan Ministry of Environment 2019). Natural gas licensees are not included in the province's emissions management regulation but are required to implement an LDAR program under an associated directive.

The biggest difference between BC's methane regulations and the federal and other provinces' is that it has a general oil and gas methane reduction target rather than activity or source-specific limits and thresholds (e.g. facility venting limit). In contrast to the federal regulations, venting and flaring volume limits are recommendations of best practice, rather than as a requirement. However, the regulations explicitly prohibit facilities from venting or flaring, except in specific circumstances (e.g. safety). The lack of a limit or regulation of those specific circumstances creates another gap in coverage. The leak definition and repair timelines are as stringent as in the federal regulations. The Government of Canada assessment finds that BC "standards apply to a greater number of facilities" (Environment and Climate Change Canada 2021, 6). BC's regulation also does not apply to liquefied natural gas facilities, which are regulated separately and lacks specific methane mitigation requirements.

Alberta's regulations have significantly more generous venting limits, leak definitions and exemptions than the federal regulation, though Alberta includes more sources in its regulated routine and non-routine vent sources. Of note is that Alberta's facility limit is 15,000 $m^3$ per month, or 14 kg per hour, roughly half of the flow of sites classified as super-emitters (Zavala-Araiza et al. 2017). Moreover, the more generous and monthly nature of the threshold exacerbates the mitigation incentive challenges we identify above with the federal regulations. Alberta also excludes wells from LDAR programs, and more concerning, exempts oil sands mining, oil sands processing and natural gas distribution pipelines from its methane regulations. These sources are subject to the large emitter system (wells can aggregate and opt in), and oil sand mining is not a major source of NIR methane emissions (3 per cent of Alberta's total). Nevertheless, it creates inconsistent treatment across oil and gas sectors. Moreover, Scarpelli et al. (2022) find oil sands mines are three of 11 methane hot-spots, suggesting the NIR underestimates oil sands methane emissions and their exclusion from methane regulations should be reconsidered.

Saskatchewan's methane regulations have the most egregious gaps in coverage and most generous exemptions, resulting in coverage of only 50 per cent of its methane emissions. The main sources of gaps are exclusion of fugitive emissions, lack of an LDAR program for wells, and generous thresholds for venting and flaring. These gaps contribute to the majority of Canada's unregulated oil and gas methane emissions.

Combustion emissions, including flaring, are covered by the fuel charge and large emitter systems, which interacts with the methane regulations and in some cases creates joint coverage (about 58 per cent of total Canadian methane emissions). Smaller facilities face the full price signal. In contrast, facilities subject to the OBPS receive an output subsidy that lowers the average cost of emissions while keeping the marginal price signal. The effect of the OBPS is higher emissions relative to a full price signal.

The federal output-based pricing system covers facilities in Manitoba, Prince Edward Island, Yukon, Nunavut, and partially in Saskatchewan[15]; other provinces and territories have their own large-emitter

[15] Saskatchewan's OBPS does not cover electricity generation and natural gas transmission pipelines, and so the federal OBPS applies to these sectors (Environment and Climate Change Canada 2021a).

systems. Methane is a specified gas under the federal OBPS, and covered emissions relevant to oil and gas include stationary combustion, industrial process and product use, venting, flaring, and leakage. However, methane from venting or leakage from crude oil and bitumen production and processing, bitumen upgrading, and natural gas production, processing and transmission are excluded from facilities' total GHGs, and therefore are not subject to emissions pricing. With this exclusion, the federal OBPS only covers methane emissions from incomplete combustion, currently 0.13 per cent of Canada's methane emissions. Similarly, Saskatchewan's OBPS only includes combustion emissions for upstream oil and gas; this is explicitly because of the presence of its methane regulations. As a result, only 1.7 per cent of Saskatchewan's emissions and 0.5 per cent of Canadian emissions are subject to an OBPS in Saskatchewan. Excluding venting and fugitive emissions from the OBPS prevents regulatory pancaking, but it undermines the efficiency and efficacy of the OBPS. Specifically, it introduces differential treatment of methane across facility types; for example, venting and fugitives are included in petroleum refining and petrochemical production facility emissions. Though performance benchmarks are sector-specific, excluding methane lowers the emission-reduction incentive as the performance benchmark is easier to achieve. An open question is the strength of the price signal through the OBPS compared to the shadow price from the regulatory approach.

In contrast, BC's large-emitter system (the CleanBC Industrial Incentive Program), fully refunds carbon tax payments above $30 per tonne for facilities meeting an emissions performance standard. This limits the price signal to $30 per tonne and undermines mitigation incentives. BC also includes all sources of methane in facility total GHG quantification, though the carbon tax is only on combustion emissions. The large-emitter system and methane regulations jointly cover approximately 84 per cent of BC's and six per cent of Canada's oil and gas methane emissions.

The majority of Alberta's methane emissions are subject to both the methane regulations and the large-emitter system. Alberta's Technology Innovation and Emission Reduction (TIER) Regulation is an output-based pricing system that includes opt-in provisions for groups of wells. TIER includes all sources of methane in facility total GHG quantification, but venting and fugitive emissions are not included in priced emissions. This effectively increases the output subsidy by creating a wedge between estimated facility intensity and priced facility intensity. However, due to uncertainty about actual methane emissions differing from estimated, this creates variation in the underlying effective subsidy, introducing distortions in what is meant to be uniform treatment across a sector. Venting and fugitive emissions reductions are eligible for offset credits. Ignoring exemptions, we estimate TIER covers 13–14 per cent of Alberta's methane emissions on its own (8 per cent of Canadian emissions), and 86–87 per cent (53 per cent) of emissions jointly with the methane regulations.

A caveat to this discussion is that Canadian emissions reporting converts methane emissions to $CO_2e$ using a GWP of 25, which persistently underestimates the methane inventory and reduces abatement incentives. A second major limitation of the pricing coverage is that calculating methane levels relies on activity and emissions factors, assuming that combustion occurs at components' engineered efficiency (e.g. 95 per cent is required in the federal regulation). This is particularly troubling for flaring, as recent evidence suggests unlit or malfunctioning flares are responsible for significant methane emissions (Zhang et al. 2020; Cusworth et al. 2021; Irakulis-Loitxate et al. 2021; Tyner and Johnson 2021; Zavala-Araiza et al. 2021). Continuing to use a pricing mechanism without accurate quantification undermines the pricing signal. Monitoring and verification of these sources will be important for maintaining the effectiveness of pricing as a mitigation technique.

Alternatively, performance-based or prescriptive regulation could mitigate incomplete combustion. A best practice in this area is regulations limiting flaring to circumstances when capture is infeasible, which is in place in the provincial methane regulations but not the federal regulations. Specific actions could include requiring high-efficiency flares and combustors in combination with increasing monitoring frequency. Similarly, regulatory directives in BC and Alberta require an economic evaluation of gas conservation versus flaring for sites with combined venting and flaring volumes above a threshold (900 $m^3$/day or 25.4 kg/h). If the net present value of a mitigation program is greater than a threshold value (-$50,000 in BC and -$55,000 in Alberta), the regulations require operators to conserve gas. However, low natural gas prices reduces the profitability of conserving gas. Using the Alberta threshold, a super-emitting site would not have to conserve gas if its mitigation program cost more than $55,000. Moreover, these evaluations are on private economics rather than the full social value, ignoring climate damages. Tyner and Johnson (2018) find 501 of 9422 oil and heavy oil sites in Alberta exceed the volume threshold, but only one could conserve at lower cost than the economic evaluation threshold and a higher NPV threshold of -$180,000 would capture only 15 more sites.

Still uncertain is the effectiveness of federal and provincial methane regulations in meeting Canada's methane emissions reduction target. According to the 2022 NIR, Canada's methane emissions from the oil and gas sector were approximately 60,500 kt $CO_2e$ in 2012, with 58,400 kt $CO_2e$ from the three western provinces.[16] To meet Canada's target, federal and provincial regulations must therefore achieve a minimum emissions reduction of 24,200 kt $CO_2e$ across Canada. According to the estimates completed for the equivalency agreements, however, projected emissions reductions from provincial regulations in British Columbia, Alberta and Saskatchewan only total 13,300 kt $CO_2e$ (Government of Canada 2019, 2020d, 2020e). This implies that even if methane emissions in the remainder of the country are completely eliminated, current regulations will fall well short of meeting Canada's target.

Challenges in methane emissions measurement contribute to further uncertainty regarding the effectiveness of current regulations. In particular, uncertainty around the value of Canada's baseline emissions in 2012 creates corresponding uncertainty about the emissions reductions that are required to meet the target of 40 to 45 per cent below baseline. In 2016, when Canada first announced its methane reduction target for the oil and gas sector, the NIR estimate of methane emissions from the sector was 45,200 kt $CO_2e$, corresponding to a minimum reduction target of 18,100 kt $CO_2e$. This is 25 per cent lower than the reduction target of 24,200 kt $CO_2e$ implied by the 2022 NIR. Top-down estimates of methane emissions suggest the reductions required to meet the oil and gas sector target may be even higher. For example, Johnson et al. (2017) provide top-down emissions estimates for Alberta and find the province will require annual methane emissions reductions of 924 kt $CH_4$ (23,100 kt $CO_2e$) to meet the reduction target. In comparison, using the 2012 baseline estimate from the 2022 NIR, the target is met with annual reductions of 636 kt $CH_4$ (15,900 kt $CO_2e$).

Adding further complication to the potential discrepancy in the methane emissions reduction target is that if the correct target is higher than the baseline, this in turn implies that emissions reductions must come from sources that have not been formally identified or which are not accurately measured (Johnson et al. 2017). More robust LDAR requirements that target fugitive emissions, as well as new technologies for identifying fugitive emissions, may help to address these unidentified sources. Current federal and provincial LDAR requirements, for example, prescribe the use of handheld sensors to identify leaks. Recognizing that monitoring with handheld sensors is a slow and labour-intensive process, current regulation limits the number of required inspections to one to three times per year (with a minimum separation period of 60 days). This creates the risk of fugitive methane emissions going undetected for extended periods of time. To address these issues, alternative detection technologies — including continuous site monitoring devices and aerial, truck and drone surveys — are being evaluated, and in

[16] The federal government does not appear to have released a baseline level of 2012 methane emissions from the oil and gas sector in any documents related to its target. The estimate we report is the sum of 2012 methane emissions from stationary combustion in the oil and gas sector, from pipeline transportation and from fugitive sources. We do not include any methane emissions associated with non-pipeline transportation in the oil and gas sector as these data are not available for oil and gas. This estimate changes slightly each year as ECCC updates its estimation methodologies.

Alberta, used by some companies as part of an alternative fugitive emissions management program. The primary objective of these technologies is to achieve equivalent (or improved) mitigation of fugitive methane emissions at lower cost (Kemp and Ravikumar 2021). A recent Alberta field trial of different LDAR technologies suggests some alternative monitoring methods (truck and plane) are more cost effective than handheld sensors, and have the potential for continuous monitoring to detect major leaks (Singh et al. 2021). As these technologies are effective at identifying high-emitting sites, and some are able to quantify emissions at lower costs than traditional sensors, their use has the potential to spill over into improving measurement of fugitive emissions (Risk, Atherton, and Gorski 2021).

We also note that it is not only fugitive emissions that contribute to the discrepancies between top-down and bottom-up methane emissions estimates. As Johnson et al. (2017) identify in Alberta, an additional likely factor is venting underreporting. This suggests regulators should introduce stricter reporting requirements that compel facilities to more accurately track and measure known sources of methane emissions. Alberta changed its venting reporting methodology, and total reported venting increased by 98.8 per cent between 2021 and 2022 (Alberta Energy Regulator 2022a). Expanded use of alternative LDAR technologies may also help identify underreporting sites. Liu et al (2021) clarify the value of modifying existing emissions reporting structures for oil and gas producers in western Canada to require disaggregation of vented and fugitive methane emissions by source. They note this will increase transparency and consistency in emissions estimates across projects, help to develop and implement effective mitigation options and allow for improved tracking of progress towards emissions reduction targets. An additional issue with venting emissions is that emergency venting to maintain safety is exempt from facility limits in some regulations, which could create an incentive to categorize non-emergency venting as an emergency to maintain compliance. Finally, notwithstanding the measurement challenges we describe above, as venting is a controlled, measure release of methane it is an ideal candidate for pricing rather than performance-based regulation. Pricing venting would significantly improve the mitigation incentive.

Given the uneven distribution of methane emissions amongst oil and gas facilities, there is also an incentive for regulation to support identification of super-emitters, and to impose stricter requirements on these sites (particularly for LDAR programs and reporting requirements). This will ensure that reductions target the largest sources of emissions. It also reduces the regulatory burden on low-emitting facilities that have potentially already made financial investments in methane emissions reductions through adoption of best practices or emissions-reducing technologies (Atherton et al. 2017). While a focus on super-emitters may create inefficiencies via differential treatment across firms or activities within the sector, these inefficiencies are already present through threshold-based regulation. Given the uncertainty in overall oil and gas methane sources and measurement, focusing on super-emitters may offer the least-cost early emissions reductions.

Last, there is a discrepancy between Canada's methane emissions reduction goal (which is regularly referenced as for the entire oil and gas sector) and its methane reduction regulation (which targets only upstream flaring, venting and fugitive sources from the conventional oil and natural gas sector, in situ oil sands facilities and transmission pipelines). Carbon pricing regulation generally covers methane emissions from incomplete combustion. This leaves, however, methane emissions from refining, natural gas distribution pipelines, oil sands mining and upgrading, and abandoned[17] oil and gas wells as largely unregulated (though some of these sources are covered under large-emitter systems). While an exact measurement of methane emissions attributable to these sources is unavailable, we approximate it at 4,340

[17] As per the NIR, abandoned wells can be further divided into those that are plugged and unplugged, with unplugged wells divided into those without recent production (inactive, temporarily abandoned/suspended or dormant) and those without an operator (orphaned).

$kt\ CO_2e$ or 7 per cent of the 2012 baseline.[18] Emissions from these sources have increased in recent years, reaching an estimate of 6,308 kt $CO_2e$ in 2020.[19] The lack of full coverage, combined with the possibility that methane emissions from uncovered sources may continue to grow, sharply increases the burden on regulated sources to decrease their emissions by well in excess of the stated goal of 40 to 45 per cent.

## Agriculture

### *Sources*

In 2020, agricultural methane emissions were 27,608 kt $CO_2e$.[20] The large majority of these emissions are methanogenic activity from livestock production, resulting from enteric fermentation (23,677 kt $CO_2e$/86 per cent of total agricultural methane) and manure management (3,891 kt $CO_2e$/14 per cent). Livestock — and, specifically, cattle — is the largest single source of methane emissions. The remaining methane from agriculture is incomplete combustion from burning agricultural crop residues (41 kt $CO_2e$/0.1 per cent).[21] Figure 10 shows slight variation across provincial sources.

Enteric fermentation is a digestive process of ruminant animals (herbivorous, hoofed mammals with chambered stomachs) where methanogens residing in the animal's digestive tract convert otherwise indigestible materials like grass and hay into accessible energy. Methane accumulates in the rumen (the first of the stomach chambers) and is emitted through eructation (belching) and exhalation.[22] The amount of enteric methane an animal produces is dependent on its type and size, the amount and composition of its feed, and feed management practices.

The main types of ruminants kept as livestock in Canada are cattle, sheep, goats and bison, with cattle the most common. Nearly 96 per cent of Canada's enteric methane emissions in 2020 came from cattle (Environment and Climate Change Canada 2022e);[23] cattle produce the most methane per head of any ruminant. Enteric methane emission rates differ by cattle breed; dairy cows produce more enteric methane per head than non-dairy cattle[24] as they require more feed to meet the energy requirements of lactation. In general, higher energy requirements translates to more feed consumption, more enteric fermentation activity and more methane production. Canada's total methane emissions from enteric fermentation peaked at 30,821 kt $CO_2e$ in 2005 and declined 23 per cent since (Figure 10). This trend follows changes in the size of Canada's cattle population. The similarity in trends is in part by construction, as cattle population is a key activity factor in estimating methane emissions from enteric fermentation.

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[18] Our estimate includes: 92 kt $CO_2e$ from oil refining and storage, 824 kt $CO_2e$ from natural gas distribution, 140 kt $CO_2e$ from abandoned oil and gas wells, and 3,284 kt $CO_2e$ from oil sands mining and upgrading (Johnson and Tyner 2020b; Environment and Climate Change Canada 2022e; 2022f).

[19] Our estimate includes: 78 kt $CO_2e$ from oil refining and storage, 991 kt $CO_2e$ from natural gas distribution, 270 kt CO2e from abandoned oil and gas wells and 4,969 kt $CO_2e$ from oil sands mining and upgrading (Environment and Climate Change Canada 2022e; 2022f).

[20] This estimate excludes methane emissions from incomplete combustion in off-road farm vehicles and stationary farm equipment, grouped with forestry in the NIR. This exclusion is insignificant, as methane emissions from both sources is only 15 kt $CO_2e$ (Environment and Climate Change Canada 2022d).

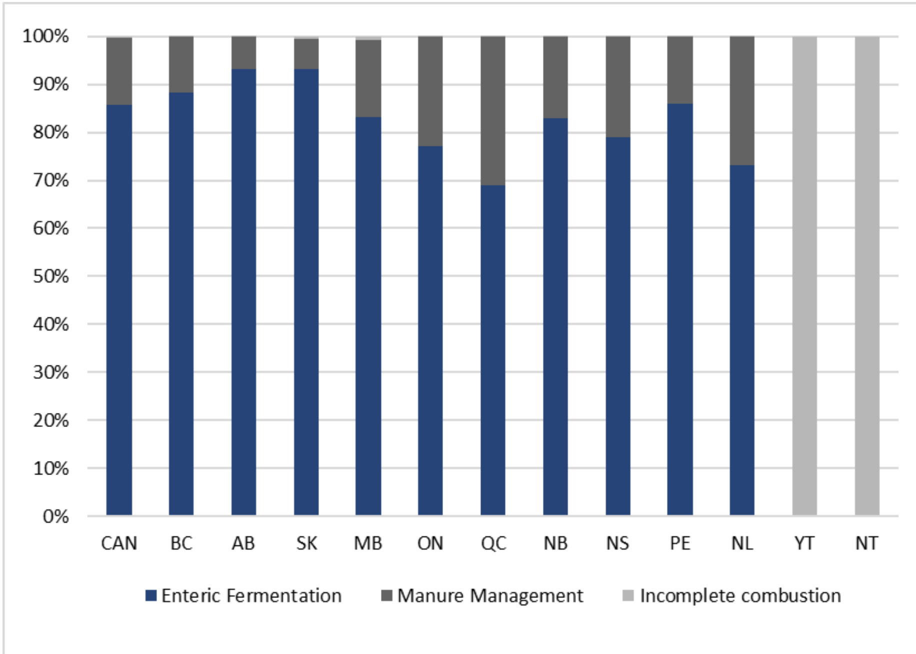
[21] Crop residues may be burned for disposal or to control disease, but the practice is becoming less common in Canada because of negative effects on soil quality and the environment (Shen et al. 2019).

[22] Some methane releases are from flatulence; estimates range from 1 to 5 percent of total ruminants' methane emissions (Agriculture and Agri-Food Canada 2008; Environment and Climate Change Canada 2022f).

[23] The NIR attributes 1,055 kt $CO_2e$ of methane emissions to other livestock in 2020. Most of these emissions are swine (527 kt $CO_2e$), sheep (182 kt $CO_2e$), buffalo (164 kt $CO_2e$) and horses (131 kt $CO_2e$).

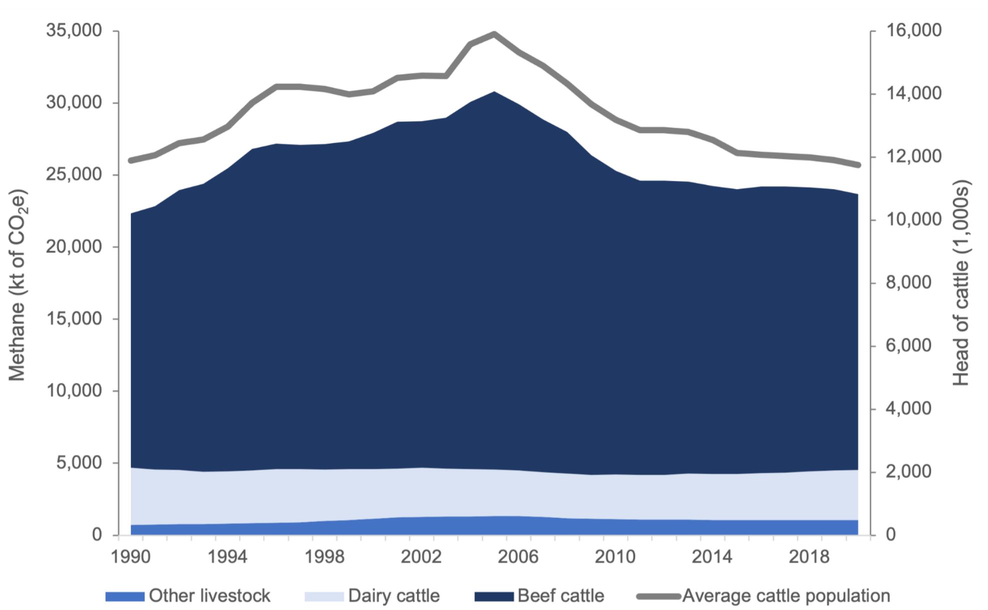
[24] Non-dairy cattle include all cattle on beef operations and non-lactating cattle on dairy operations (primarily heifers, which are females that have not yet given birth, and calves, which are under one year of age).

**Figure 10: 2020 Agriculture Methane Emissions Shares by Emissions Source by Jurisdiction**




Note: Incomplete combustion includes field burning of agricultural residues and stationary and off-road transportation in agriculture and forestry. Field burning is the majority (73 per cent) of incomplete combustion emissions. Nunavut has no reported methane emissions. Incomplete combustion from off-road transportation is 100 per cent of Yukon and Northwest Territories agricultural methane emissions. Incomplete combustion is a very small share of Canadian and provincial emissions.
Source: Authors' calculations using Environment and Climate Change Canada (2022d).

**Figure 11: Methane Emissions by Livestock from Enteric Fermentation**




Note: Emissions estimates from specific agricultural sources are only available nationally.
Source: Authors' calculations using Environment and Climate Change Canada (2022e).

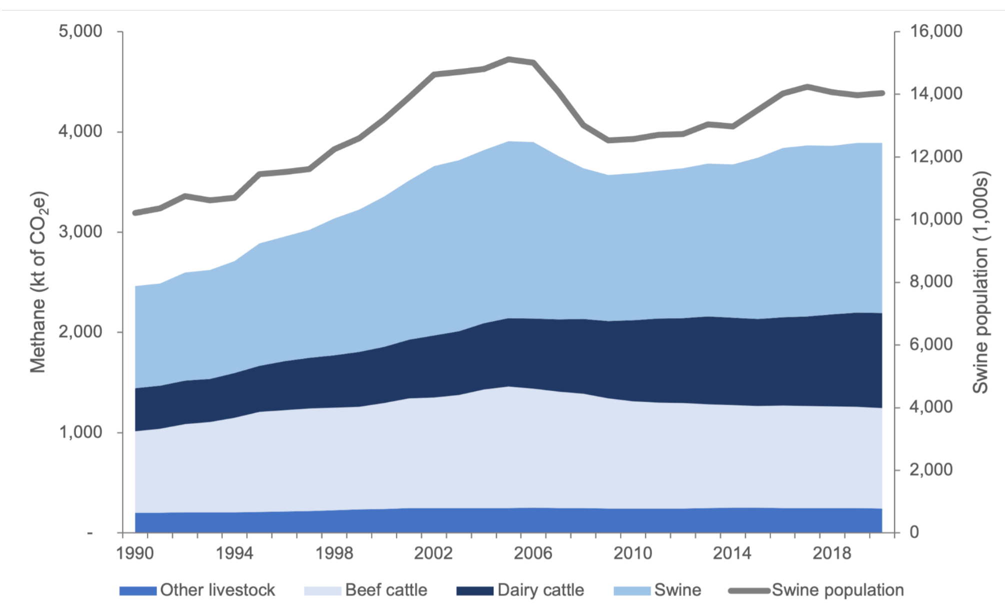
Enteric methane volumes per animal have increased over time for both non-dairy cattle and dairy cows. Between 1990 and 2020, the enteric methane emitted per dairy cow increased by 24 per cent. The cause of the emissions increase is major gains in milk production rates, with average dairy cow milk production increasing by 54 per cent over the same period (Environment and Climate Change Canada 2022f). Similarly, the average non-dairy cow today produces 6 per cent more enteric methane than in 1990, primarily because the weight of the average beef cow has increased due to market preferences, resulting in more feed required per animal.

The other significant share of Canada's methane from agriculture comes from livestock manure collection, storage and use. Manure undergoing anaerobic decomposition by methanogens releases methane. The manure's characteristics (influenced by the type of animal and feed) and manure management practices determine the rate of anaerobic decomposition and therefore methane production. Manure management systems, and practices within systems, vary regionally, by animal type and over time.

Manure storage is a major determinant of methane emissions volumes, as it sets the conditions for manure decomposition. Anaerobic conditions are more likely to occur in intensive agriculture operations where many animals are confined to an area and manure is stored in large piles, for example. Manure storage (dry vs wet) is an important factor in emission rates. Liquid manure management systems, where manure is stored wet in tanks or lagoons, generally result in more methane than solid, dry systems. Mixing water with the manure acts as a barrier to oxygen, increasing anaerobic decomposition.

Among livestock, swine manure is almost exclusively stored wet. Accordingly, it contributes the most methane from manure of any animal group and total methane emissions from manure management track closely with Canada's swine population (Figure 12). For dairy cows and heifers, Canada saw a shift from solid to liquid manure-management systems between 1990 and 2020, contributing to a 208 per cent increase in per-animal manure methane emissions (and a 119 per cent increase in total emissions from these sources). In contrast, manure from non-dairy cattle is typically stored dry. Due to the large population of non-dairy cattle, however, this group is still a marginally larger source of methane emissions.

**Figure 12: Methane Emissions by Livestock from Manure Management**




Source: Authors' calculations using Environment and Climate Change Canada (2022d; 2022e).

In addition to manure storage, frequency and timing of storage emptying and field spreading affects methane emissions. The sooner manure is moved from storage and spread on crops as fertilizer, where it experiences high oxygen exposure, the shorter the anaerobic decomposition period and the less methane emitted. Climate and weather can also affect methane production, as warmer temperatures and rainfall both increase methanogenic activity.

These differences in sources highlight important differences in potential policy actions and policy focus for addressing enteric fermentation emissions compared to manure-sourced methane. We turn to mitigation options and costs next, and then conclude with a discussion of Canada's current policy environment.

### *Mitigation Options and Costs*

Policies implementing the polluter-pays principle in the agriculture sector — where agricultural producers are taxed or otherwise pay for greenhouse gas emissions resulting from their operations — has been stifled, both globally and in Canada, by concerns about imposing costs on producers and resulting competitiveness and emissions leakage effects (OECD 2019). Many of these concerns reflect the challenges associated with the costs of emissions measurement, reporting, and verification. Specifically, the agriculture sector is comprised of a large number of heterogeneous producers with mostly diffuse sources of emissions. In contrast, costs associated with measurement, reporting and verification of these emissions are fixed and invariant to farm size (Bellassen et al. 2015). Producers therefore face proportionally different cost burdens from participation in mitigation policies, including emissions-pricing schemes. For example, producers operating more intensive, confined livestock operations (i.e. more easily measured and managed point-source emissions) will have lower emissions-tracking costs in comparison to a smaller-scale grazing operation (i.e. more diffuse emissions, less easy to measure and manage). Using emissions proxies and process-based emissions models instead of direct emissions measurements can help reduce differential costs. Even after accounting for this reduction, however, these approaches are less effective and less cost-effective overall than policies that target emissions directly (OECD 2019).

An alternative to polluter-pay policies is beneficiary-pay policies, where producers are paid for emissions reductions. Examples include government subsidies and offset markets, administered either by the government or as subscription-based private programs where farm-product consumers pay for methane reductions at the farm level. Adoption of expensive technologies such as anaerobic digesters are especially well-suited to support through beneficiary-pays approaches (Kay and Sneeringer 2011). Similar to the challenges facing polluter-pay policies, beneficiary-pay policies risk introducing distortions into agricultural markets. Offset markets, for example, are criticized for the high cost imposed on producers for registering and marketing emissions reductions, disproportionately affecting smaller producers. It can also be difficult to measure the offsets' additionality, showing that the emissions reduced are a direct result of the offset program and not a reduction that would have otherwise occurred. To mitigate these challenges, hybrid market-based approaches may be favourable. These include tax-and-subsidy policies that recycle emissions tax revenue back to producers to subsidise adoption of low-emission technologies (similar to the model used for large emitters across Canada) or emissions-permit trading schemes.

Governments can also implement policy aimed at creating an enabling market environment. They can help companies overcome barriers to producing methane-reducing feed additives and technologies at scale, for example, through financial support and incentives or fostering cross-sector partnerships. Another tool is introducing standards and labelling schemes to signal low-GHG products (for both agricultural inputs and outputs).

The most common and well-researched strategy to reduce methane is to alter an animal's diet by improving feed efficiency. Depending on the animal and the composition of its feed, cattle can lose between 2 and 11 per cent of feed energy as enteric methane (National Center for Environmental Economics 2014). This represents a loss of energy that the animal could otherwise use to produce muscle or milk. Improving feed efficiency reduces both methane emissions and producer feed costs, creating a natural incentive for producers to invest in reducing enteric methane emissions. Changing the type, quality and composition of feed improves livestock feed efficiency. Increasing fat and grain in rations, for example, are ways to reduce methane from livestock (Agriculture and Agri-Food Canada 2019b; 2020a). Of all feed types, high-grain rations where more than 90 per cent of the animal's dietary dry matter is grain has the most meaningful methane reduction, of 10 to 100 per cent (Agriculture and Agri-Food Canada 2008). Certain grains achieve greater methane reductions; for example, corn is preferred over barley.

There are, however, trade-offs associated with a switch to high-grain feed. First, feeding livestock with grain can counteract the benefit of them converting fibrous material unsuitable for direct human consumption into milk and meat. Grain not otherwise suited to human consumption, such as malting barley, avoids this trade-off. Second, increased grain production requires increased production and transportation of chemical nitrogen fertilizer, an emissions-intensive product. Another trade-off in feed selection is that feed high in dietary protein can cause higher excess nitrogen excretion, resulting in higher $N_2O$ emissions — more potent than methane — from manure (The National Centre for Livestock and the Environment n.d.). Further research to assess the lifecycle greenhouse gas emissions associated with different livestock diets is necessary to quantify the trade-offs and climate benefits of a change.

Another mitigation strategy is adding substances hindering methane production to animal feed. There are natural compounds, synthetic chemicals, and fats and oils that inhibit methanogenic activity in the rumen when added to livestock feed. For example, Kinley et al. (2020) show that Australian beef steers receiving feed made up of 0.10 per cent and 0.20 per cent Asparagopsis (red seaweed) have decreased methane emissions of up to 40 per cent and 98 per cent, respectively. Another option is to add nitrates, which improves rumen fermentation and changes the pathway of hydrogen to produce ammonia rather than methane (Troy et al. 2015; Duthie et al. 2018). Other feed additives causing less enteric methane include ionophores (an antimicrobial agent) and fats or oilseed. Promising additives include plant extracts, biochar, and chemical compounds such as 3-nitrooxypropanol. Hristov et al. (2015) find 3-nitrooxypropanol reduces methane from dairy cows by 30 per cent. Other feed-related mitigation strategies include feeding cattle forages at optimum maturity, which can maximize digestible energy content and reduce methane emissions by eight per cent, and formulating rations to better match animal nutritional requirements (Boadi and Wittenberg 2002).

Producers using grazing systems have fewer options to alter feed. The most readily available option is to improve feed efficiency through pasture management, which involves practices to increase the quality and availability of forage (Agriculture and Agri-Food Canada 2008). A common strategy, for example, is to time grazing to match peak grain quality.

Non-feed-related ways to reduce enteric methane include genetic selection and potentially vaccination. Certain animals have higher feed-conversion ratios than others, which means they are better at converting feed into functional energy, with less energy lost as enteric methane. Genetic selection to foster this trait can lead to more efficient animals that emit less methane (Basarab et al. 2013). Research is underway developing animal vaccines that prevent or reduce enteric methane production. Agriculture and Agri-Food Canada (2019b) estimates ten years before a vaccine may be ready for deployment, however.

Improving the productivity of individual animals (fewer livestock to achieve the same farm-level output) reduces both enteric methane and methane from manure. Options for achieving lower livestock populations include extending dairy cows' lactation period by switching to more efficient breeds or improving reproductive performance; shortening the time to market for beef cows by increasing rates of weight gain; improving cows' birth rate to require fewer replacement heifers; and culling the breeding herd based on breeding soundness.

In manure management, practices that increase aeration and exposure to oxygen and inhibit methanogenic activity reduce methane emissions. This includes choosing dry systems over liquid systems where possible, storing manure at cooler temperatures, separating solid and liquid manure, and emptying storage systems more frequently. Biological filters can also be used to remove methane from manure, and composting manure can reduce methane emissions (though it may increase $N_2O$ emissions).

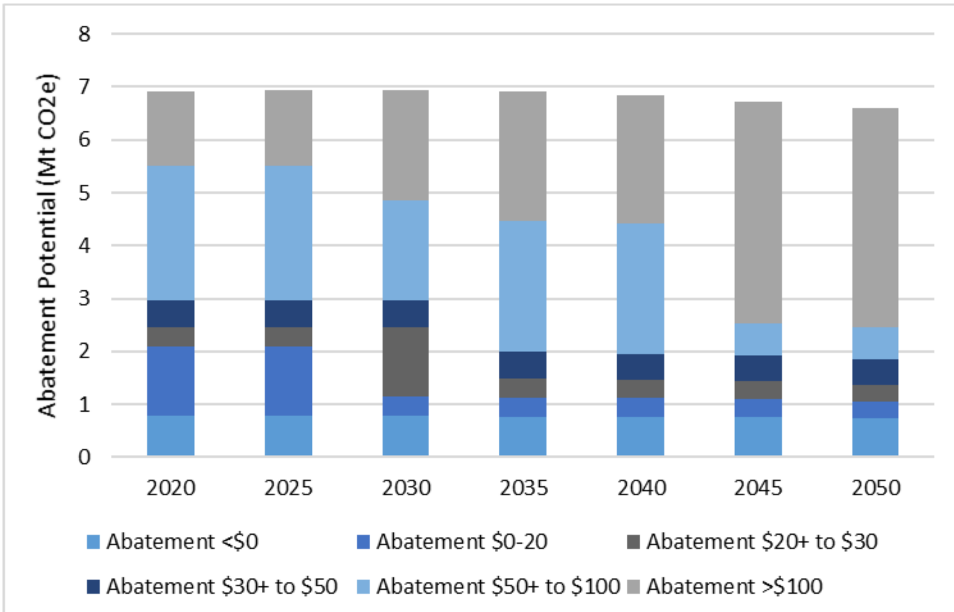
A higher-impact approach is using an anaerobic digester, a facility that captures methane from micro-organisms decomposing manure in the absence of oxygen. The captured methane becomes fuel, offsetting farm fossil-fuel needs. Anaerobic digesters have the potential to significantly reduce methane from manure, but there are barriers to widespread adoption at individual farms (Clark, Wright, and Slomp 2015). First is technical feasibility, including farm infrastructure and design and electricity grid connection. Some farms may lack the infrastructure to accommodate a digester, and the capital investment and technical expertise required to make these changes may act as barriers to uptake. Second is installation costs and electricity and natural gas prices, which influence a farm's cost-benefit decision around deriving its energy and electricity needs from anaerobic digestion.

Finally, while not an explicit mitigation strategy, beef demand plays a significant role in determining methane emissions from both enteric fermentation and manure management. Accordingly, dietary shifts, such as growing demand for plant-based meat substitutes, have the potential to contribute to reductions in methane emissions. Heller and Keoleian (2018) find the production process for a plant-based burger generates 90 per cent fewer greenhouse gas emissions relative to a conventional beef patty. The per capita availability of beef in Canada — a proxy for consumption — has been decreasing for the last 45 years, falling by over 50 per cent since its peak in the mid-1970s (Statistics Canada 2021a; 2021b; 2021c). The cattle population, in contrast, has fallen by less than 20 per cent over this same period, with per capita domestic consumption declines offset by growth in both Canada's population and in cattle and beef exports (Statistics Canada 2020). Recent surveys show that only 25 to 50 per cent of Canadians are open to reducing their beef consumption (Charlebois, Somogyi, and Music 2018; Angus Reid Institute 2019; Agri-Food Analytics Lab 2021), and both Canada's population and global demand for beef are forecast to grow (Statistics Canada 2019; OECD/FAO 2021). Accordingly, it seems unlikely that domestic growth in plant-based meat consumption will translate into significant reductions in methane emissions.

Cost estimates of methane abatement in the agricultural sector vary both within and between mitigation strategies. Manure management costs range from -\$27 to +\$200 USD per tonne of $CO_2e$, while livestock management costs range from \$0 to +\$1378 USD per tonne of $CO_2e$ (Martin and Riordan 2020; DeFrabrizio et al. 2021; Navius Research Inc. 2021; Agricultural Policy Framework Task Force 2022). Methane abatement costs from agriculture have such high variability due to uncertainty in both GHG reduction potential and costs (Weersink et al. 2005; Navius Research Inc. 2021). Negative costs in manure management may stem from anaerobic digesters' ability to create heat and electricity revenue, which the Environmental Protection Agency values at \$65 USD per head (U.S. EPA 2019). Additionally, older farms may find it more difficult and costly to incorporate the aforementioned mitigation methods, while newer operations may see more profitable results (Weersink et al. 2005).

The above challenges, combined with lack of data on specific methane sources and farm or facility characteristics makes constructing a marginal abatement cost curve for Canada impossible. Therefore, it is difficult to make compelling comparisons to the cost of emissions, which sits at \$50 per tonne $CO_2e$ in 2022, rising to \$170 in 2030. That said, there is some evidence on the range of possible abatement costs in Canada. Martin and Riordan, for example, suggest the average agricultural abatement cost exceeds Canada's carbon price at \$88 per tonne of $CO_2e$ (Martin and Riordan 2020). However, other work points to abatement methods that fall under the cost of carbon, such as manure composting, feed additives and intensive rotational grazing. Navius Research Inc. (2021) discusses abatement methods to reduce GHG emissions in British Columbia. Manure composting has the lowest abatement cost of \$5-13 per tonne of $CO_2e$, with an upfront cost of \$21,429 and zero operating costs, whole feed additives and intensive rotational grazing have higher abatement costs at \$8-58 and \$28-60 per tonne of $CO_2e$, respectively (Navius Research Inc. 2021). Additionally, they have no upfront costs and operate at a cost of \$25/head/year for feed additives and \$24/hectare/year for intensive rotational grazing. Although manure composting is more cost-effective, feed additives and intensive rotational grazing have three times the GHG reduction potential (Martin and Riordan 2020; DeFrabrizio et al. 2021; Navius Research Inc. 2021; Agricultural Policy Framework Task Force 2022).. Finally, the U.S. EPA provides estimates of methane abatement potential and costs over time for livestock in Canada (Figure 13), calculating abatement is only available for 20 per cent of livestock methane emissions in any given year. However, 28 to 43 per cent of emissions that can be abated have costs below $50 USD per tonne of $CO_2$e, and an additional third of abatement options between $50 and $100 USD per tonne $CO_2$e (United States Environmental Protection Agency [EPA] n.d.).

**Figure 13: Livestock Methane Abatement Potential and Costs (USD), 2020 to 2050**




Note: Costs in USD per tonne $CO_2$e. Total abatement potential is 20 per cent of agricultural emissions in each year. Data does not match abatement actions to costs; abatement actions include feed additives, antibiotics, growth hormones and intensive grazing.
Source: US EPA (n.d.).

### *Current Policy Approach and Gaps*

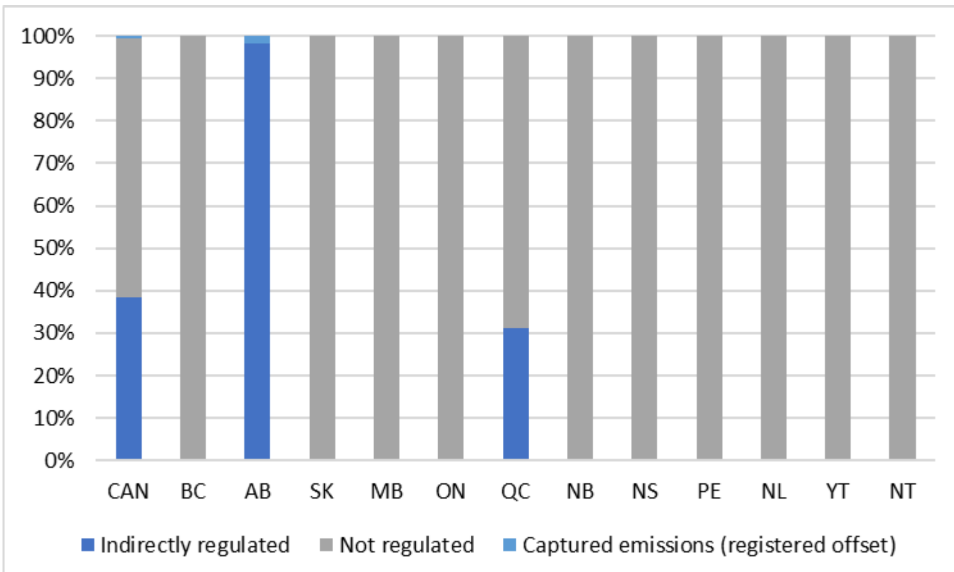
As almost all of Canada's agricultural methane emissions come from livestock, mitigation efforts are primarily focused on farm-level livestock management practices. There are currently no regulations in Canada requiring management and reduction of agricultural methane. Federal and provincial carbon pricing programs exclude non-$CO_2$ emissions and most combustion emissions from agriculture. As a result, methane emissions from agriculture are the largest source of unregulated and unpriced greenhouse gas emissions in Canada. This lack of regulation is consistent with other countries and reflect the challenges we describe above. Canada's federal and provincial governments have instead implemented voluntary programs that seek to reward participating farmers for greenhouse gas reductions at the farm level. Such programs include carbon credit schemes, farm-level planning support and funding opportunities.

In June 2022 the Government of Canada launched its offset market via the Canadian Greenhouse Gas Offset Credit System Regulations (Environment and Climate Change Canada n.d.).Three provinces — BC, Alberta, and Quebec — have government-run offset markets, Saskatchewan is developing an offset system (Saskatchewan Ministry of Environment 2019; Government of Saskatchewan 2020), and Manitoba and New Brunswick are exploring their potential (Government of Manitoba 2017; 2018; Government of New Brunswick 2019). New Brunswick's OBPS allows for offset credits but no market is established. Nova Scotia passed an act to create an offset market in 2010, but is not in force (Nova Scotia 2010). The remaining provinces and territories have taken no action in developing offset markets.

Alberta and Quebec are currently the only jurisdictions with offset protocols for agriculture, though the federal government is developing a protocol for livestock feed management (Environment and Climate

Change Canada n.d.). Both provincial markets include protocols that allow participating farmers to earn tradable emissions credits for specific practice improvements resulting in greenhouse gas reductions. Alberta's system currently includes three protocols relevant to methane: feedlot practices, whereby farmers earn credits for emissions reductions through decreasing the amount of time cattle spend in high-density, confined feedlots; genetics, whereby farmers earn credits for emissions reductions from breeding cattle for more efficient feed conversion rates; and biogas, whereby farmers earn credits for generating biogas from agricultural waste (Government of Alberta n.d.). In Quebec's system, the only protocol for agricultural methane is capture and destruction of methane from covered manure storage facilities (Québec 2017). Together, these protocols indirectly regulate 39 per cent of Canadian methane emissions, though this percentage reflects the potential coverage rather than actual. Specifically, manure accounts for 31 per cent of Quebec's agricultural methane emissions, but there are no projects in its offset registry (Ministère de l'Environnement et de la Lutte contre les changements climatiques n.d.). Alberta has two biogas projects and three cattle-feed projects registered and active in its offset market, with annual emissions reductions of approximately 157 kt $CO_2e$ (1.6 per cent of Alberta's and 0.6 per cent of Canada's agricultural methane emissions). The biogas facilities' feedstocks include livestock manure, animal by-products, and organic residues, overstating potential reductions in agriculture (Alberta Carbon Registries n.d.; n.d.c).

**Figure 14: Approximate Policy Coverage of Agricultural Methane Emissions by Jurisdiction**




Note: The emissions shares are a best-case scenario in the absence of data on emissions by source cross-tabulated with the policy gaps described here. Only Alberta has registered offset projects; captured emissions are overstated as the biogas offset projects include non-agricultural organic waste.
Source: Authors' calculations from Environment and Climate Change Canada (2022d) and Alberta Carbon Registries (n.d.).

With programs coming into effect across the country, emissions offset markets — and accompanying agricultural methane protocols — are expanding. There is additional indirect potential coverage from federal and provincial clean fuel standards. These require renewable blending in transportation fuels, with eligible feedstocks including animal waste. The standards create an alternative market for manure methane abatement, where fuel-providers purchase captured methane to meet their blending requirement, and one potentially less complex than an offset market. However, scalability and cost may be a barrier (Williams 2022). The federal Clean Fuel Regulation includes a tradeable credit market for fuels produced from renewable feedstock (including animal waste), but again scalability, cost and administrative complexity may limit participation from agricultural sources (Williams 2022). Finally, the federal and provincial emissions pricing systems exempt biomass combustion emissions. This creates an incentive for on-farm fuel switching via an anaerobic digester. Similarly, BC's offset market includes a protocol for fuel-switching, another potential nudge (Government of British Columbia n.d.).

While not originally developed to target methane emissions, Environmental Farm Programs (EFPs) are another mechanism that can support farm-level emissions reductions. EFPs are voluntary plans that farmers complete to increase their environmental awareness and reduce agricultural operations' impact. EFPs may address energy efficiency, livestock facility management, manure storage and handling, pasture management, soil management, and nutrient management. Although only a small number of provinces have identified EFPs as part of their climate change strategy (Government of New Brunswick 2016; Government of Newfoundland and Labrador 2019), they are available to farmers across the country, generally administered through provincial not-for-profit farm organizations and funded through joint federal-provincial agreements under the Canadian Agricultural Partnership. As a result, they represent a significant opportunity to establish widespread farm-specific plans for methane emissions reductions.

Through the Agricultural Greenhouse Gases Program, the Government of Canada also funded research and pilot projects that assess opportunities for farm-level GHG reductions (Agriculture and Agri-Food Canada 2018). The program specifically supported research on methane mitigation, with livestock systems identified as one of its key priority areas. Currently approved projects consider opportunities for emissions reductions across all aspects of livestock systems, including feed selection and grazing, and animal and manure management systems. Lastly, the Government of Canada developed software to estimate GHGs for individual farms and scenario analysis of mitigation options (Agriculture and Agri-Food Canada n.d.).

## Waste

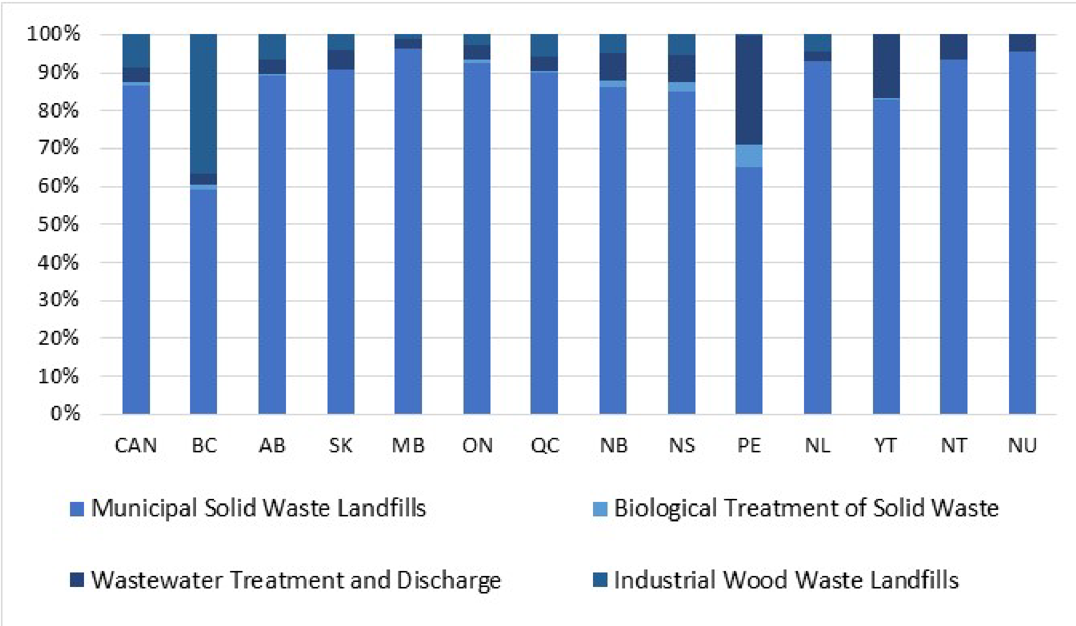
### *Sources*

The waste sector accounted for 25,547 kt $CO_2$e of methane emissions in 2020. Methanogenic activity from organic solid-waste disposal comprises the majority of these emissions: municipal solid waste (MSW) landfills (22,135 kt $CO_2$e/87 per cent of total waste methane emissions) and industrial wood waste landfills (2,178 kt $CO_2$e/9 per cent). The remaining emissions in the sector are from wastewater treatment and discharge (1,052 kt $CO_2$e/4 per cent), biological treatment of solid waste (178 kt $CO_2$e/1 per cent), waste incineration and open burning (1 kt $CO_2$e/0.004 per cent), and incomplete combustion of landfill gas used for heat or energy (2.8 kt $CH_4$/0.01 per cent). In the first two cases, methane emissions are a result of methanogenic activity, while in the latter case emissions are from incomplete combustion. Figure 15 shows slight variation across provincial and territorial sources, with outliers defined by methane emissions from wood waste (BC) and wastewater (PEI and Yukon).

MSW landfills are regulated, publicly run facilities that are the primary destination for most Canadian waste. This includes residential, industrial, commercial and institutional sources, as well as waste from construction and demolition activity (Environment and Climate Change Canada 2022f). Anaerobic decomposition of buried organic waste by methanogens creates landfill methane emissions. Organic waste is any waste that is composed of natural materials or is derived from a live source. This includes food waste, yard and park waste, paper and cardboard, wood, textiles, disposable diapers, pet waste, sludge, rubber, leather, and construction debris.

Industrial wood-waste landfills are private operations by companies in the pulp and paper and solid wood industries. All provinces have emissions from wood waste landfills, though this is dominated by BC (Figure 15). Nearly 100 per cent of the waste in these landfills is organic matter. As a result, despite accounting for a small fraction of the total waste sent to landfill (0.4 per cent in 2020), industrial wood-waste landfills account for nearly 9 per cent of total methane emissions attributable to landfills (Environment and Climate Change Canada 2022d). Importantly, this is because of an assumption that there is no methane capture or flaring at these sites. These emissions estimates do not include methane emissions from incomplete combustion in the pulp and paper sector.

**Figure 15: 2020 Waste Methane Emissions Shares by Emissions Source by Jurisdiction**




Note: Not included in the figure are methane emissions from incomplete combustion of landfill gas used for heat or energy (2.8 kt $CH_4$/0.01 per cent of waste methane emissions) and waste incineration and open burning (1 kt $CO_2e$/0.004 per cent). The estimates for the former are only available nationally.
Source: Authors' calculations from Environment and Climate Change Canada (2022d).

Waste starts decomposing in a landfill 10 to 50 days after deposit (Environment and Climate Change Canada 2022c). Decomposition follows an exponential decay function, with annual methane emissions linearly related to the annual amount of decomposed waste. Accordingly, methane emissions are highest in the initial years after waste deposit and decrease exponentially over time. Landfills may emit methane for 100 years or more, with most of the emissions occurring in the first 20 years after deposition (Levelton & Associates Ltd. 1991 as cited in Environment and Climate Change Canada 2022e).

The largest determinants of landfill methane emissions are the quantity of organic waste deposits and the relative composition of the waste. The latter is important as only a portion of any type of organic waste is degradable and further, only a portion of degradable waste will decompose under landfill conditions. The IPCC refers to these characteristics as the share of degradable organic carbon (DOC) and the fraction of degradable organic carbon decomposed ($DOC_F$). The DOC and $DOC_F$ determine the fraction of organic waste that will decompose and generate methane emissions. For example, the IPCC estimates the DOC and $DOC_F$ for food waste are 15 and 70 per cent, respectively. This implies that, on average, for every one tonne of food waste deposited, 0.105 tonnes (10.5 per cent) will generate methane emissions. The IPCC estimates of DOC values for specific categories of organic waste range from a low of 15 per cent for food waste to a high of 43 per cent for wood (IPCC 2006). The $DOC_F$ ranges from a low of 10 per cent for less-decomposable waste to a high of 70 per cent for highly decomposable waste (IPCC 2019).[25]

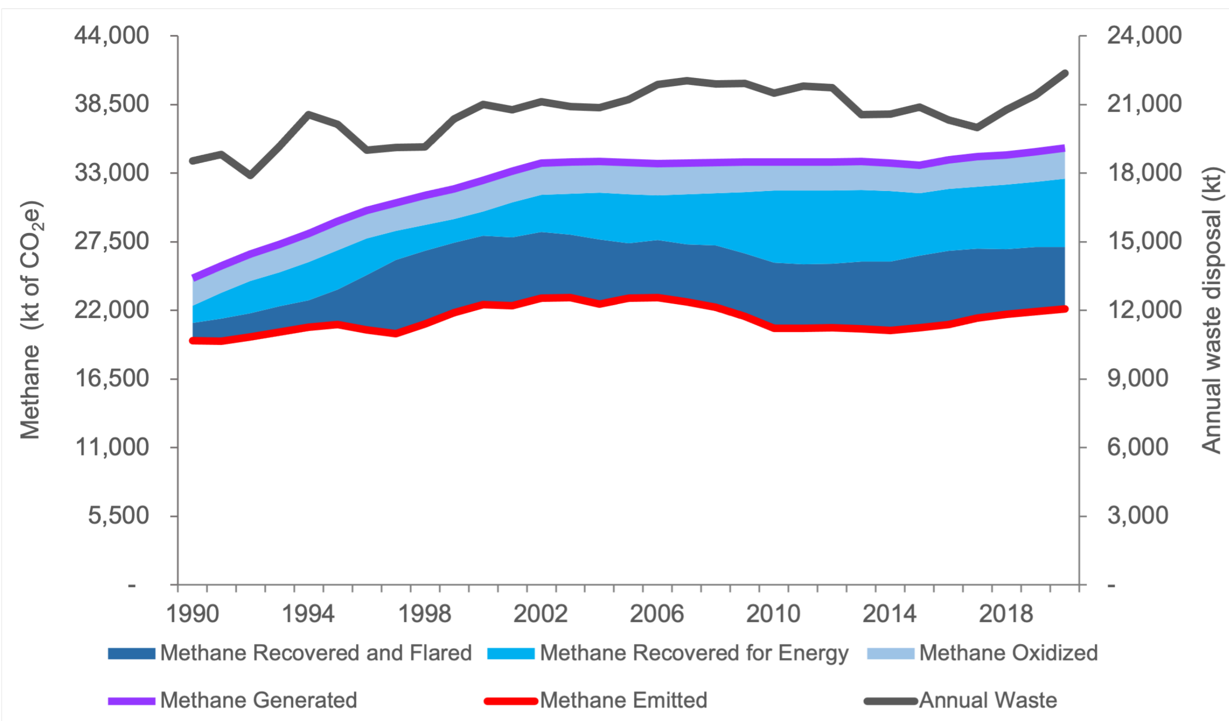
[25] Examples of highly decomposable waste are food waste and grass; examples of moderately decomposable waste are paper products; and examples of less decomposable waste are tree branches and harvested wood products (IPCC 2019). Notably, however, there can also be significant variation within these categories. For example, the IPCC guidelines also note that the $DOC_F$ for paper products ranges from 21 to 96 per cent.

Another important determinant of methane emissions from landfills is decomposing waste's rate of exponential decay. A higher rate of exponential decay means that waste will decompose faster, which in turn means that it will emit higher amounts of methane in the years after initial deposit. This is again influenced by the type of landfilled waste, with highly decomposable waste (organic waste with a higher $DOC_F$) tending to break down at a faster rate. As waste decomposition is a microbial reaction, the environmental conditions of the landfill will also influence methane emissions.

Last, methanogen oxidization by the landfill cover affects fugitive methane volumes. Landfill regulations typically require that landfill sites put down a daily cover of soil or other material, and a final cover when a landfill is at capacity and will no longer be used. Oxidization occurs when the methanogens generated by organic decomposition pass through the cover and react with methane-consuming bacteria (methanotrophs). The reaction converts the methane to carbon dioxide, which, although still a greenhouse gas, is preferable to methane due to its smaller global warming potential.

A unique attribute of methane emissions from landfills is that only accumulated waste matters in determining current-year emissions. While current decisions about waste diversion and treatment are still important, these decisions only reduce future methane emissions. Methane generation from previously landfilled organic waste's decomposition is unavoidable and mitigation is only possible through landfill cover or methane capture. This is most evident when considering the trends in landfill methane emissions over time. For example, despite annual waste deposits to MSW landfills fluctuating from one year to the next, the amount of methane generated follows a relative smooth path (Figure 16). A steady drop in emitted methane between 2006 and 2010 is only due to substantial increases in volumes of methane captured and flared (+650 kt $CO_2$e) and captured and used for energy (+2,250 kt $CO_2$e) at landfill sites.

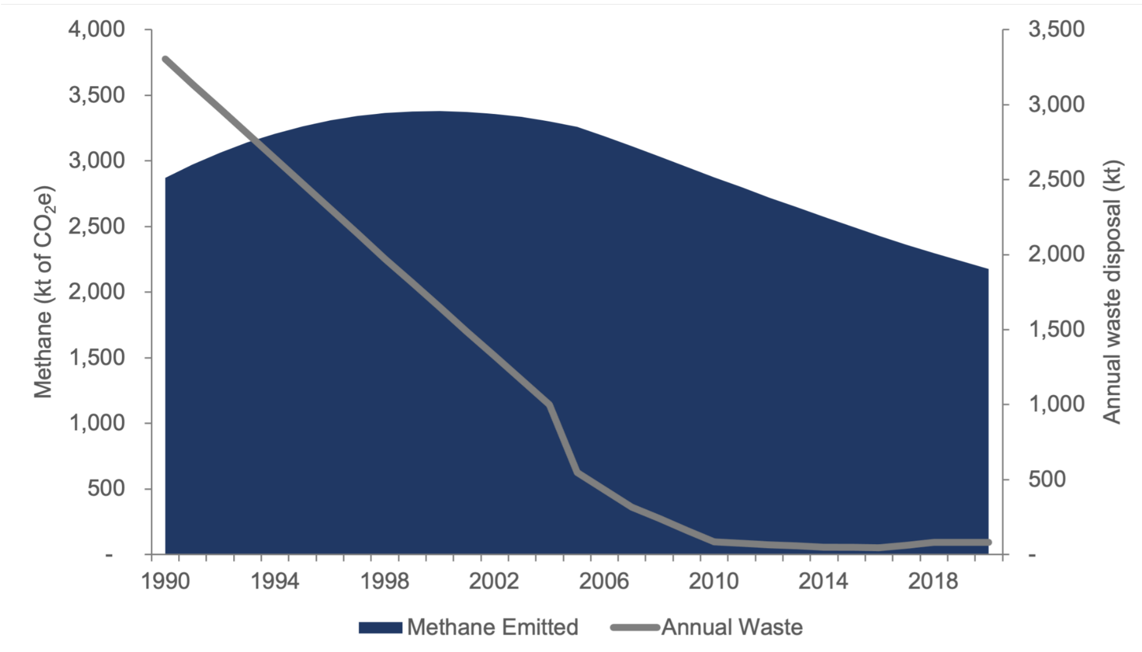
**Figure 16: Methane Generated from Municipal Solid Waste Landfills**




Note: Methane emitted is equal to methane generated less the amounts of generated methane that are oxidized, recovered and flared, and recovered for energy (used as biogas for heat or electricity generation).
Source: Authors' calculations using Environment and Climate Change Canada (2022e).

The effect of accumulated waste on annual methane emissions is even more pronounced in wood waste landfills, where annual deposited waste decreased by 98 per cent between 1990 and 2020 (Figure 17). In comparison, annual methane emissions declined by only 24 per cent over the same period. Further, annual methane emissions did not start decreasing until 2001, by which point estimates of deposits to wood waste landfills had already fallen by 55 per cent relative to their peak in 1990.

**Figure 17: Wood Waste Landfill Methane Emissions**




Note: The NIR assumes that none of the methane generated at wood waste landfills is captured and combusted. Rather, all generated methane emits to the atmosphere.
Source: Authors' calculations using data from Environment and Climate Change Canada (2022e).

Methane emissions from wastewater are a function of the water's organic load. The key measure is the per-capita organics loading rate,[26] which approximates each individual's daily contribution to the organic load in wastewater. As this measure increases, the amount of organics subject to decomposition, and accordingly methane emissions, also increases. It is more common in Canada for organic waste to be treated or to decompose in an aerobic treatment system, where the availability of oxygen suppresses methanogenic activity. In 2020, only 22 per cent of Canada's population discharged their wastewater to an anaerobic treatment system that generates methane emissions.[27] The most common is a septic system (serving 15.3 per cent of Canada's population), where approximately half of the organic load in wastewater settles in a septic tank and decomposes under anaerobic conditions (Scheehle and Doorn 2001).[28]

Biological treatment of solid waste accounts for methane emissions from both composting and anaerobic digestion. Composting organic waste means it decomposes in an aerobic environment and does not generate any methane emissions. In practice, however, it is nearly impossible for a composting site to maintain

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[26] Measurement is $BOD_5$/person/day, where $BOD_5$ (five-day biological oxygen demand) measures the amount of oxygen consumed by microorganisms over a 5-day period while breaking down organic matter found in wastewater.
[27] We classify a wastewater treatment system as anaerobic if its methane correction factor, which converts the theoretical maximum organic load in wastewater to a methane emissions factor, is 0.1 or greater.
[28] The remaining half of the organic load in septic systems flows through to a drainage field and decomposes under aerobic conditions.

aerobic conditions for all deposited waste at all times. As a result, while composting leads to a drastic reduction in methane emissions relative to landfills, all compost sites will generally have some small level of methane emissions.[29] The key determinant of methane emissions from composting is how well a compost site is able to maintain aerobic conditions. Beyond this, they are subject to the same determinants as methane emissions from a solid waste landfill. Key among these is the oxidization rate as compost has a high share of methanotrophic bacteria, which will oxidize a significant share of the methanogens formed in anaerobic pockets of the compost site (Lou and Nair 2009). Anaerobic digesters are an alternative option for organic waste treatment. Similar to the agriculture sector, organic waste that is sent to an anaerobic digester is broken down by micro-organisms in an environment without oxygen. The resulting methane emissions are captured and upgraded and the biogas is used as fuel. Direct methane emissions from anaerobic digesters are the amount of gas that is lost through on-site leakage.

*Mitigation Options and Costs*

In this section, we focus on mitigation options for methane emissions from solid-waste landfills, as there are few mitigation options for methane emissions from biological treatment of solid waste and wastewater treatment. Biological treatment of solid waste is itself a mitigation option (it avoids sending waste to landfill). Further reducing emissions therefore requires reducing waste generation. The main option for mitigating methane emissions from wastewater treatment is to transition treatment technologies from anaerobic to aerobic systems. However, the largest source of anaerobic wastewater emissions in Canada is septic systems, with limited aerobic replacement options.

Mitigation options for methane emissions from the waste sector generally fit in two categories: upstream diversion and downstream recovery. With upstream diversion, organic waste is rerouted from a waste management stream where it will undergo anaerobic decomposition. With downstream recovery, the anaerobic decomposition of organic waste continues to generate methane emissions but landfill management strategies lead to the reduction or capture of these emissions before they are released to the atmosphere.

There are multiple diversion options. The primary option in waste management is to send waste to an incinerator or energy-from-waste facility. Facility capacity limits this, however. Canada had 46 publicly owned thermal waste facilities in 2018 (Statistics Canada 2021c). ECCC classifies only six of these facilities as large, however, and only a small share (approximately 4 per cent in 2020) of municipal solid waste is incinerated each year (Environment and Climate Change Canada 2019; 2022f). Additionally, since 2010, five major waste-to-energy projects were cancelled, largely attributable to two factors. First, incineration is higher cost than landfilling, and second, current waste-reduction efforts create uncertainty around the volume of future waste streams and whether they will be sufficient to support a thermal treatment facility (Chung 2018). Of additional concern is whether new thermal waste facilities may negate waste diversion efforts. Baxter et al. (2016), for example, find that individuals are less likely to divert waste (compost or recycle) if they know waste is sent to a thermal treatment facility.

These limitations on facility-level waste diversion create a strong argument for focusing efforts at households and businesses, incentivizing diversion though penalties or substitutes (Ragan et al. 2018; Winter 2022). The two most common options are recycling and composting. Recycling, which is primarily an option for paper and wood waste, diverts organic waste from the waste stream. Accordingly, it completely mitigates methane emissions. Composting, in comparison, is primarily a diversion option for food and yard (garden) waste, soiled paper products and pet waste.[30] Initiatives that aim at reducing waste or reusing items that may otherwise enter the waste stream also fall in the diversion category. Unlike

[29] We estimate that composting reduces total lifetime decomposition emissions by 96 to 99 per cent relative to landfills, following the NIR methodology for methane missions from landfilled waste and composting.
[30] Some municipalities also accept diapers and smaller types of wood waste (e.g., popsicle sticks or wood shavings) in their composting programs.

recycling and composting, which are generally only applicable to specific subcategories of organic waste, reduce and reuse options exist across all organic waste categories. Notably, however, while government can directly support — and even legislate — use of recycling and compost, opportunities for direct government involvement in reuse and reduce initiatives are more limited. The most common avenues of government involvement tend to be indirect and can include education campaigns, funding opportunities and research.

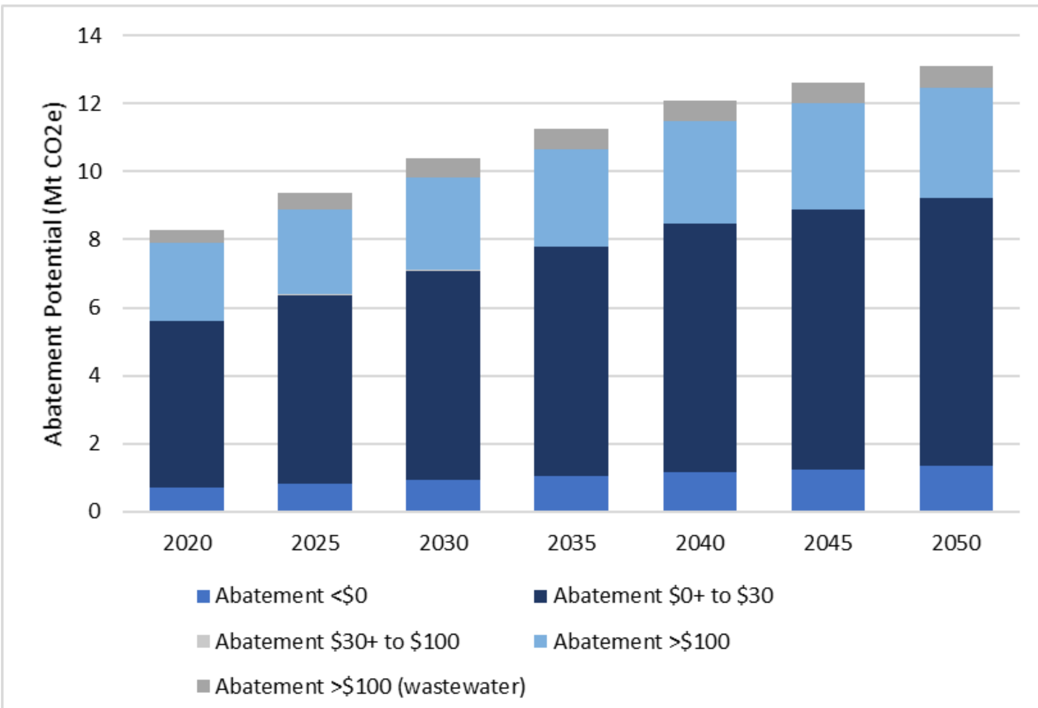
Substantive increases in composting and recycling over the last 30 years, largely motivated by the introduction of municipal collection programs, has helped to limit the growth in landfilled waste. Despite this shift, however, organic waste continues to make up the majority of landfilled waste in Canada each year. In 2016, Canada sent 20.3 million tonnes of waste to landfill, with organic waste accounting for 63 per cent of this total (Environment and Climate Change Canada 2020c). The two largest sources of landfilled organic waste are paper (2.5 million tonnes) and food (5.8 million tonnes), two categories for which diversion alternatives are readily available. Further, the national paper diversion rate was only 57 per cent in 2016 while the diversion rate for food and yard waste was only 27 per cent. Diversion of these sources likely require municipalities changing how they collect and charge for waste; for a detailed discussion of these options see Ragan et al. (2018). Municipal budget constraints may also hinder diversion efforts. These factors, along with the lag between increases in waste diversion and decreases in landfill methane emissions, necessitates downstream recovery policies to achieve significant reductions in methane emissions from waste.

There are two primary options for reducing methane from landfills. The first is landfill gas recovery, where wells are drilled into the landfill to retrieve methane. The retrieved methane is pumped to the surface, processed, and is then flared, used for generating heat or electricity, or sold as renewable natural gas (U.S. Environmental Protection Agency n.d.). In 2020, landfill-gas recovery systems captured 418 tonnes of methane (10,450 tonnes $CO_2e$), 30 per cent of total landfill methane emissions (Environment and Climate Change Canada 2022g). The second option is through landfill cover. The landfill cover oxidizes methanogens and reduces the amount of atmospheric methane released. The NIR's estimation methodology assumes an oxidization rate of 10 per cent, corresponding 2020 mitigation of just under 2,500 kt $CO_2e$. There is evidence that this rate is likely an underestimate, though the estimates are not Canada-specific (Chanton, Powelson, and Green 2009). Choosing a cover to minimize methane emissions means the oxidization rate can increase substantially. For example, organic material has a greater share of methanotrophic bacteria and will therefore have higher oxidization rates than a conventional material such as soil (Conestoga-Rovers & Associates 2011). In British Columbia, fertilizer derived from wastewater biosolids was combined with woodchips and sawdust and applied as a final cover to several regional landfills. The estimated reduction in methane emissions attributable to this cover is 90 per cent (MetroVancouver n.d.). As another example, an evapotranspiration cover retains precipitation by design, minimizing the amount of moisture that reaches the landfilled waste and resulting in a drier environment less favourable to methanogenic activity.

Estimates of the costs of methane abatement in the waste sector are limited and widely variable. The United Nations estimates average global mitigation costs for waste sector methane, ranging from nearly -\$240 to +\$160 USD per tonne of $CO_2e$ (United Nations Environment Programme and Clean Air Coalition 2021). The wide range in costs are largely due to different assumptions about global organic waste diversion rates, landfill-diversion benefits. The large negative cost estimates assign explicit value to products derived from recycled material and energy from waste that displaces non-renewable gas or electricity. The Climate and Clean Air Coalition (n.d.) estimates global mitigation costs at -\$116 USD per tonne $CO_2e$. DeFrabizio et al. (2021) prices various global waste mitigation methods in 2050, including landfill gas to feedstock (<\$1/t USD $CO_2e$), landfill gas to power (<\$1/t USD $CO_2e$), landfill gas to flare (<\$1/t USD $CO_2e$), composting (\$4/t $CO_2e$), and mechanical biological treatment (\$10/t USD $CO_2e$). However, the marginal abatement cost curves for the waste sector will tend to be higher and steeper in more developed countries where lower cost abatement measures tend to already have widespread adoption (U.S. EPA 2019). This in turn will result in relatively higher average costs of methane abatement.

Specific to Canada, in a 2022 discussion paper on reducing methane emissions from Canada's municipal solid waste landfills, ECCC identifies an increase in methane recovery at landfills could reduce emissions by at least 12 Mt $CO_2e$ annually by 2030, at an average cost of less than $50 per tonne (Environment and Climate Change Canada 2022a). In contrast, the US EPA Non-$CO_2$ Greenhouse Gas Data Tool estimates that only 4-5 per cent of Canada's methane emissions from the waste sector can be achieved at negative cost, with landfill gas recovery for direct use or electricity generation offering the largest emissions reductions (Figure 18). An additional 43 to 46 per cent of emissions are classified as technically feasible reductions at costs above zero. The cost of most of these reductions (69 per cent) are estimated at below $30 USD per tonne $CO_2e$ with the remaining options having costs in excess of $100 per tonne.

**Figure 18: Landfill and Wastewater Methane Abatement Potential and Costs (USD), 2020 to 2050**



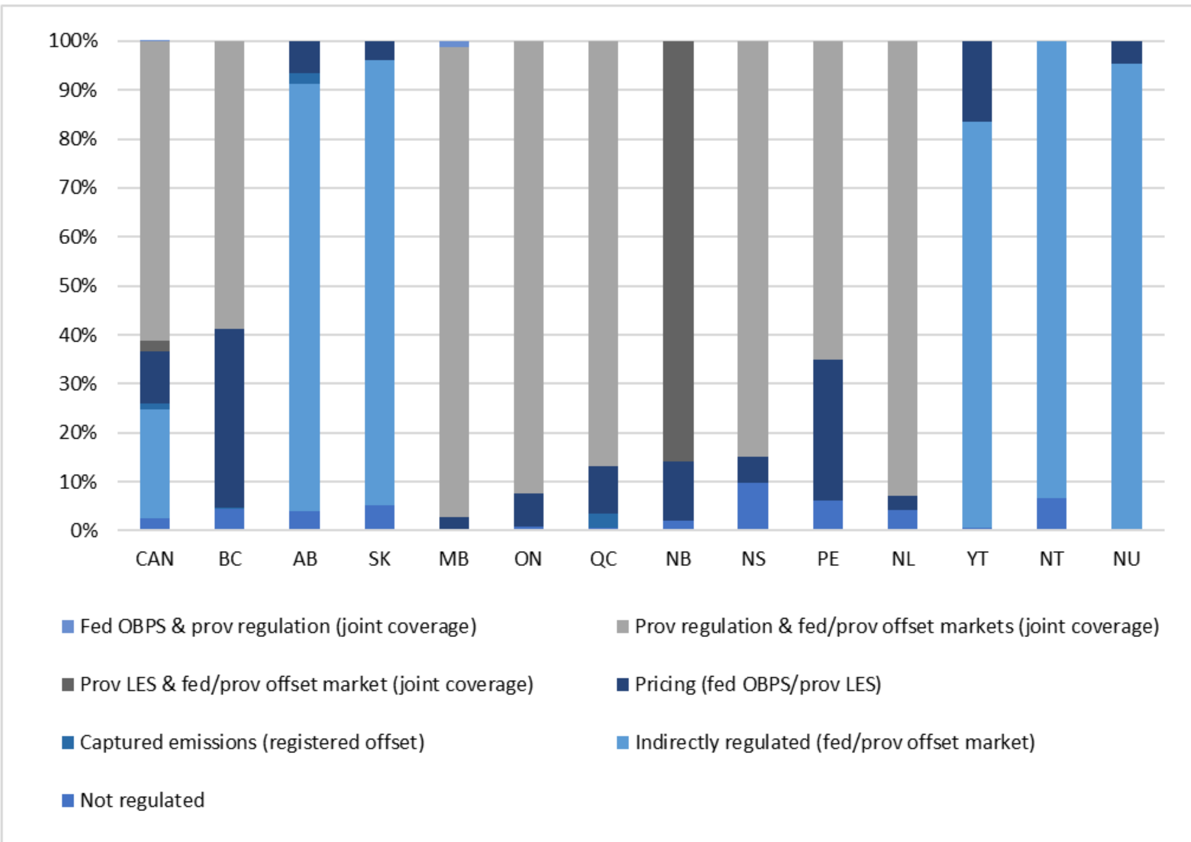

Note: Costs in USD per tonne $CO_2e$. Wastewater only has abatement costs above $100 USD/t $CO_2e$.
Source: US Environmental Protection Agency (n.d.).

Despite this average cost being well below the future trajectory for Canada's emissions price, uptake of these projects may still be slowed by the large up-front costs for new facilities and expansion (Environment and Climate Change Canada 2020b). High up-front costs can similarly deter investments in alternative waste processing facilities. For example, Davis (2014) evaluates the feasibility of anaerobic digestion for City of Vancouver food waste estimated facility capital costs (in 2014) of $20 to $34 million and annual operating costs of $23 to $44 per tonne of food waste diverted, a methane abatement cost of approximately $26-51 per tonne of $CO_2e$ (2014 dollars, ignoring capital costs). As we note above, high investment costs also had a role in numerous cancellations of proposed waste-to-energy projects. Even with this uncertainty, the waste sector's mitigation methods have a smaller variance in cost than agriculture or oil and gas. This means that most mitigation methods in the waste sector cost much less than Canada's emissions price. If capital costs are not a significant economic barrier to adoption and implementation, the waste sector has the ability to reduce methane emissions at a considerably low cost.

*Current Policy Approach and Gaps*

Methane emissions from waste face a mix of direct and indirect regulation, including pricing. The Government of Canada does not have any explicit regulations that target reducing methane emissions from landfills, though it has committed to developing draft regulations by 2024 (Environment and Climate Change Canada 2020a). Figure 19 shows an approximation of the policy coverage by jurisdiction. Importantly, the not-regulated category in Figure 19 is an underestimate due to the gaps and exemptions we describe in Table 2, and regulated or priced categories are over-estimates due to threshold-based approaches to regulating waste methane. The figure describes a best-case scenario of coverage in the absence of exemptions, and displays large differences in methane regulation across the provinces and territories.

**Figure 19: Approximate Policy Coverage of Waste Methane Emissions by Jurisdiction**




Note: The emissions shares are a best-case scenario in the absence of data on emissions by source cross-tabulated with the policy gaps in Table 2. The 'not-regulated' category is an underestimate of indeterminate size. Indirectly regulated includes emissions covered by either provincial or federal offset protocols. Excludes stationary combustion emissions in pulp and paper. All BC (one) and Quebec (16) registered offset projects are capture and flare, not capture and use.
Source: Authors' calculations from Environment and Climate Change Canada (2022d), Alberta Carbon Registries (n.d.), Government of British Columbia (n.d.), (Ministère de l'Environnement et de la Lutte contre les changements climatiques (n.d.) and Table 2.

Six provinces — BC, Manitoba, Ontario, Quebec, Nova Scotia and Newfoundland and Labrador — directly regulate municipal solid waste landfill gas for safety, accounting for 62 per cent of Canadian waste methane emissions. Manitoba and Quebec's regulations do not distinguish between MSW landfills and industrial landfills, increasing the regulatory coverage to 63 per cent. The regulations require collection and in some instances flaring or capture for use. Importantly, however, these regulations do not directly target methane mitigation, and so there is no preferential treatment of capture for use over flaring, or flaring over venting.

This forms a key gap in waste-sector methane regulation, and presence of regulation is not indicative of stringency. Moreover, the regulations generally rely on a weight threshold (either total waste in place or annual deliveries) instead of emissions to determine whether methane management needs to take place. The policy creates no incentives for mitigation below the threshold, though the benefit of threshold is it doesn't require continuous monitoring. Three potential, and simple, ways to improve landfill methane regulation is to require monitoring from the start; require capture as a function of emissions rather than weight; and prioritize use over flaring while prohibiting venting.

As a result, direct regulation of landfill emissions is currently limited to a small number of provincial initiatives, with landfills in most provinces not facing any explicit mitigation requirements. There is, however, some interaction with provincial large-emitter and the federal output-based pricing system. Specifically, the federal OBPS includes waste emissions from landfills and wastewater treatment in its facility definition, expanding pricing coverage to pulp and paper landfills and wastewater treatment in some provinces. It excludes MSW landfills, and so this accounts for only 0.31 per cent of waste emissions. Similarly, provincial large-emitter systems provide some pricing coverage, though these systems are more variable. For example, New Brunswick's OBPS includes wastewater and waste emissions (landfill emissions and landfill gas flaring) in facility GHGs. In contrast, Quebec only includes process emissions and wastewater emissions, excluding landfill emissions for pulp and paper. Provincial large-emitter systems could price up to 11 per cent of total waste emissions. The differences in facility definition and regulated activities across the different large-emitter systems mean that the majority of waste methane emissions from large emitters remain unpriced.

There are, however, growing sources of indirect regulation via eligibility in offset markets. The lack of federal government involvement in regulation of methane emissions from landfills is likely attributable to waste sector regulation falling primarily under provincial jurisdiction, while the day-to-day management of the waste system is primarily a municipal responsibility. Carbon offset markets in BC, Alberta and Quebec include protocols for landfill gas capture and combustion, creating the possibility of significant increases in priced emissions (particularly as Alberta does not regulate methane from landfills). However, currently only small proportions are captured, at 0.2 per cent of BC's waste emissions, two per cent of Alberta's and three per cent of Quebec's, accounting for one per cent nationally. Moreover, the Quebec offset projects are all capture and flare.

A new (June 2022) MSW landfill methane protocol under the federal offset credit system provides indirect regulation for methane capture and destruction (Environment and Climate Change Canada 2022h). This has the potential to expand pricing of MSW emissions to 86 per cent of waste emissions (assuming all provincial sources are eligible). Importantly, the protocol's methane quantification only includes avoided methane emissions. It does not include emissions reductions from using the captured methane for fossil fuel displacement, allowing projects to generate fuel-switching credits under other systems (e.g. clean fuel standards). However, the protocol excludes projects with emissions reductions "as a result of federal, provincial or territorial regulations, municipal by-laws, or any other legally binding mandates such as operating permits," including "legal requirements to recover and destroy all or a portion of [landfill gas]" to reduce GHG emissions or control release due to safety or odor control (Environment and Climate Change Canada 2022h).This strict interpretation of legal additionality, including exclusion of a change from flaring to capture for use, limits the potential pricing coverage in provinces with existing landfill regulation. The overlap is 61 per cent of Canadian waste emissions, shrinking the federal offset system's coverage to 21 per cent of waste emissions.

**Table 2: Provincial and Territorial Waste Methane Regulation, Exemptions and Interactions**

| | Policies | Direct Regulation | | Large Emitter Treatment | |
|---|---|---|---|---|---|
| | | **Characteristics** | **Exemptions and Gaps** | **Characteristics** | **Exemptions and Gaps** |
| **BC** | Provincial carbon tax, provincial large emitter system, provincial landfill regulations. | Landfills with 100,000 t municipal solid waste in place or receiving 10,000 tonnes municipal solid waste per year must assess methane emissions.<br><br>If assessed methane generation exceeds 1 kt $CH_4$ per year, landfills must implement management practices.<br><br>Management practices include collection, flaring, cover use.<br><br>Requires captured gas to be flared unless alternative achieves equivalent emission reductions. | Does not require capture for use as an alternative to flaring.<br><br>Only covers municipal solid waste landfills.<br><br>Excludes landfills below thresholds.<br><br>Threshold tied to waste in place rather than emissions.<br><br>No requirement to monitor or assess landfill gas until weight threshold reached. | Performance standard for pulp and paper and wood products facilities with annual emissions above 10,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification. | Facilities below threshold.<br><br>Biomethane exempt from carbon tax.<br><br>LE priced emissions are only from incomplete combustion.<br><br>Direct rebates of incremental carbon tax above $30 CAD/tonne for emissions intensity below standard. Eligible facility emissions include combustion but excludes $CO_2$ from biomass.<br><br>Excludes landfills and wastewater treatment. |

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|---|---|---|---|---|---|
| **AB** | Federal fuel charge, provincial large emitter system. | Requires a plan for landfill gas management.<br><br>Plan may include detection, collection, flaring, venting, or recovery for use. | Does not require capture for use as an alternative to flaring.<br><br>Does not require capture or flaring as an alternative to venting.<br><br>No requirement to monitor. | Output-based pricing for pulp and paper and wood products facilities with annual emissions above 100,000 t $CO_2e$.<br><br>Opt-in above 10,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Eligible offset protocols include landfills and waste-to-energy. | Facilities below threshold.<br><br>Biomethane exempt from federal fuel charge.<br><br>Eligible facility emissions include combustion but excludes $CO_2$ from biomass.<br><br>Excludes landfills and wastewater treatment facilities. |
| **SK** | Federal fuel charge, provincial large emitter system with federal top-up. | No direct regulation of the waste sector. | | Output-based pricing facilities with annual emissions above 25,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Includes pulp and paper. | Facilities below threshold.<br><br>Biomethane exempt from federal fuel charge.<br><br>Eligible facility emissions include combustion, venting, flaring, waste, and wastewater but excludes $CO_2$ from biomass.<br><br>Excludes landfills and wastewater treatment facilities. |

| | | | | | |
|---|---|---|---|---|---|
| **ON** | Federal fuel charge, provincial large emitter system, provincial landfill regulations. | Mandatory landfill gas collection for new or expanding sites with total waste disposal capacity greater than 1.5 million $m^3$ (2.5 million t waste).<br><br>Allows for landfills above threshold to show landfill gas generation is not of significant concern. | Does not require capture for use as an alternative to flaring.<br><br>Excludes landfills below threshold.<br><br>Excludes non-MSW landfills.<br><br>Threshold tied to waste capacity rather than emissions.<br><br>No requirement to monitor or assess landfill gas until capacity threshold reached. | Output-based pricing facilities with annual emissions above 50,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions.<br><br>Includes pulp and paper.<br><br>Includes landfills and wastewater treatment in facility definition. | Facilities below threshold.<br><br>Excludes $CO_2$ from biomass combustion.<br><br>Excludes MSW landfills. |

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| **QC** | Provincial cap and trade system, provincial landfill methane regulations. | Mandatory landfill gas collection for landfills with a final cover or receiving 100,000 tonnes per year.<br><br>Mandatory landfill gas collection within five years for landfills receiving less than 100,000 tonnes per year.<br><br>Landfill gas collection system must have pumping device and methane must be combusted if not captured for landfills receiving 50,000 t or more waste per year or capacity above 1.5 million $m^3$.<br><br>Pulp and paper mills must have landfill gas capture systems in place upon closure. | Does not require capture for use as an alternative to flaring.<br><br>Excludes landfills below threshold.<br><br>Threshold tied to waste capacity rather than emissions.<br><br>No requirement to monitor or assess landfill gas until capacity threshold reached. | Cap and trade with free permit allocation for facilities with annual emissions above 25,000 t $CO_2e$ and fuel distributors.<br><br>Voluntary participation for facilities above 10,000 t $CO_2e$.<br><br>Includes pulp and paper; emissions sources are production processes and wastewater treatment.<br><br>Includes wastewater emissions from other industrial sources.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions.<br><br>Eligible offset protocols include landfills receiving less than 50,000 t waste per year and have capacity below 1.5 million $m^3$. | Excludes facilities below threshold.<br><br>Excludes $CO_2$ from biomass combustion.<br><br>Excludes methane from MSW and industrial landfills except through offset system. |

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|---|---|---|---|---|---|
| **NB** | Provincial fuel charge and large emitter system. | No direct regulation of the waste sector. | | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2$e.<br><br>Voluntary participation for facilities above 10,000 t $CO_2$e.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Includes landfill emissions and wastewater emissions.<br><br>Priced emissions are all facility emissions. | Facilities below threshold.<br><br>Excludes $CO_2$ from biomass combustion.<br><br>Excludes waste fuel combustion used for heat or work. |
| **NS** | Provincial cap and trade system, federal methane regulations. | Requires installation of venting or collection systems to control and manage landfill gas.<br><br>Requires new landfills to be assessed for waste-to-energy viability. | Does not require capture for use as an alternative to flaring.<br><br>Does not require capture or flaring as an alternative to venting.<br><br>Excludes non-MSW landfills. | Cap and trade with free permit allocation for facilities with annual emissions above 50,000 t $CO_2$e. No voluntary participation.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Priced emissions are all facility emissions.<br><br>Includes pulp and paper and $CH_4$ from biomass. | Facilities below threshold.<br><br>Excludes $CO_2$ from biomass combustion.<br><br>Excludes emissions from industrial wastewater and non-combustion sources in waste.<br><br>Excludes landfills. |

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|---|---|---|---|---|---|
| **NL** | Provincial fuel charge and large emitter system. | Requires installation of venting or collection systems to control and manage landfill gas.<br><br>Requires landfills to be assessed for waste-to-energy viability, and proponents demonstrate venting or flaring more practical than conserving for use. | Does not require capture for use as an alternative to flaring or venting.<br><br>Does not require flaring as an alternative to venting.<br><br>Excludes non-MSW landfills. | Output-based pricing for facilities with annual emissions above 25,000 t $CO_2e$.<br><br>Voluntary participation for facilities above 15,000 t $CO_2e$.<br><br>Includes emissions from biomass combustion.<br><br>Includes wastewater treatment for covered industrial activities. | Facilities below threshold.<br><br>Priced emissions are only from incomplete combustion.<br><br>Excludes biomass emissions for facilities below 15,000 t $CO_2e$.<br><br>Excludes pulp and paper unless captured by general stationary combustion. |
| **MB** | Federal fuel charge, federal large emitter system, provincial landfill regulations. | Landfills with 750,000 t waste in place must assess mitigation opportunities and implement actions to mitigate via controlling, collecting, flaring or using. | Does not require capture for use as an alternative to flaring.<br><br>Excludes landfills below threshold.<br><br>Threshold tied to waste in place rather than emissions.<br><br>No requirement to monitor or assess landfill gas until weight threshold reached. | Output-based pricing for facilities with annual emissions above 50,000 t $CO_2e$.<br><br>Includes all sources of methane in facility total GHG quantification.<br><br>Includes pulp and paper. | |

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|---|---|---|---|---|---|
| **PEI** | Provincial fuel charge, federal large emitter system, provincial landfill regulations. | Requires installation of venting or collection systems to control and manage landfill gas.<br><br>Requires new landfills to be assessed for waste-to-energy viability. | Does not require capture for use as an alternative to flaring.<br><br>Does not require capture or flaring as an alternative to venting.<br><br>Excludes non-MSW landfills. | Includes landfills and wastewater treatment in facility definition. | |
| **YK** | Federal fuel charge and large emitter system. | No direct regulation of the waste sector.<br><br>Class 1 landfills may require landfill gas monitoring. | | | |
| **NU** | Federal fuel charge, large emitter system | No direct regulation of the waste sector. | | | |
| **NT** | Territorial carbon tax | No direct regulation of the waste sector.<br><br>Allows for open burning of paper products and untreated wood. | | Carbon tax with rebates, not applicable to waste sector. | Tax only on fossil fuels.<br><br>Excludes landfills and wastewater management from rebates. |

Note: Analysis here is specific to waste activities. Includes relevant conservation provisions from acts and regulations that do not specifically target methane reductions.

There is additional indirect potential coverage from federal and provincial clean fuel standards. The standards create an alternative market for methane capture and use, where fuel-providers purchase captured methane to meet their blending requirement. This option is potentially less complex than an offset market, as the additionality requirements appear less strict. Landfill diversion is supported by both clean fuel standards and offset markets. BC's offset market includes a fuel-switching protocol, with uptake from several sawmills using residual biomass as a feedstock for heat-energy systems. Similarly, Alberta has protocols supporting fuel production from biomass and energy generation from biomass waste.

Outside of the new offset market and clean fuel regulations, the federal government's main contribution to methane reduction in the waste sector is through various funding programs that support research and development, educational programs and retrofits to current waste management sites. With food waste continuing to be the largest category of all residual waste landfilled in Canada, the federal government has also identified achieving reductions in food waste as an emerging area of focus (Agriculture and Agri-Food Canada 2019a). Again, however, the primary action it has announced in support of this objective is a new funding program (Agriculture and Agri-Food Canada 2020b).

The absence of wider-spread regulations requiring landfill gas combustion and capture for use represents a significant gap in Canada's overall climate policy. In the U.S., for example, regulations under the Clean Air Act require all landfills above a certain size to install and operate a system to collect and control landfill gas. The U.S. Environmental Protection Agency (EPA) additionally runs a Landfill Methane Outreach Program which ". . . works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills". As of August 2020, 726 of 1,289 open landfills in the LMOP's project database had either a flare installed or an operating project for landfill gas recovery and use (U.S. Environmental Protection Agency 2020). In comparison, Canada has only 99 landfill gas capture systems in place (Canadian Biogas Association 2021). Also of note is that due to safety concerns, most provinces have regulatory requirements for landfill gas monitoring and capture (should gas levels exceed a certain limit). In the absence of accompanying regulation requiring landfill-gas combustion, direct venting of the gas to the atmosphere is considered an acceptable method of disposal.

Landfill diversion bans are another example of concrete actions by provincial and municipal governments to reduce methane emissions from landfills. Nova Scotia was an early mover in this regard, introducing landfill bans on corrugated cardboard, newsprint, and leaf and yard waste in 1996, and extending it to include all compostable organic material in 1997 (Nova Scotia 2019). Prince Edward Island currently has the most comprehensive program, which requires mandatory sorting of all waste in the province. Improperly sorted residential waste will not be collected while commercial waste may either be rejected or subject to a disposal surcharge.

There are no other current province-wide bans on organic waste, although Ontario is considering introducing one in 2022, and numerous other provinces have either organic-waste diversion targets or offer funding to support municipal diversion initiatives. Alberta has also established offset credit protocols for aerobic composting projects and for energy generation from biomass-waste combustion. In British Columbia, municipal organic waste bans are currently in place in Metro Vancouver, the Capital Regional District (Victoria) and Nanaimo. These bans cover 64 per cent of British Columbia's population (Government of British Columbia n.d.). Another common municipal diversion strategy is disposal surcharges on waste delivered direct to landfill and exceeding a fixed percentage of recyclables or organic materials. At the household level, municipalities may place strict limits on the amount of curbside waste collection, while allowing more flexibility in volumes of recycling and compost.

Last, product stewardship and extended producer responsibility (EPR) programs, most commonly adopted at the provincial level, are an increasingly common approach for supporting waste diversion from landfills. Under these programs, suppliers assume some level of responsibility for the post-consumer phase — effectively the disposal — of materials they sell. Programs typically take the form of suppliers providing funding to support municipally-run recycling programs (product stewardship), a supplier organization assuming full financial and physical responsibility for product disposal — full EPR — or some combination of the two — shared EPR — (Arnold 2019). While these programs extend to a range of waste categories, the most notable from the perspective of reducing methane emissions are those for packaging and paper products (PPP). British Columbia, Saskatchewan, Manitoba, Ontario and Quebec currently have either a product stewardship or an EPR program for PPP in place. A number of these provinces are in the process of strengthening their programs (transitioning from product stewardship to full EPR) while most of the remaining provinces and territories are actively considering or are in the process of developing programs.

## Conclusion

In this paper, we provide a detailed review of Canada's methane emissions, discussing the contribution of the three sectors responsible for almost 100 per cent of Canada's anthropogenic emissions — oil and gas, agriculture and waste — and mitigation opportunities for each. Our review reveals that emissions measurement challenges hinder methane management across all sources. Methane releases from many diffuse sources, natural and anthropogenic, which makes it difficult to track and quantify, as well as to identify all individual sources and attribute emissions to any one specific point source. For this reason, there is high uncertainty surrounding current estimates.

The high uncertainty in estimates of the level of methane emissions leads to uncertainty in the contribution of methane to Canada's overall greenhouse gas emissions profile. Further exacerbating these uncertainties are the different values for methane's GWP. Of particular note is that the IPCC's current recommendation is for countries to translate methane estimates into carbon-dioxide equivalent units using a 100-year GWP of 25, while the most recent knowledge suggests the 100-year GWP falls in the range of 28 to 36. This indicates that Canada's baseline methane emissions estimate — before accounting for any errors due to measurement challenges — is an underestimate by 20 to 30 per cent. This in turn means that any emissions reduction goals, such as the government's target for the oil and gas sector, will require more aggressive policy.

Measurement challenges also affect policy options to mitigate emissions. Financial penalties such as an emissions price, for example, are less viable due to their reliance on accurate measurement and attribution. Similarly, difficulty determining accurate emissions baselines is a barrier to effective performance-based regulation. Concerns of imposing high measurement costs on producers further hinders policy action.

As a powerful climate-forcing greenhouse gas with measurement and management challenges, methane demands greater attention and action. Political interest thus far has been narrow in scope, focused primarily on managing methane from the oil and gas sector. With federal and provincial regulatory frameworks now in place for the management of most sources of oil and gas methane, we can expect to see tangible methane reductions and lessons in efficient methane regulation. This creates the need — and opportunity — for further research on regulatory outcomes and how these relate to regulatory design across jurisdictions. In the near-term, further research is required to verify baseline methane emissions estimates for the oil and gas sector, to independently track emissions reductions, and to identify unreported emissions sources or reporting errors that may impede progress towards Canada's target of achieving a 45 per cent reduction in oil and gas methane against 2012 levels by 2025. Also important is recognition that coverage is incomplete for some oil and gas methane sources (the downstream sector, oil sands mining and upgrading, and abandoned oil and gas wells), and additional policy levers are necessary to address these gaps.

In contrast to the oil and gas sector, there is little political or policy action to address methane emissions from agriculture and waste. As a result, methane emissions from agriculture is the largest source of unregulated and unpriced greenhouse gas emissions in Canada. Opportunities exist for creative, hybrid market-based approaches to stimulate farm-level emissions reductions while limiting market distortions. These opportunities will not be realized, however, without further research and policy development. In the waste sector, the absence of regulations requiring landfill gas mitigation represents a significant gap in Canada's overall climate policy. Jurisdictional challenges appear to be hindering landfill-specific mitigation at scale. The federal promise to develop landfill emissions regulations is a step in the right direction. Opportunities also exist for further emissions reductions through household- and business-level waste diversion, particularly through extended producer responsibility models. As there is a limited body of knowledge on policy options for managing methane from agriculture and waste, further research in both sectors is essential.

Despite methane's significant contribution to Canada's greenhouse gas emissions profile, it continues to receive insufficient attention in climate change discussions. Across all methane emissions sources there is an on-going need for further research on cost-effective regulation, especially the design of rules that incentivize development and adoption of best practices and emissions-reduction technology. Federal and provincial governments should also address improving and standardizing current methane emission estimates, formally identify unregulated emissions sources, and explore either stricter regulations or well-defined market-based approaches with measurable outcomes. Looking ahead, Canada's long-term climate goals are ambitious. Taking steps to ascertain the true level of Canada's methane emissions and to develop a comprehensive and concrete plan that addresses methane from all sources is an important part of securing a smooth path towards these goals.

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