TECHNICAL ASSESSMENT FOR OIL AND GAS METHANE MANAGEMENT

SECTOR: ENERGY

AGENCY LEVEL: UTILITIES AND INDUSTRIES

KEYWORDS: METHANE, NATURAL GAS, INFRASTRUCTURE, FOSSIL FUELS

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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ACRONYMS AND SYMBOLS USED

CCS = carbon capture and storage

CH_4 = methane

CO_{2e} = carbon dioxide equivalent

EPA = United States Environmental Protection Agency

Gt = gigatonne, billion metric tons

IEA = International Energy Agency

LDAR = leak detection and repair

MBTU = million British thermal units

mcf = thousand cubic feet (of natural gas)

Mt = megatonne, million metric tons

Executive Summary

In addition to the carbon dioxide emissions associated with the use of fossil fuels, the oil and gas supply chains pose a significant climate problem: methane. This potent greenhouse gas is emitted throughout, from upstream oil and gas production to downstream distribution. Some of these emissions are unintentional – leaks that must be found before they can be fixed. Others are intentional – devices and practices that bleed natural gas (which is typically over 90% methane) as a part of their normal functioning. Altogether, methane emissions from oil and gas production and distribution constitute about 15% of global non-carbon dioxide greenhouse gas emissions.

Existing technologies and practices can abate a significant portion of this methane. A significant portion of this can in turn be achieved at no net lifetime cost, given that from a gas producer's perspective reduced methane emissions translate into reduced product losses. But emissions from this sector have continued to rise in recent years, indicating that there are significant barriers to the adoption of abatement solutions. These include capital constraints and misalignment of incentives.

This abatement opportunity has several unique aspects. It is a transition measure. In contrast to many other Drawdown solutions, the abatement opportunity is expected to decrease towards mid-century as the world increases climate ambition and reduces the use of fossil fuels. It is focused exclusively on methane, a greenhouse gas with different warming effects to carbon dioxide. These features, combined with the relative availability and cheapness of solutions, make this sector a strong candidate for quick climate action.

Modeling this sector also poses formidable challenges. There is no single device that will fix all the methane emissions from the oil and gas supply chains. Rather, dozens of devices and practices with varying costs and performance must be modeled together. Similarly, there is no detailed, global trajectory for oil and gas methane emissions in the future. Though the general trend is expected to decrease globally, certain regions or time periods may experience growth in the use of these fuels, and, concomitantly, methane emissions.

In light of these challenges the current analysis, which is the first version of this solution for Project Drawdown, presents global results that we intend to be generally indicative and comparable to Drawdown's other 80-plus solution models. The solutions analyzed include around a dozen categories of the abatement measures with the highest estimated global potentials in datasets from the literature. A total addressable market was defined by the current technically-abatable sector emissions and projected to mid-century along a trajectory that is aligned with Project Drawdown's modeling framework. Adoption scenarios are modeled with three levels of abatement ambition. Cumulatively, emissions reductions from this solution from 2020-2050 range from 5-21 gigatonnes of carbon dioxide equivalent.

1. Literature Review

1.1. State of Oil and Gas Methane Management

Project Drawdown defines oil and gas methane management as practices and methodologies for reducing methane emissions in the oil and natural gas supply chains. Methane emissions occur throughout these supply chains from a combination of fugitive leaks from imperfections in equipment and intentional emissions from operations and maintenance procedures and from equipment designed to bleed methane. The term methane management refers to the fact that in many cases mitigation of methane emissions results in natural gas savings that can be used as an energy product. This solution comprises many practices and technologies with varying attributes. They are all currently in use to some extent.

Oil and natural gas have a global legacy as fundamental sources of energy. The supply chain supporting these energy systems has existed for over a century and fueled generations of growth. In recent decades natural gas has provided a means of reducing the carbon intensity of electricity generation by displacing generation – in some parts of the world – by coal. And though the world must phase out the use of fossil fuels altogether in order to avoid the worst effects of climate change, natural gas and oil are expected to be around, in some capacity, for decades to come during this transition. In addition to the issue of carbon dioxide emissions from the use of oil and gas, the supply chains for these fuels pose another climate issue: emissions of methane, a potent greenhouse gas, from leaks and intentional emissions also contribute significantly to global warming. A spectrum of existing technologies and methods can be used to find and abate the majority of these emissions.

The supply chains for oil and natural gas are often intertwined (Figure 1). Methane is released both intentionally and unintentionally throughout these systems. In the production phase, the farthest upstream, oil and natural gas are often produced together from the same geologic formation. Significant emissions occur in oil production when gas is vented due to lack of collection infrastructure – methane typically makes up over 90% of the product we know as natural gas.

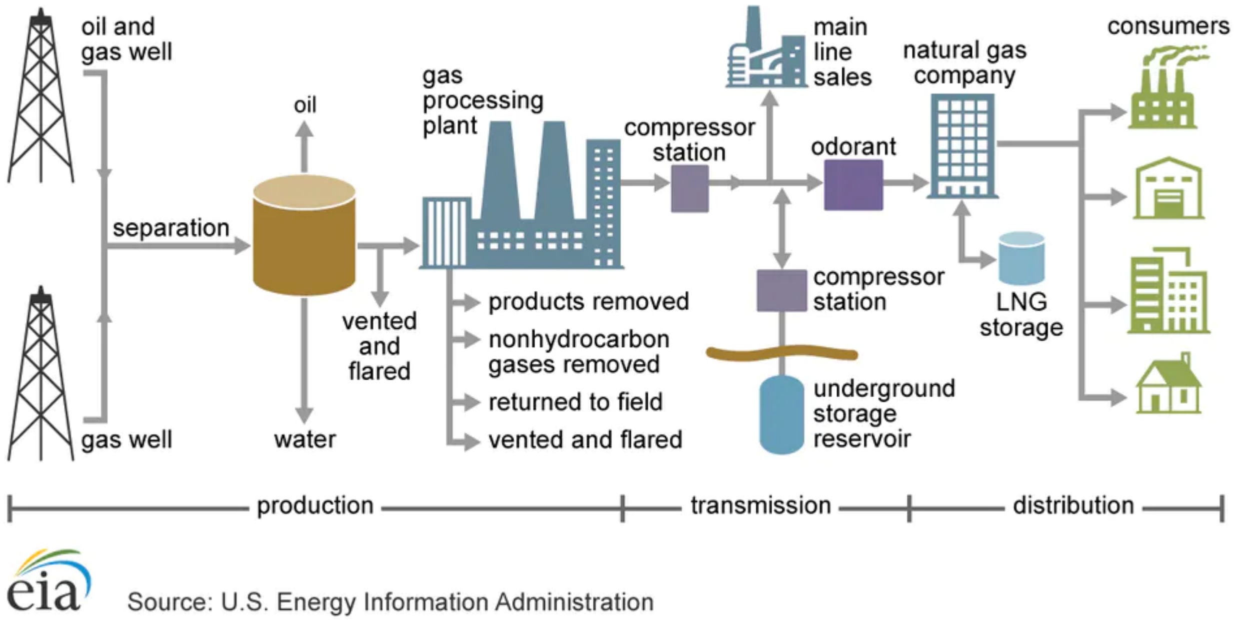

Figure 1: The oil and gas supply chains (EIA).

Farther downstream in the supply chains most methane emissions come from the infrastructure that transports and distributes natural gas (Figure 2). Here the gas travels under pressure and methane emissions occur from several categories of sources:

- Fugitive emissions or leaks occur from imperfections in pipes, connectors, compressors, valves, and other components.
- Natural gas is occasionally released intentionally during operation and maintenance procedures that require certain sections of the supply chain to be depressurized or blown-down; the natural gas is freely vented to the atmosphere.
- Control devices in the supply chain often rely on pressurized natural gas to pneumatically drive their functions; the gas is subsequently bled to atmosphere.
- Other devices in the supply chain use the natural gas as a fuel and incur a certain amount of combustion slip, that is, exhausted, un-combusted methane. Incomplete combustion can also occur when flares are used to combust methane for destructive conversion to carbon dioxide.
- At the farthest downstream section in the natural gas supply chain methane releases occur from the distribution pipes that relay the gas to end users, and to a small extent from the devices that use this gas: furnaces, boilers, cookers, and industrial process equipment.

In a study of methane emissions from the United States natural gas supply chain, the top five individual sources of emissions (Figure 3) included emissions from the above categories of fugitive emissions, intentional venting, and combustion slip, reinforcing that all the above categories must be addressed for effective mitigation.

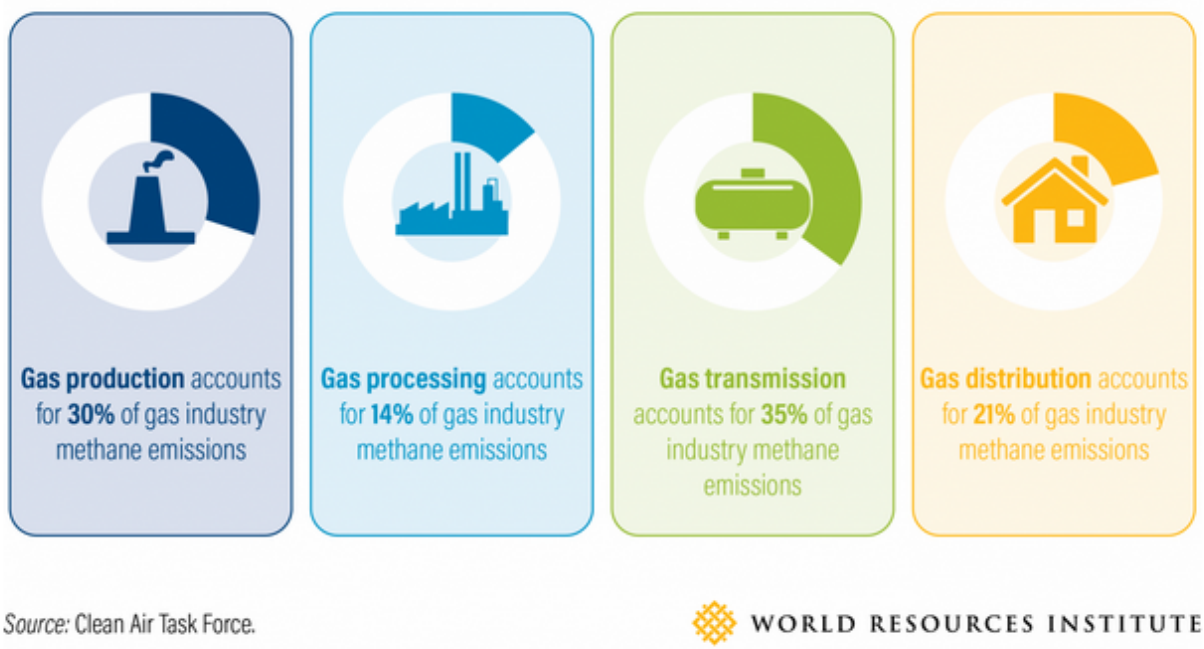

Figure 2: Methane emission categories in the natural gas supply chains.

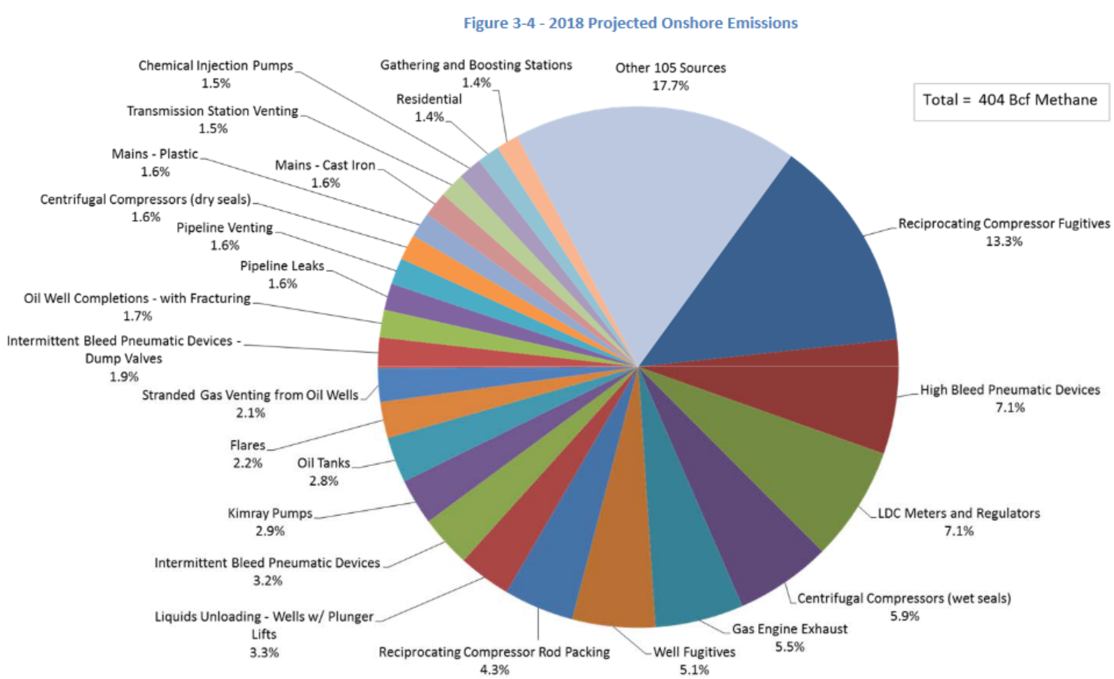

Figure 3: Emissions source categories from United State natural gas supply chain (ICF International, 2014).

1.2. THE SCALE OF THE GLOBAL CHALLENGE

Global methane emissions over the course of the last decade have continued to increase (Saunois et al., 2020). This increase in the last decade has been faster than any in the last three decades (CCAC and UNEP, 2021). According to a 2015 inventory (US EPA, 2019b), methane releases from the oil and gas sector make up 14% of global non-CO_2 greenhouse gas emissions, expressed in CO_2-equivalent (CO_{2e}) terms on a 100-year equivalency basis[1]. Reducing these methane emissions represents an opportunity for rapid potential results in avoided global temperature increases, as methane is a greenhouse gas many times more potent than carbon dioxide, but with a shorter atmospheric lifetime (Ocko et al., 2021).

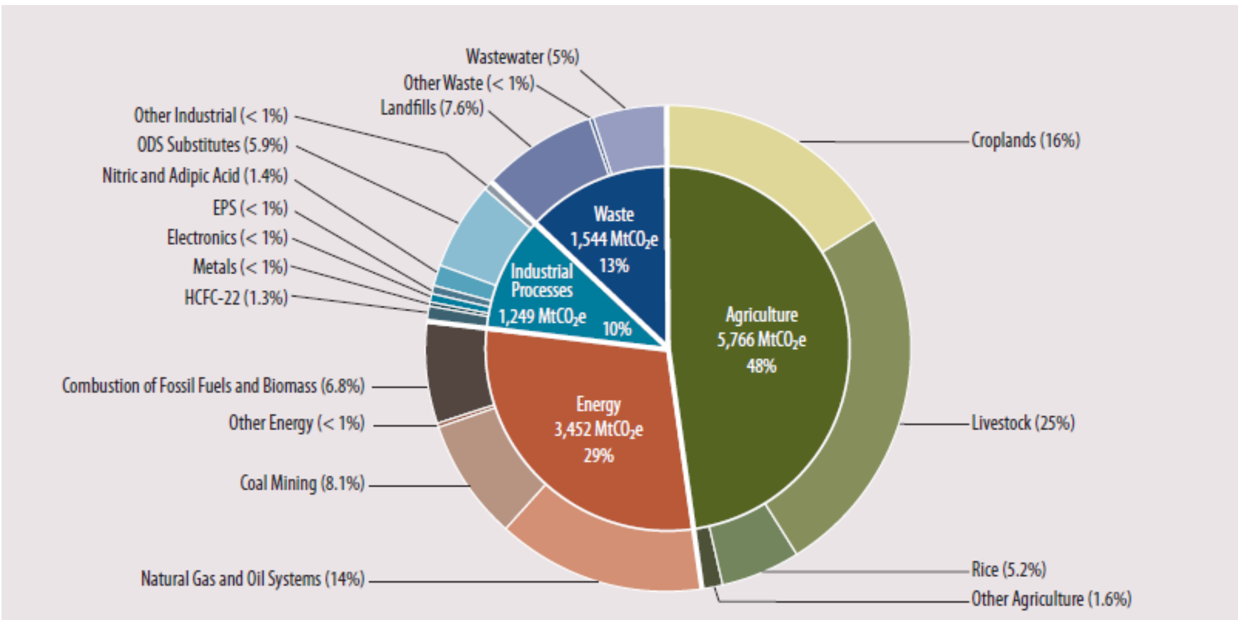

Figure 4: Global non-CO_2 greenhouse gas emissions expressed on CO_2-equivalent basis (US EPA, 2019b).

Methane emissions from oil and gas supply chains are concentrated in a relatively small number of countries. The top five countries represent over 60% of the projected emissions from this sector in 2030 (Figure 5) and the top ten countries represent over 70% of projected emissions on the same projection (US EPA, 2019b).

[1] The Intergovernmental Panel on Climate Change's Fifth Assessment Report calculates that a tonne of methane has the global warming potential of 28 tonnes of carbon dioxide over a 100-year period, or 84 tonnes of carbon dioxide over a 20-year period.

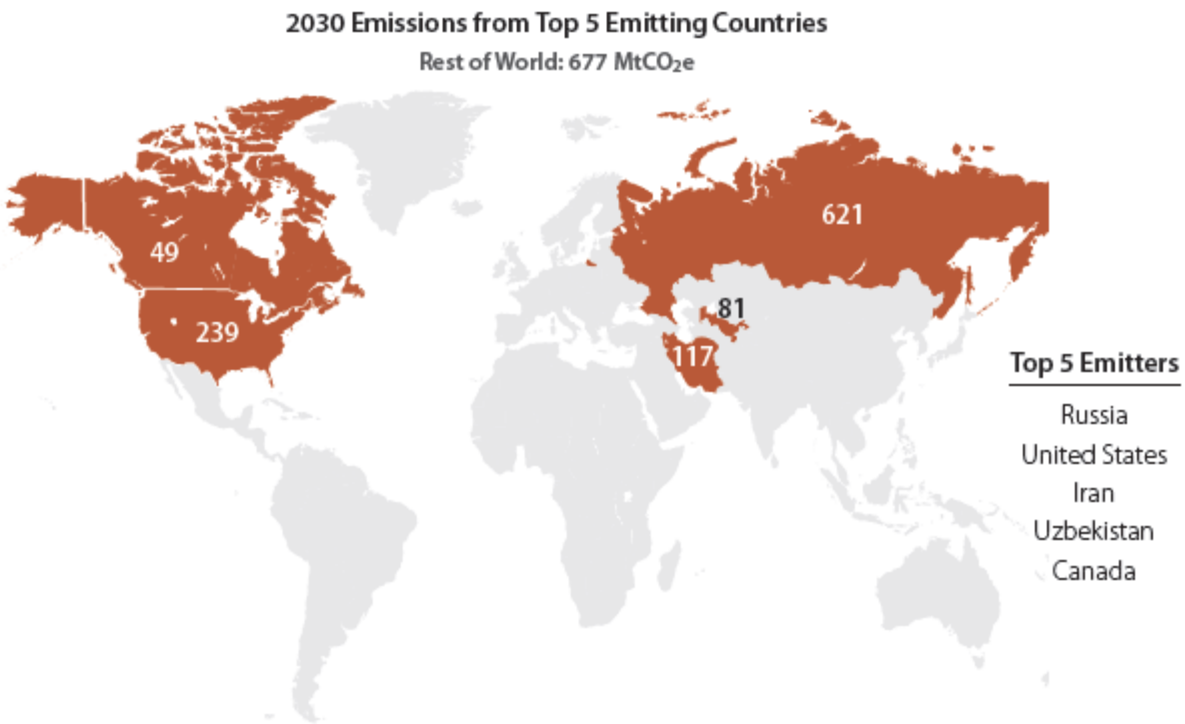

Figure 5: Methane emissions from oil and gas sector expressed in Mt CO_2e, projected for 2030 based on 2015 inventory data (US EPA, 2019b).

Methane emissions have increased alongside production volumes of oil and gas in recent decades. The growth of shale gas in the United States is a notable example, with concomitant methane impacts through the entire supply chain (Höglund-Isaksson et al., 2020; Waxman et al., 2020). Though methane emissions from the sector have increased over the past few decades, on an *intensity* basis – per unit of production – they have fallen throughout this same timeframe, indicating that some level of relative supply-chain abatement is taking place (US EPA, 2019b), likely through a combination of improved practices and newer infrastructure, which generally emits less. In the United States natural gas supply chain this rate has often been expressed as a percentage of natural gas leaked compared to the produced volume. This has fallen from over 3% in 1990 to less than 2% as estimated in 2014, a period of increasing oil and gas production (Figure 6).

A characteristic that is conserved throughout these supply chains is that a small number of sources represent a disproportionately large volume of total emissions:

- 5% of sources account for 60% of emitted volume in the Barnett Shale (Zavala-Araiza et al., 2015)
- 5% of leaks account for 50% of emitted volume in natural gas systems in general (Brandt et al., 2016)

- Similar trend of super-emitters observed in abandoned oil and gas wells in the United States (Kang et al., 2016).

These super-emitter cases pose at the same time an abatement opportunity and challenge. Concentrating on finding and fixing a small amount of sources can lead to a significant abatement of overall emissions; however, the remaining fixes, which represent the vast majority of leak cases by number, will therefore in general come at increasing cost and diminishing return. A challenge is also posed to the design of abatement policies to allow operators to prioritize addressing these super-emitters.

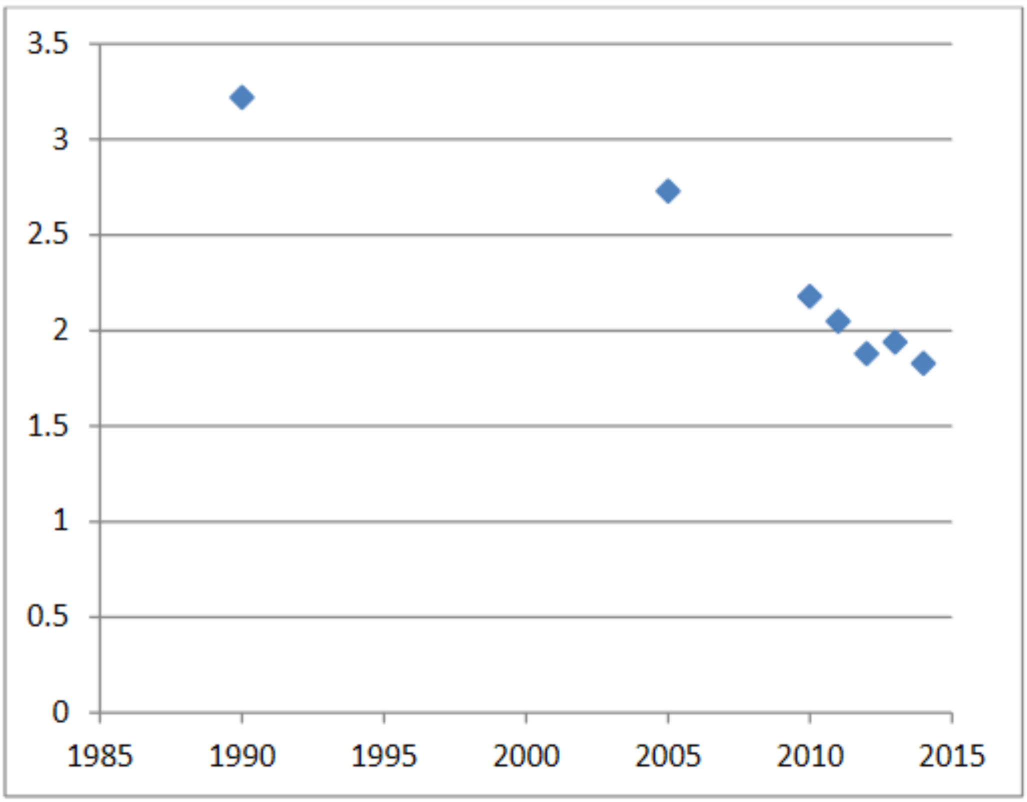

Figure 6: Intensity of natural gas losses as percentage of volume produced in the United States (Munnings & Krupnick, 2017).

1.3. ABATEMENT TECHNIQUES

Existing technologies and practices can abate up to an estimated 70% of the annual methane emissions from the oil and gas supply chains (IEA, 2021b). This can be achieved by a suite of technologies and methods with varying costs, effectiveness, and suitability – there is no single solution that addresses the whole issue. There is a wealth of technical literature on the methods and devices already in implementation (American Gas Association, 2014; ICF International, 2014; IEA, 2021a; US EPA, 2019a, 2019b; Zimmerle et al., 2015). The US Environmental Protection Agency's (EPA) Gas STAR program additionally has an information repository of over 70 practices and technologies that have been voluntarily implemented by US operators.[2] The top ten measures by mass of methane abated under this program are presented in Figure 7. An alternative global perspective is provided in Figure 8, which additionally demonstrates that a significant portion of these fixes is achievable at no net lifetime cost based on the value of the saved product – from a producer's perspective, methane emissions are simply lost natural gas product. Both of these figures represent the diversity of options available and the diversity of emissions sources that they address.

The abatement options can be broadly classified as:

- Device conversion, replacement, and installation
- Changes to operations and maintenance practices
- Leak detection and repair
- Infrastructure overhaul.

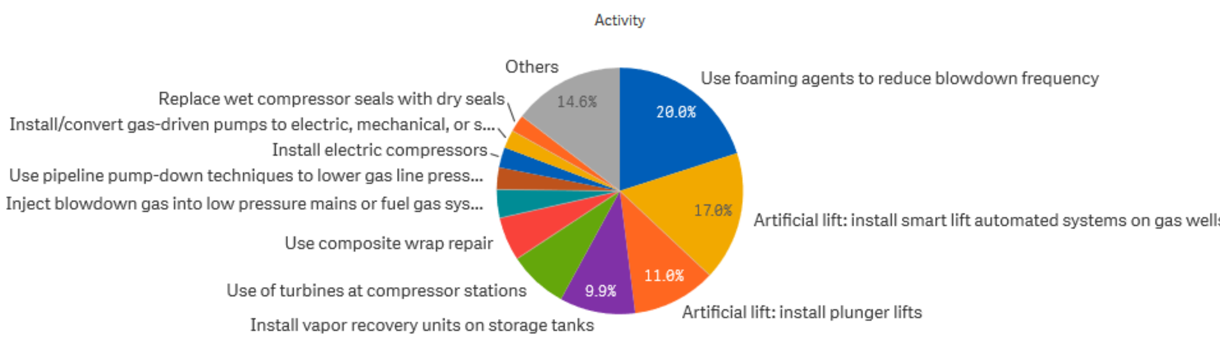

Figure 7: Top categories of methane abatement measures implemented in 2019 in the United States (US EPA Gas STAR).

[2] https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions

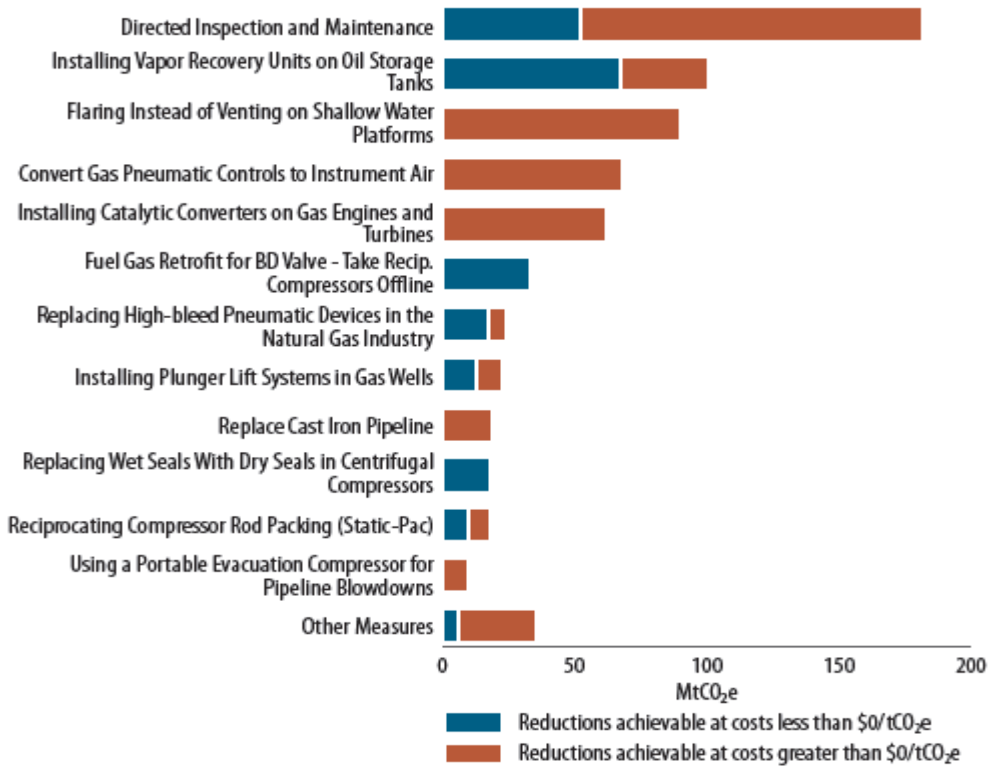

Figure 8: Methane abatement opportunities in global assessment of oil and gas supply chains – 2030 estimate (US EPA, 2019a).

Device conversion, replacement, and installation

This category typically addresses the known methane emissions sources from stationary devices. Examples include converting gas-pneumatic controls to air-pneumatic controls,[3] and installation of new venting control devices to equipment such as storage tanks and well heads. These methods can address fugitive leaks, intentional venting, and combustion slip categories of methane emissions.

Changes to operations and maintenance practices

Alternative practices can reduce intentional venting and fugitive emissions. Examples include maintenance procedures that do not require blow-down or venting of the section of pipe being worked on (American Gas Association, 2014). Improved monitoring of product flows also alerts operators to system faults such as leaks.

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[3] For example: https://www.epa.gov/natural-gas-star-program/convert-gas-pneumatic-controls-instrument-air

Leak detection and repair

Fugitive emissions must first be found before they can be fixed. Leak detection and repair (LDAR) is the term describing the systematic screening, inspection, maintenance, repair, and recording of emissions sources in this category. LDAR or directed inspection and maintenance can be classified in the above category of changes to operational practices (US EPA, 2019b), but the growing number of techniques for conducting LDAR warrants an expanded discussion. The detection portion of LDAR can be carried out by an increasing number of methods (Datu Research, 2017; Fox et al., 2019; Kemp et al., 2016):

- Optical gas imaging
- Audio-visual-olfactory
- Volumetric bag
- Portable analyzing
- Hi-flow sampling
- Laser spectroscopy
- Acoustic detection
- Canine detection[4]

And instrumentation can be mounted on a variety of platforms (Figure 9):

- Handheld
- Truck mounted
- Stationary ground application
- Helicopter or fixed-wing aircraft
- Unmanned aerial vehicle
- Satellite

The cost of high-technology methods can be justified by the volume of leaks detected (Kemp et al., 2016), which can translate into cost savings once repaired. New methods are emerging and costs are likely to decrease with these advances. However, these advances are likely to be more efficient at finding and fixing the largest emitting sources and it is likely that the smallest leaks in the system will still be difficult to find and abate, which provides an insight into the technical potential limit of abatement in this sector.

The effectiveness of LDAR is linked to the frequency at which it is conducted. It has been previously reported that annual inspections can lead to 40% reduction in fugitive emissions, while monthly inspections lead to 80% reduction (ICF International, 2014). When fixed leaks are checked about a year later, 90% of

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[4] https://www.the-sniffers.com/pipeline-integrity/field-surveys-and-services/leak-detection-with-sniffing-dogs/

the repairs have been found to still be effective. In the same intervening time, however, new leaks occur on previously treated sections of infrastructure, meaning that LDAR represents a recurring operational cost and that frequent campaigns are required to maintain emissions abatement (Ravikumar et al., 2020).

Figure 9: Aerial detection of a methane leak from a storage facility (University of Michigan)[5]

Infrastructure overhaul

In some cases, natural gas transmission and distribution infrastructure is overhauled or replaced. Leaking pipes can be re-lined with plastic or replaced altogether with newer materials. At a cost of $1-5 million per mile of replacement (American Gas Association, 2014) pipeline overhaul is not expected to be justifiable on the basis on methane emissions reductions alone (US EPA, 2019b). The primary motivation is typically safety, end-of-life replacement, new construction, or retro-fitting for alternative future uses of the natural gas grid. Methane emissions reductions often occur as a co-benefit to these upgrades, as newer pipes and novel materials generally leak less (Figure 10). Cities that have replaced gas distribution systems with polyethylene or treated steel have significant reductions in methane leaks (Gallagher et al., 2015), however, these new materials still leak and to an extent greater than previously assumed by greenhouse gas inventories (Weller et al., 2020). The greatest abatement potential in this category is the replacement of the

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[5] https://news.engin.umich.edu/2016/08/methane-leaks-a-new-way-to-find-and-fix-in-real-time/#img2

oldest cast-iron gas pipelines with new polyethylene or steel pipeline, but this will always incur a net positive lifetime cost and ranks low in terms of abatement opportunities in the sector (Figure 8). The trend of super-emitter sources is conserved in this category of the supply chain: 40% of emissions came from only 8% of sources in a study of US distribution pipelines (Weller et al., 2020).

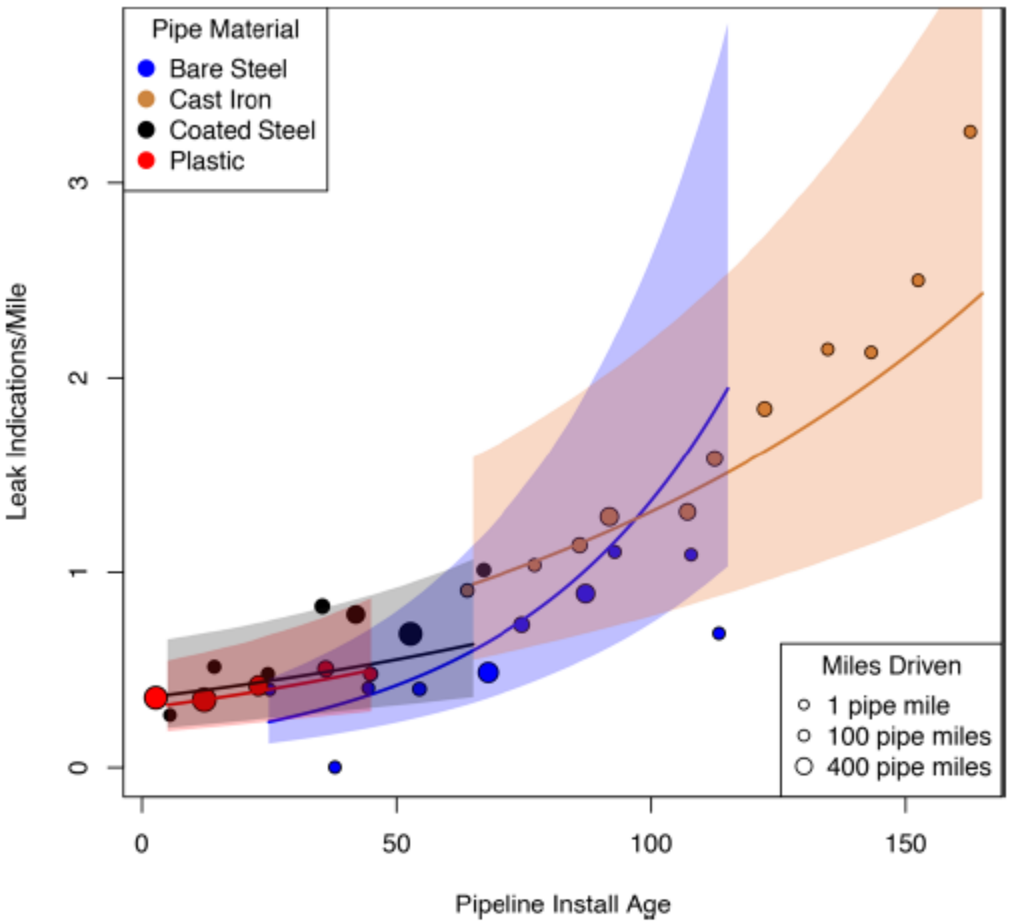

Figure 10: Methane leaks by natural gas distribution pipeline material and age (Weller et al., 2020).

1.4. THE FUTURE OF THE OIL AND GAS SUPPLY CHAINS

Improved methane management in the oil and gas supply chains must be examined in the context of the future direction of this infrastructure, which is connected to multiple sector activities and other Drawdown Solutions (Figure 12). Natural gas over the last decade has contributed to emissions reductions in some countries by displacing coal-fired electricity generation, leading some to suggest that gas will grow in the future as a "bridge fuel" to lower-carbon alternatives. But this narrative is troubled by the growing acknowledgment that all fossil fuel use must be drastically reduced if we are to meet our climate goals.

Abundant and cheap natural gas supply, as has been seen in the past decade or so in the United States, is on its own unlikely to lead to emissions reductions – policy is needed to ensure the displacement of higher-carbon energy sources and to minimize methane leakage (Lazarus et al., 2015). A global shift to natural gas has even been modeled to cause a net increase in emissions, due in part to methane releases from the supply chain infrastructure (Wigley, 2011). An International Energy Agency scenario from 2011 that envisioned an outsized role for natural gas as a bridging fuel for several decades would lead to global warming of almost 4 °C (McGlade et al., 2018), which is clearly not compatible with today's climate goals. That agency's latest pathway modeling for net-zero in 2050 marks a turn-around in this narrative and foresees a drastic decline in all fossil fuel use to mid-century. Though meeting these targets means that there should be no new developments in fossil fuel production (IEA, 2021c), natural gas and oil[6] from existing production is expected to continue to play a role in the world's energy mix – in some fashion – for the coming decades, even in net-zero pathways (IEA, 2021c; Mac Kinnon et al., 2018; J. H. Williams et al., 2021). The United Kingdom's landmark net-zero report (UK Committee on Climate Change, 2019) frames the climate-aligned options for the natural gas distribution infrastructure in that country: by mid-century, it must be phased out or repurposed to low-carbon alternatives.

Carbon lock-in

The phase-out or conversion of natural gas infrastructure cannot be examined without acknowledging carbon lock-in, or the tendency of this kind of infrastructure to resist change due to legacy market, social, and political factors. Large-scale and far-reaching technologies, like natural gas infrastructure, have greater institutional strength to persist (Erickson et al., 2015). "Locking in" of carbon-intensive technologies can "lock out" alternatives. Investing in improving this infrastructure to reduce methane leaks could be seen as further entrenching the lock-in effect. The risk of lock-in is amplified by the relative abundance and low price of natural gas, which delays stringent action and the development of low-carbon alternatives (Jacoby et al., 2012). Oil and gas infrastructure can last up to eighty years (Wright et al., 2018), meaning that investments in this infrastructure now should consider mid-century climate goals and that early phase-out or conversion of the infrastructure could be met with resistance by those with interests in maximizing the useful life of the investment.

Alternative uses for the infrastructure

The natural gas supply chain infrastructure could have an alternative future transporting low-carbon fuels such as renewable or low-carbon hydrogen, biomethane, and synthetic methane (Blanton et al., 2021). There

[6] We focus on natural gas infrastructure, with the discussion assumed to apply to the portions of oil infrastructure that also generate methane emissions.

has been much recent, renewed interest in the future expansion of hydrogen as an energy carrier to fulfill many of the uses that natural gas currently addresses (IEA, 2019). Blending hydrogen into existing natural gas infrastructure at 5-15% may be feasible without significant changes in equipment or increased risk for end-users (Melaina et al., 2013). Local blends of 20% have been tested[7] and are commonly suggested as an acceptable level.

A global transition to hydrogen blending in the natural gas grid, let alone a complete replacement of natural gas by hydrogen, would require substantial increases in hydrogen production and changes to the way it is made. Current hydrogen production is used mostly for industrial processes and less than 0.1% of this is produced by electrolysis of water, the production pathway envisioned for use with renewable energy (IEA, 2019). Though hydrogen production from fossil fuels with carbon capture and storage (CCS) is another potential production pathway for low-carbon hydrogen, zero-emissions production cannot be attained because CCS is expected to be only about 90% effective in most applications, and – again – because of the methane emissions that occur upstream in the fossil fuel supply chain. Furthermore, without proper governance of hydrogen production and infrastructure, there is a risk that decarbonization is stalled at the level of blending that enables continued fossil fuel use and therefore carbon lock-in (Van de Graaf et al., 2020).

In addition to the above issues with a large-scale hydrogen conversion of the gas infrastructure, practical hurdles also remain. Hydrogen can make steel pipelines more brittle and susceptible to cracking, meaning that large sections of current infrastructure would need to be replaced with softer steel or polyethylene pipe (Dodds & Demoullin, 2013). And hydrogen is less energy dense on a volume basis, meaning that infrastructure would need to be expanded to provide the equivalent power of natural gas, and new pipelines would likely need to be built to connect hydrogen production facilities to the grid (Blanton et al., 2021).

Several other alternative fuels and uses have been proposed for the natural gas supply chains:

- Renewable natural gas can refer to both biomethane and synthetic methane – fuels that are similar to natural gas in that they are made mostly of methane, but differing from natural gas in that they are, in principle, sourced from low-carbon activities. Biomethane is formed from biological processing such as anaerobic digestion of manure. Synthetic methane is formed from the combination of CO_2 with hydrogen, presumably both envisioned to come from low-carbon or biogenic sources. Current production levels of these fuels are low compared to fossil natural gas. It must also be noted that renewable natural gas can be climate intensive, stemming from methane leaks that occur during production (Grubert, 2020).

[7] For example: https://www.theguardian.com/environment/2020/jan/24/hydrogen-uk-gas-grid-keele-university

- Another potential purpose for natural gas pipelines is conversion to carry carbon dioxide to support permanent storage or utilization with carbon capture. CCS and other negative emissions technologies that intend to permanently store CO_2 underground will likely require some CO_2 transportation infrastructure (J. H. Williams et al., 2021). Though, like hydrogen, this is still a very uncertain future and far from the scale of the current natural gas infrastructure.

1.5. ADOPTION PATH

1.2.1 Current Adoption

Improved methane management in the oil and gas supply chains consists of techniques and technologies that have been proven over decades of use and often save money for the infrastructure owners and operators by reducing lost product. Based on 2020 gas prices, as estimated 11% of annual global methane emissions from this sector could be abated at no net lifetime cost (IEA, 2021a). Higher percentages of no-net-cost abatement are possible at higher gas prices that justify the expense of finding and fixing emission sources.

In the United States, the EPA's Gas STAR program has catalogued 72 technologies and practices that have been voluntarily implemented for reducing methane emissions. Partners to this program abated 46 million mcf (thousand cubic feet) of natural gas emissions in 2019, equivalent to 22.1 Mt CO_2e, or 11% of EPA's USA inventory emissions for this sector.[8] This figure indicates that, in the USA, a significant amount of abatement is currently taking place. However, it is difficult to use this figure as an indication of adoption in Project Drawdown's typical methodology because the amount of abatement is a counterfactual scenario that cannot be physically measured and does not transparently convey the assumptions of emissions that would have taken place in the absence of implementation. This is a recurring measurement challenge throughout our analysis of this solution. The EPA data also indicate that reported abatement has not steadily increased; this is likely due to variations in the production cycle linked with natural gas prices.

The level of adoption of this solution may also be estimated from a policy perspective. The IEA policies database[9] lists 258 methane control policies from dozens of jurisdictions. In any case, the continued emissions from this sector indicate that there is significant need for increased adoption.

[8] Based on 5.19×10^4 cf/t methane and global warming potential of 25, for consistency with EPA's data

[9] https://www.iea.org/policies?topic=Methane

1.2.2 Trends to Accelerate Adoption

A number of recent trends may accelerate the adoption of methane management in the oil and gas supply chains:

- Increased research of global methane emissions and the potential global temperature savings opportunity by rapid abatement (CCAC and UNEP, 2021; Ocko et al., 2021)
- Policy: In addition to existing policies such as in IEA's database (IEA, 2021a) there are notable developments:
    - The European Union's Methane Strategy and forthcoming legislation[10]
    - A proposed agency for mitigating methane from abandoned oil and gas infrastructure in the USA
- Voluntary programs, for example:
    - The Global Methane Initiative, an international public-private partnership
    - Gas STAR's Methane Challenge
    - The Methane Guiding Principles
    - The Climate and Clean Air Coalition Oil and Gas Methane Partnership
- The forthcoming Net-Zero Producer's Forum, a group of ministries of leading energy-producing countries, which has indicated a commitment to reducing methane emissions from fossil energy production[11]
- Technology improvements:
    - With the potential to increase the technical abatement potential in the sector (US EPA, 2019b)
    - Improved methane emission detection methods, notably by satellite (Figure 11), which additionally contribute to increased transparency and awareness of the issue

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[10] https://ec.europa.eu/energy/topics/oil-gas-and-coal/methane-emissions_en

[11] https://www.energy.gov/articles/joint-statement-establishing-net-zero-producers-forum-between-energy-ministries-canada

Figure 11: Satellite-measured oil and gas methane leaks (IEA, 2020b).

- Pollution controls that put a direct price on pollution: methane emissions reductions can arise as a co-benefit to pricing other pollutants that also occur along the supply chain, such as volatile organic compounds (ICF International, 2014)
- Financial incentives through climate finance and carbon markets:
    - The Pilot Auction Facility for Methane and Climate Change Mitigation, which stimulates investment in methane reduction projects
    - The UN's Clean Development Mechanism (and potentially its successor mechanism, currently under international negotiation) which includes projects and methodologies for carbon credits arising from methane abatement in oil and gas supply chains
    - The continued expansion of voluntary and compliance carbon pricing systems, some of which address methane emissions (World Bank, 2020, 2021)

1.2.3 Barriers to Adoption

This solution consists of proven technologies and practices that can often be implemented at no net lifetime cost, yet methane emissions from this sector continue to rise. Clearly, there are additional barriers that are not addressed. While marginal abatement cost curves for this sector (ICF International, 2014; IEA, 2021b; US EPA, 2019a, 2019b) can be a useful guidance tool for prioritizing abatement actions, this kind of analysis does not typically reflect transaction costs and other hurdles to implementing the abatement measures. A number of barriers to implementation exist:

- Misalignment of incentives (ICF International, 2014; IEA, 2021a): Due to company or supply chain infrastructure, the incentive of fixing methane emissions does not always return to the fixer. One situation could be a gas distribution company, separate from the production company, that is able to recover losses from emissions by charging higher prices to customers, as has been done historically (Webb, 2015). Abating emissions in these cases can still produce economic benefits through reduced prices for customers (ICF International, 2014), but the financial hurdle for abatement action remains in place. An extension of this issue is reflected in inactive oil and gas wells that continue to emit methane after companies abandon them out of bankruptcy, lack of regulatory requirement, or lack of financial incentive (Kang et al., 2019; J. P. Williams et al., 2021).
- Lack of infrastructure or markets to accommodate excess gas production (IEA, 2021a), for example, when gas is produced alongside oil, which can be more readily transported by alternative means such as rail, but gas collection infrastructure has not yet been developed.
- Policy in need of improvement. Improved policy design has been researched. Policies designed for reducing super-emitter locations, rather than each facility having to reduce methane emissions by an absolute amount, may be the most efficient option (Mayfield et al., 2017). Similarly, policies would be most effective by being technology agnostic, to allow solutions to be adapted to the leaks detected (Ravikumar & Brandt, 2017). In model comparison studies, most methane emissions occur as a result of policies directed at methane reduction; methane emissions reductions do not significantly come as a benefit alongside policies targeting CO_2 emissions, except insofar as reduced demand for fossil fuels that leads to reduced fossil fuel production (Harmsen et al., 2019). There are regulations in place to limit methane emissions from this sector, but many apply only to new infrastructure, leaving existing infrastructure and its many emissions sources unaddressed (ICF International, 2014). Furthermore, non-hazardous leaks in many jurisdictions do not require repair and costs of wasted, leaked gas are recovered by passing onto the ratepayer (Webb, 2015). At a global level, there is a "methane blind spot" in countries' net-zero targets, leading to lack of clarity and comparability over how methane fits into climate goals and countries' own ambitions for emissions reductions (Rogelj et al., 2021).
- Lack of capital (IEA, 2021a): Though investment in abatement measures often has a positive net present value due to reduced product losses, an initial capital investment is still often required. Fossil fuel companies are subject to business cycles that affect their capital availability. Capital is likely to be directed to investments with the highest return, which have historically been in new production. With indications that these kinds of investments must cease in order for alignment with

net-zero (IEA, 2021c), alongside potential increased financial pressure on fossil fuel companies as the world transitions to cleaner alternatives, it seems possible that capital constraints could continue to pose a challenge to emissions abatement in the sector.

- Super-emitter distribution pattern: Depending on the method of leak detection and repair, hundreds or thousands of measurements must be taken in order to identify the largest emitting sources on a certain stretch of infrastructure (Marchese & Zimmerle, 2019). Conversely, as remote detection methods such as satellite and aerial detection advance, they will likely be used for identifying the largest emitters, which risks leaving the large number of smaller sources unaddressed. In either case, the requirement to perform comprehensive and frequent leak detection campaigns, which represent an operational cost, may be a barrier to swift abatement.
- Lack of information: There may be lack of awareness about costs and incentives (IEA, 2021a) or lack of historical measurements such as firm-level inventories (Munnings & Krupnick, 2017) that would be compatible with policies to help reduce methane emissions.

1.2.4 Adoption Potential

The IEA's current estimate is that 70% of sector emissions could be abated using existing technologies and practices (IEA, 2021b). It should be noted that the US EPA's estimate is much lower, at only 34% (US EPA, 2019b). The upper limit of this potential may be expanded by technology development, but a significant portion of emissions is expected to remain unabated. This may be due to:

- LDAR effectiveness is dependent on frequency, and new emissions sources are identified on previously-remedied infrastructure during subsequent campaigns
- There is an additional time lag between detecting leaks and fixing them
- There is a skewed distribution of emissions rates from sources – there is likely a very large number of low-emitting sources that are impractical to remedy
- Abandoned infrastructure continues to emit methane even after production ceases.

Other studies have identified higher technical abatement potentials for mid-century or for individual parts of the oil and gas supply chains. (Höglund-Isaksson et al., 2020).

1.3 Advantages and Disadvantages of Oil and Gas Methane Management

1.3.1 Similar Solutions

Methane management in the oil and gas supply chains is an infrastructure solution that is connected to numerous other sectors and activities (Figure 12). Within the global energy system, changes in demand from oil and gas-consuming sectors such as transportation, electricity generation, buildings, and industrial processes will directly affect the demand for the supporting infrastructure. There are also potential future alternative uses for the infrastructure such as for transporting hydrogen, synthetic methane, biogas, or carbon dioxide. Several of Project Drawdown's existing solutions could contribute to these uses by the production of biogas. This solution is also related to those Drawdown Solutions with a methane emissions component, as mitigation in these areas has different atmospheric effects to those solutions that address other greenhouse gases.

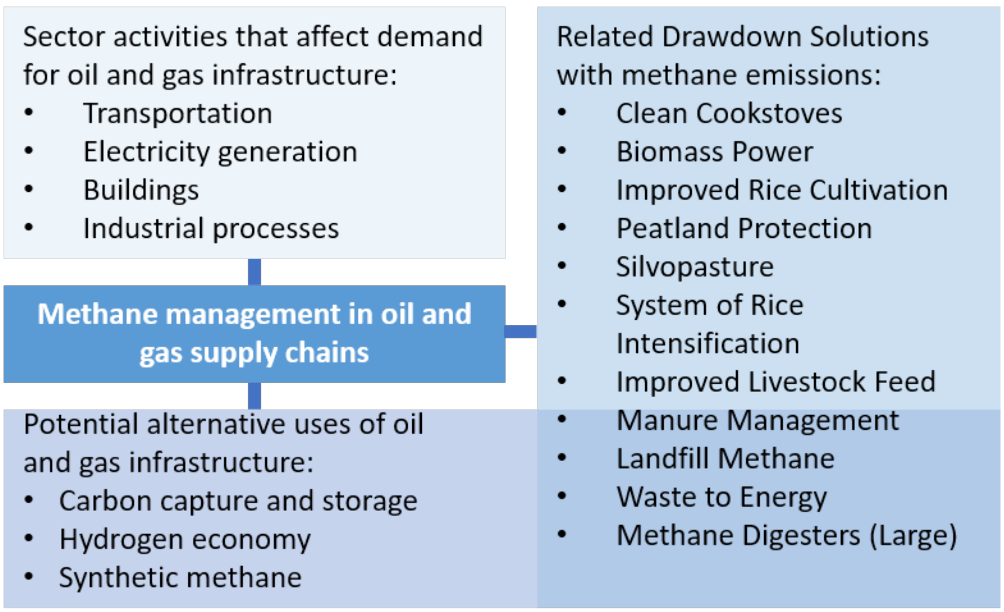


Figure 12: Contextual framing with related solutions and processes.

Coal mine methane management is a closely related solution that has not yet been examined in the Project Drawdown framework. By comparison with methane emissions from the oil and gas supply chains, the coal mining sector contributes about half of this amount to global non-CO_2 greenhouse gas emissions (Figure 4) or about 8% of all global non-CO_2 greenhouse gas emissions. Though this is a significant abatement challenge and opportunity, it differs from methane management in the oil and gas supply chains in several key ways that warrant separate treatment (US EPA, 2019b):

- Different and less diverse abatement measures.
- Only a small fraction of abatement is available at no net cost – the abatement method with greatest potential relies on destructive conversion (combustion) and has no associated revenue,
- Activities concentrated in upstream mining operation sites, whereas oil and gas supply chains span from upstream to downstream and have more widespread infrastructure.

1.3.2 Arguments for Adoption

The volume of methane released from the oil and gas supply chains is an attractive abatement opportunity. Reducing methane emissions can yield quick reductions in expected global temperature increase (Ocko et al., 2021), the technologies to abate a significant portion of this volume exist today (Shoemaker et al., 2013), and because the leaked methane is itself a saleable product in the form of natural gas abatement costs can be offset with savings from recovered product. The abatement solutions in this category tend to be cheap and fast. Of the 72 recommended technologies and measures in the EPA Gas STAR program, only two have estimated payback periods longer than three years. The extent of savings depends on the natural gas price, and therefore the amount of abatement achievable at no net cost shifts accordingly.

Adoption of this solution can also be framed in a "no-regrets" context, where minimizing methane emissions today is beneficial, regardless of the future use of the infrastructure. Apart from the immediate climate and cost benefits, future alternative uses of the natural gas and oil infrastructure benefit from a system with minimal emissions:

- Hydrogen is able to leak through smaller spaces than methane. It is expected to be relatively expensive to produce, so leaks should be minimized. It also may itself act as a weak greenhouse gas. Furthermore, hydrogen leaks are dangerous – there is a significant safety benefit to avoiding them.
- Biomethane and synthetic methane physically have the same short-term warming effect as fossil-natural gas, so a switch to these fuels also requires that the infrastructure emissions be minimized.
- If natural gas pipelines are converted to CO_2 transport for permanent storage in conjunction with carbon capture, then minimizing emissions or "reversals" would be paramount, especially considering that the CO_2 will likely have been captured at great cost.

1.3.3 Additional Benefits and Burdens

The companies and agencies that implement this solution will likely realize several additional benefits:

- Acting early on reducing methane emissions keeps companies ahead of the curve of regulatory advances that may bring additional costs or controls (US EPA, 2007)
- Companies that reduce methane emissions and make lower-carbon oil and gas products may be more appealing to consumers (IEA, 2021c)
- Reducing methane emissions can help retain a skilled workforce. This may be especially important as the sector faces transition pressures. For example, LDAR firms experienced 5-30% growth in business in the United States in the period following adoption of methane regulations. (Datu Research, 2017).

Additional co-benefits and burdens, many of which have been discussed above, are summarized in Table 1.

Table 1: Additional benefits and burdens summary.

Advantages and co-benefits	Disadvantages and additional burdens
• Improved consumer safety (Gallagher et al., 2015) • Improved operational safety[12] • Improved local air quality (Gallagher et al., 2015), specifically through: • Reduced ozone formation[13] • Reduced volatile organic compounds (ICF International, 2014) • Reduced hazardous air pollutants (ICF International, 2014)	• Carbon lock in • Setting infrastructure up for renewable natural gas still risks methane-based global warming (Grubert, 2020) • Additional cost to natural gas operators. Costs could be passed along to consumers. Needs to be weighed against societal benefits of social cost of methane. • Potential rebound: if gas is marketed as cleaner, may increase market share and absolute consumption, leading to increased net greenhouse gas emissions. • Installation of flares, which combust methane to carbon dioxide to reduce the potency of the greenhouse effect, emit black carbon which is itself a climate forcer with additional negative environmental and human health effects (CCAC and UNEP, 2021).

2 Methodology

2.1 Introduction

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution

[12] https://www.epa.gov/sites/production/files/2016-06/documents/installflares.pdf

[13] https://ec.europa.eu/energy/topics/oil-gas-and-coal/methane-emissions_en

was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. The adoptions of both conventional technologies and practices and the solution technologies and practices were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment) constitutes the results.

2.2 Data Sources

This model relies on inputs from previous studies by government agencies, international agencies, non-governmental organizations, and peer-reviewed academic literature. Additional details and sources are provided below for each key input. Briefly, estimates of the abatement potential of technologies and practices were compiled from two prominent sources (IEA, 2021b; US EPA, 2019b) and custom adoption scenarios applied to future trajectories of this abatement opportunity, based on Project Drawdown assumptions. Cost data were compiled from US EPA's Gas STAR program and another study of US oil and gas methane abatement opportunities (ICF International, 2014).

2.3 Total Addressable Market

The total addressable market (TAM) was defined as the technical potential for oil and gas methane abatement by existing technologies and practices, measured in megatonnes of methane (Mt CH_4). Because we evaluate results over a thirty-year period, the TAM needed to be projected for annual estimates from 2020-2050. Using the 2020 starting value as defined above, the technical abatement potential was scaled to Project Drawdown's trajectory for natural gas usage in the electricity generation sector. This is a necessary methodological step to capture the system-wide changes that occur in Project Drawdown's three modeled worlds – a "plausible" world (PDS1), a "Drawdown" world (PDS2), and a maximum mitigation world (PDS3). As the largest natural gas use in Drawdown's integrated model, we make the assumption that oil and gas methane emissions will follow a similar trajectory as the share of natural gas in the electricity generation sector. Each adoption scenario was combined with the respective TAM for PDS1, PDS2, and PDS3.

Recognizing that the above approach relies on several assumptions and does not fully capture the system-wide nature of methane emissions from oil and gas use, we consider several alternatives, for illustration (see 2.4.3; 3.5).

2.4 ADOPTION SCENARIOS

A key challenge of modeling this solution is that it consists of numerous individual technologies and practices with differing costs, abatement potentials, and lifetimes. A generic functional unit was therefore defined as 1 megatonne of methane (Mt CH_4) abated. A corresponding generic implementation unit was defined as 1 Mt CH_4/yr installed abatement capacity. Adoption scenarios were defined in terms of the percentage of the technical abatement potential (i.e., the TAM) reached in each year.

2.4.1 Reference Case / Current Adoption

Current adoption of this solution is difficult to measure, given that abatement relies on a hypothetical counterfactual of the emissions that would have occurred in the absence of the measure. Current estimates are incomparable. For the purposes of modeling, we set the current adoption at 0%, which is consistent with the TAM definition as the current technical potential for abatement of current emissions. The reference case (REF) against which the adoption cases are compared, is defined as 0% adoption of abatement measures in every year, equivalent to today's ambition level.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for this solution. In contrast to many other Project Drawdown solutions, oil and gas methane management is expected to be a transition measure with a TAM that declines over time as global climate ambition increases and the world shifts away from fossil fuels. The year 2030, representing relatively near-term action, therefore serves as an important milestone in the adoption of this solution and we set three trajectories based on targeted adoption of abatement in that year. Because the TAM changes with adoption of other solutions that reduce fossil fuels, each PDS was combined with the corresponding TAM from Project Drawdown's integrated model (see 2.3).

PDS1 - A linear increase to 50% of TAM in 2030, followed by continued linear increase on the same trajectory until 100% of TAM is reached, then maintaining 100% of TAM in each year thereafter.

PDS2 - A linear increase to 75% of TAM in 2030, followed by continued linear increase on the same trajectory until 100% of TAM is reached, then maintaining 100% of TAM in each year thereafter.

PDS3 - A linear increase to 100% of TAM in 2030, then maintaining 100% of TAM in each year thereafter.

2.4.3 Alternative model scenarios

Acknowledging that Project Drawdown's typical integration framework may not capture all system-wide interactions for this solution, we consider two additional cases, for illustration.

Alternative scenario 1

Considers the adoptions cases as described above, but all applied only to the TAM from PDS1, rather than pairwise combinations of PDS with respective TAM.

Alternative scenario 2

Considers the adoptions cases as described above, but all applied to an external TAM generated from the IEA's Net Zero Emissions (NZE) scenario (IEA, 2021c). Modeled 2020-2050 oil and gas production volumes from this scenario were averaged, scaled to a value of one at the base year of 2020, and then applied to the same 2020 starting technical potential for abatable methane as used in the other TAMs in this model. The key assumption of this scenario is that oil and gas methane emissions are proportional to the average expected production volumes.

Results from these alternative scenarios are presented for illustration in 3.5.

2.5 INPUTS

This solution consists of numerous individual technologies and practices with differing abatement potentials, costs, and technical attributes. A typical approach to harmonize such diverse sub-solutions for analysis is to combine amortized costs with abatement potential in a marginal abatement cost curve, as was done by two prominent sources that serve as inputs to our analysis (IEA, 2021c; US EPA, 2019b). However, this approach was found to be incompatible with Project Drawdown's methodology, which disaggregates first costs and operating costs and additionally accounts for the replacement of implementation units based on their lifespan. We therefore adopted a different generalization approach, as described below, of simulating a "generic abatement device" that has the weighted average features of the sub-solutions it represents. Of course, like the marginal abatement cost curve approach, this method has its own advantages and disadvantages, as discussed later in this report.

The IEA and EPA marginal abatement curve studies group the sub-solutions into about a dozen categories. We cross-matched these categories between studies and allocated any non-matching categories to an "all other" category. The total abatement potential for each category was filtered from the corresponding datasets. The share of each category's abatement potential in the overall abatement (i.e. TAM) served as the weighting proportion applied to arrive at the generic abatement device or implementation unit (Figure 13). The "all-other" category was assigned the average values of the attributes of the preceding categories.

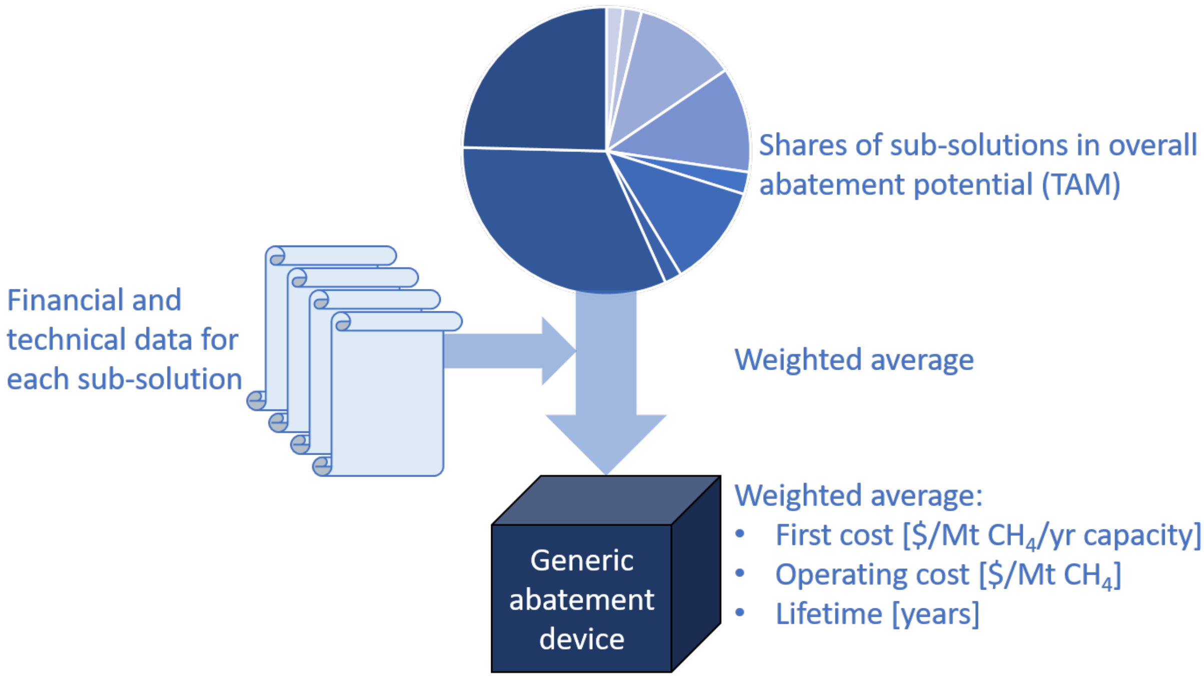


Figure 13: Generic abatement device modeling method.

2.5.1 Climate Inputs

A generic functional unit was defined as 1 megatonne of methane (Mt CH_4) abated. A corresponding generic implementation unit was defined as 1 Mt CH_4/yr installed capacity. Each functional unit corresponds to a climate impact of 28 Mt CO_2-e emissions reduction, using the 100-year global warming potential equivalent of methane, based on the Fifth Assessment Report from the Intergovernmental Panel on Climate Change. The abatement potential of each sub-solution accounts for the methane content of the natural gas at the point of implementation based on averages provided by EPA Gas STAR.

Table 2: Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Emissions reductions	*Mt CO_2-e reduced per Mt CH_4 abated*	28-28	28	1	1

2.5.2 Financial Inputs

Cost data were obtained from US EPA's Gas Star Recommended Technologies factsheets for categories that were most closely aligned with our cross-matched categories, and supplemented in some cases with data from a more recent analysis (ICF International, 2014). Cost data were normalized to the abatement potential of each sub-solution category by dividing first cost or operating cost by the annual abatement potential of each technology or practice. Sub-solutions that result in a relative savings of natural gas by reduced emissions have this credit applied against the operating cost. A fixed price of $4/mcf of natural gas was used in the analysis, for consistency with literature sources (ICF International, 2014; US EPA, 2019b). All operating costs are treated as variable operating costs. Cost and technical data for the sub-solution category of leak detection and repair, the effectiveness of which differs with implementation frequency and the portion of the supply chain where it is implemented, were combined from five distinct EPA Gas STAR LDAR case studies, with an average used to represent LDAR as a whole. All costs were scaled for inflation to 2014 dollars for consistency with Drawdown's other solutions.

Table 3: Financial Inputs for Solution – generic abatement device

	Units	Model Input	Data Points (#)	Sources (#)
First costs	*\$/Mt CH_4/yr capacity*	1,536,000,000	12	2
Variable Operation and Maintenance Costs	*\$/Mt CH_4*	74,600,000	12	2

2.5.3 Technical Inputs

A weighted average lifetime of the generic abatement device was derived based on the reported and assumed lifetimes of the sub-solution categories. Where a lifetime was reported in the data or example financial analysis, these values were used. Sub-solutions with compressors are assumed to have five-year lifetimes before a rebuild is necessary; sub-solutions with minimal moving parts are assumed to have a twenty year lifespan; reported costs for leak detection and repair are assumed to recur annually, except when a different interval was specified. For the purposes of calculation in the Project Drawdown model, the generic abatement device is assumed to operate 100% of the time. This is not an overestimate of performance because the abatement potentials from the data sources report the average annual value. For tractability, the lifespan and replacement of conventional practices and technologies being replaced were not analyzed.

Table 4: Technical Inputs for Solution

	Units	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity	*years*	9.81	12	2
Average Annual Use	*Hours/year*	8760	Assumption for consistency with model format	

2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The proportions of each abatement sub-solution category remain the same over time. This was a necessary assumption to determine a weighted-average generic abatement device that could be modeled consistently over the analysis period. We furthermore assume that this generic abatement device represents the attributes of the sub-solutions adequately enough to provide an indication of the sector-wide costs and abatement potential, acknowledging that this approach overlooks technical and geographic detail that may lead to very different results in practice.

Assumption 2: The technical abatement potential, expressed as percentage of sector emissions that can be abated with existing technologies and practices, remains the same over time. This assumption is unlikely to be true in practice. The technical abatement potential will likely increase with technology improvements, as was modeled by US EPA (2019). Adding this detail to our current model would require better understanding of the baseline sector emissions to which the technical potential percentage is applied.

Assumption 3: As mentioned earlier in the description of TAM, we have assumed that the sector methane emissions follow a trajectory similar to that of natural gas in the share of global electricity generation. This assumption was the best of examined options for making the current solution compatible with Project Drawdown's integrated modeling framework. Alternatives are compared later for illustration.

2.7 INTEGRATION

Project Drawdown solution models are integrated in a complete modeling framework to avoid double-counting of emissions savings. This specific solution poses the challenge of relying on abatement estimates that in turn rely on varying exogenous baseline assumptions about the future of methane emissions from the oil and gas sector. Of the alternatives examined, our modeling approach of scaling the sector emissions to the trajectory of the share of natural gas in the electricity generation sector is the most robust; Drawdown's electricity generation model draws on numerous external sources to inform scenarios and many other solutions models reference it in turn. The chosen trajectories for this solution model can be considered conservative: because baseline emissions in all cases decline towards zero in mid-century, emissions *savings* measured against this baseline are likely to be more conservative than against an increasing baseline. The ideal integration would consider all production and uses of natural gas and oil to mid-century and correlate this with expected sector methane emissions. Lacking this level of detail for the time being, we present two additional alternative model scenarios for illustration.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

Model-specific limitation and further potential development are discussed below. Broader limitations and contextualization of the results are discussed in 4.2.

This is the first version of this solution model in the Drawdown framework. It relies on numerous assumptions and simplifications to arrive at global estimates that are intended to be broadly indicative of the costs and abatement potentials of the sector as a whole, and comparable to results from Drawdown's 80-plus existing models.

Modeling limitations and areas for further development include:

- Generic abatement device modeling approach: This approach was a necessary step for model consistency; however, it sacrifices geographic and technical detail that other sources have incorporated. Weighting may not be effective for reflecting how device lifespan affects abatement: the average lifespan is weighted, like the other variables, by the share of the device in the overall TAM or abatement potential; however, there may be correlations between the variables of capital cost and lifespan that are not properly reflected in this simple averaging method.
- Technical detail: Our literature review identified an abundance of technical detail for individual technologies and practices, but cost and performance data are all primarily from 2006 EPA Gas STAR collections. Even more recent modeling efforts (ICF International, 2014, 2015; US EPA, 2019b) reference this historic dataset. Additional data sources and more contemporary information

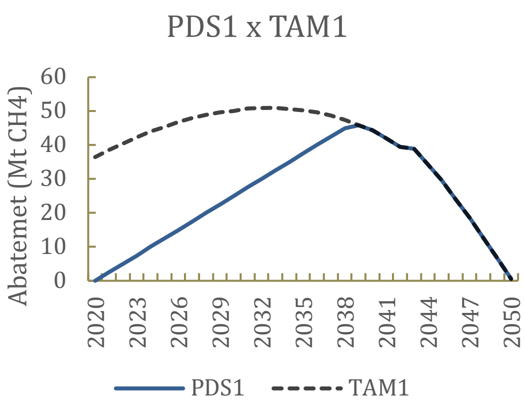
on the state and costs of technologies would improve and likely change model results. Additionally, our model overlooks the fact that some capital upgrades also bring about reductions in operating costs, for example, switching from wet seals to dry seals at compressor stations.

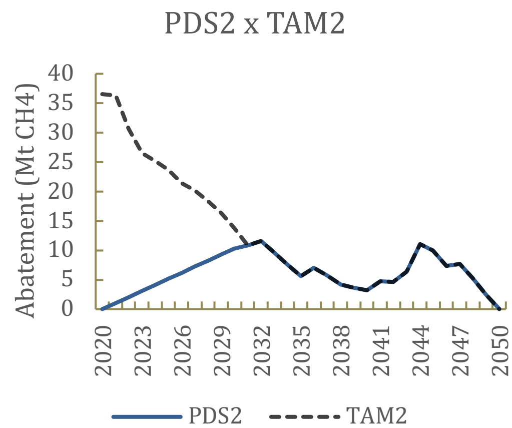
- Indirect emissions: Some sub-solutions, for example switching from gas-pneumatic controls to compressed air, require electricity for operation, which we did not model due to the complications presented by the generic abatement device approach.
- In case of early replacement of equipment, there may be a salvage value associated with the legacy equipment, which is not included in our model but would translate into reduced net costs of implementing the new measure.
- In the literature and in this model there is a lack of treatment of transaction costs and barriers that may be present in actual implementation of this solution.
- Absolute emissions vs emissions savings: For consistency with literature sources and Drawdown's modeling framework, climate impacts are measured as emissions savings compared to a conventional baseline. This presents several challenges for modeling the current solution. Literature sources on this sector report emissions reductions relative to a baseline scenario, but these baselines rely on differing assumptions and are often not reported. Only an integrated approach that considers how this baseline changes over time can present abatement figures that may be considered consistent. It seems a more robust approach would be to model the absolute emissions of the sector and examine these effects in an integrated climate model.
- Abandoned infrastructure: This is an area of emerging importance. A common assumption in our model and some literature sources is that sector methane emissions will, all else equal, be proportional to the production volumes of oil and gas. However, if abandoned infrastructure continues to emit significant methane without significant production (Kang et al., 2019; J. P. Williams et al., 2021), then the scale of the abatement challenge may currently be under-represented.
- Future model versions may benefit from using the Nelson-Farrar price indices to adjust cost estimates for inflation. The current analysis uses standard inflation factors from the US Bureau of Labor Statistics, for consistency with other Project Drawdown Solutions.

3 Results

3.2 Adoption

Below are shown the world adoptions of the solution, each combined with the corresponding TAM.





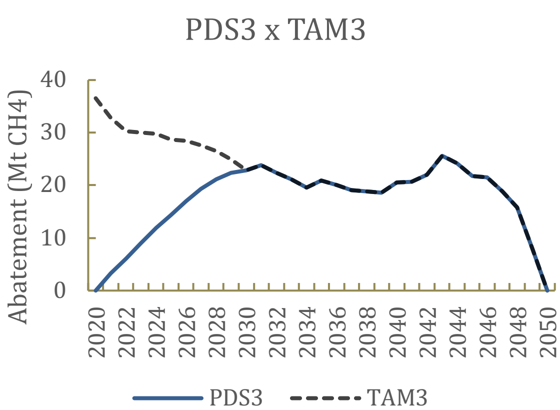


Figure 14: World Annual Adoption 2020-2050

3.3 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6).

Table 5: Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
PDS1	1.28	21.39	0.70	0.01
PDS2	0.32	5.18	0.29	0.00
PDS3	0.72	14.87	0.64	0.00

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 6: Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
PDS1	1.68	-0.03
PDS2	0.40	-0.01
PDS3	1.16	-0.02

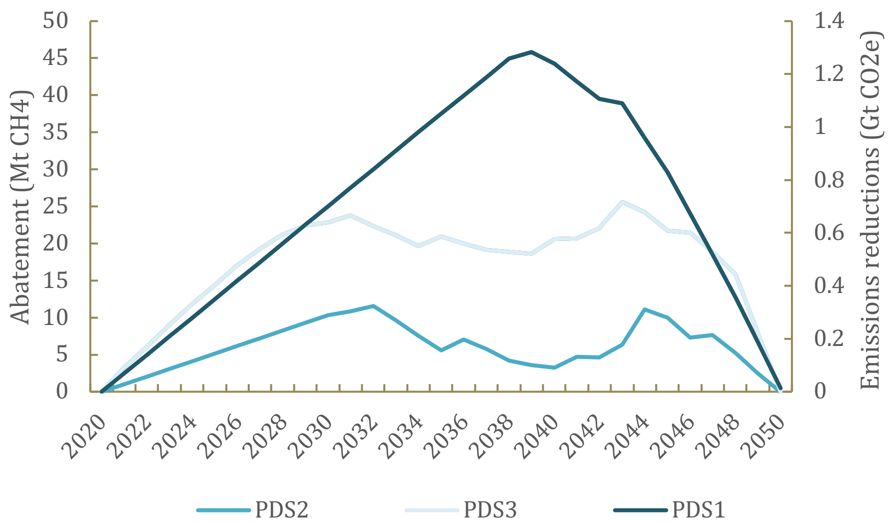


Figure 15: World annual greenhouse gas emissions reduction.

3.4 Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 7: Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Average abatement cost 2020-2050
	2020-2050 Billion USD	*2020-2050 Billion USD*	*2020-2050 Billion USD*	$/tCO$_2$-e
PDS1	127.95	127.95	-56.84	8.64
PDS2	49.09	49.09	-13.72	12.12
PDS3	95.73	95.73	-39.44	9.09

3.5 ALTERNATIVE SCENARIOS

Alternative scenario 1

Adoption scenarios are all applied to the TAM from PDS1, to highlight differences between adoption cases against a consistent TAM.

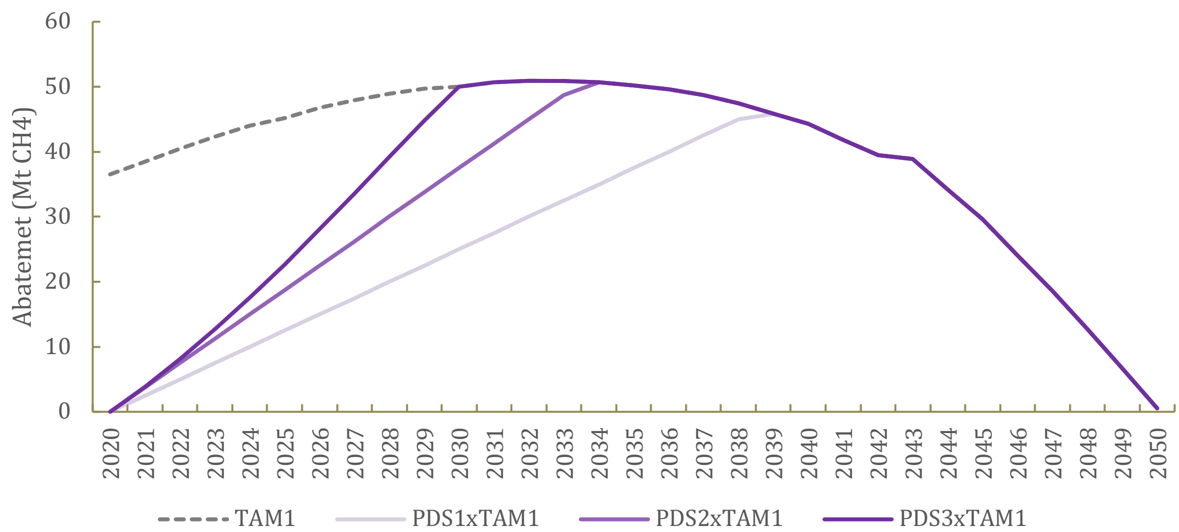


Figure 16: Adoption cases in alternative scenario 1.

Table 8: Key climate results in alternative scenario 1.

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
PDS1	1.28	21.39	0.70	0.01
PDS2	1.42	25.88	1.05	0.01
PDS3	1.43	27.89	1.40	0.01

Table 9: Key financial results in alternative scenario 1.

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Average abatement cost 2020-2050
	2020-2050 Billion USD	*2020-2050 Billion USD*	*2020-2050 Billion USD*	$/t$CO_2$-e
PDS1	127.95	127.95	-56.84	8.64
PDS2	135.42	135.42	-68.72	7.89
PDS3	138.30	138.30	-69.38	7.62

Alternative scenario 2

Adoption scenarios are all applied to an exogenous TAM, modified from the IEA's Net Zero Emissions scenario (IEA, 2021c) for oil and gas production.[14]

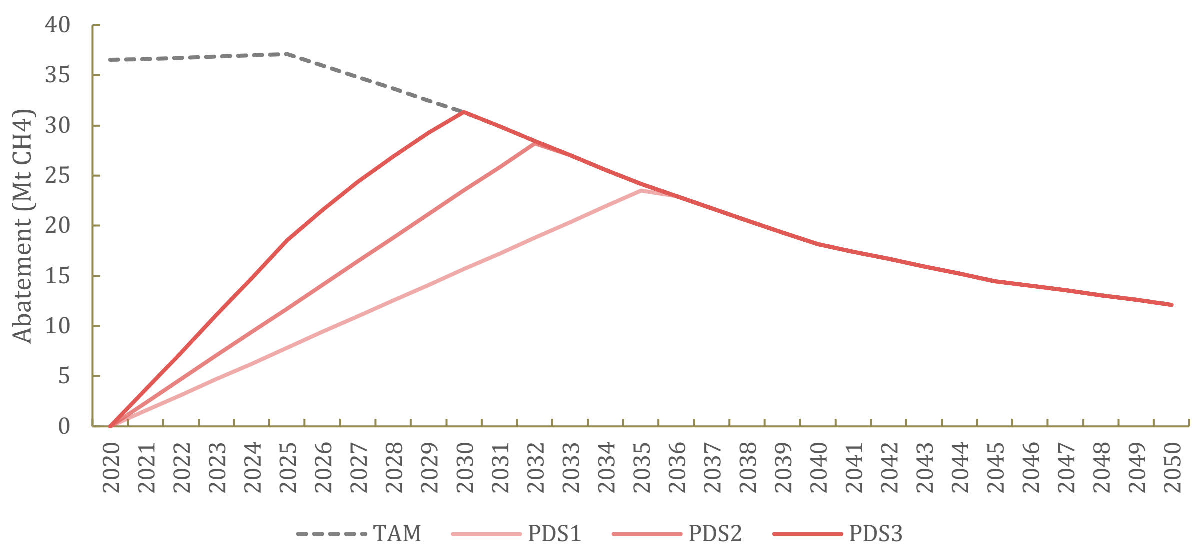


Figure 17: Adoption in alternative scenario 2.

Table 10: Key climate results in alternative scenario 2.

[14] Based on data from International Energy Agency (2021) Net Zero by 2050 – Data product – IEA; as modified by Project Drawdown from data for figure 3.2 in source.

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
PDS1	0.66	12.21	0.44	0.34
PDS2	0.79	14.23	0.66	0.34
PDS3	0.88	16.02	0.88	0.34

Table 11: Key financial results in alternative scenario 2.

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Average abatement cost 2020-2050
	2020-2050 Billion USD	*2020-2050 Billion USD*	*2020-2050 Billion USD*	\$/tCO_2-e
PDS1	60.18	60.18	-32.42	7.58
PDS2	72.22	72.22	-37.75	7.73
PDS3	81.29	81.29	-45.12	7.73

4 Discussion

Some general characteristics of our modeling approach and the abatement opportunity in this sector are immediately apparent from the results. As we have modeled it, this is a transition measure, i.e., the abatement opportunity eventually declines with time and will likely approach zero as the world increases climate ambition and reduces fossil fuel consumption. The exact trajectory of the oil and gas sector, and by extension methane emissions from his sector, is unknown. The TAMs presented in our main modeling scenarios represent three possible pathways (Figure 14). TAM1 is noticeable in that the role of natural gas increases significantly until about 2030, then declines sharply. TAM2 is, unexpectedly, lower than TAM3. This aberrance is a result of integration among Project Drawdown's solution models, wherein the share of natural gas was calculated by subtraction after adoption of all other solutions. All three TAMs decline to zero in 2050. When combined pairwise with increasing ambition scenarios PDS1, PDS2, and PDS3, the overall emissions savings range from 5-21 Gt CO_2e over the period 2020-2050. It is evident from the annual emissions reduction over this period (Figure 15) that quick initial action yields higher cumulative emissions savings.

Alternative scenarios 1 and 2 attempt to correct for the aberrance in TAM values that appears in the primary model results. Alternative scenario 2 additionally uses an exogenous trajectory for the oil and gas sector, which we have modified and scaled to correlate to sector methane emissions, that does not reach zero in 2050. In such a scenario, some oil and gas remain in the economy for use in materials and hard-to-abate sectors (e.g., aviation, industrial heat processes, distributed residential heating) (IEA, 2021c). Cumulative emissions savings from this alternative scenario are broadly comparable to PDS1 and PDS3 in the primary results.

The negative operating savings indicated for each scenario is equivalent to a net operating cost for this solution. This already includes a credit applied for the value of natural gas saved ($4/mcf) during methane abatement processes, where applicable. The lifetime operating cost and average abatement cost are highly sensitive to this input. For illustration: running scenario PDS1 without the natural gas credit yields a 67% increase in lifetime operational costs and an 85% increase in average abatement cost. Modeling with a fixed $4/mcf gas credit is consistent with other studies (ICF International, 2014; US EPA, 2019a) but may not be representative over a multi-decade period where significant changes to the sector are expected. The IEA's marginal abatement cost curves, which are annually updated, reinforce how significant an effect the gas price can have: at 2019 gas prices, almost half of sector abatement would have been possible at no net cost or less; at 2020 gas prices, this dropped to only 11% (IEA, 2020a, 2021b). In any case, average abatement costs are relatively cheap compared to solutions in other sectors. Combined with the comparatively short, intense radiative forcing from methane emissions, this seems to make a compelling case for a quick climate fix.

There are a few more complications that seem under-represented in the literature, however. Our TAM is defined as the amount of methane technically abatable in the sector and therefore does not illuminate the magnitude of non-abatable methane emissions, which is actually quite significant. The technically abatable portion may currently be between 34% and 70% (IEA, 2021b; US EPA, 2019b). Though the technical abatement potential may increase in the future, it is not expected to do so significantly (US EPA, 2019a), meaning that a significant portion could remain unabated, even with technology improvement and high mitigation ambition. If these factors mean that maintaining abatement comes at a significant operational cost, then questions are raised about the economic efficiency of these solutions versus phasing out this infrastructure in favor of low-carbon energy sources that operate cleanly without additional abatement cost.

4.2 Limitations

The most apparent limitation of our modeling method in the results is the average abatement cost. The generic abatement device modeling approach fails to capture what marginal abatement cost curves for the sector show very well – that increased ambition generally comes at increasing cost, due to the distribution of abatement opportunities with diverse costs and effectiveness. Results in Table 7 indicate that the average marginal abatement cost varies little among PDS1, PDS2, and PDS3, whereas marginal abatement cost curves from the IEA and EPA would indicate a pronounced increase in average abatement cost at higher levels of ambition.

Despite the limitations of the generic abatement device approach, a benefit of this method is that it allows modeling of capital costs. This is chronically obfuscated by marginal abatement cost curves, where the presentation of certain abatement measures at no lifetime cost suggests to some that they can occur for free. The IEA even identifies capital constraints as a barrier to adoption of this solution (IEA, 2021a), yet none of the sources we surveyed provided aggregate capital costs for global datasets. Capital costs are a necessary input into the development of these marginal abatement cost curves, so it would be beneficial if in future versions these values would be reported alongside the main results of agency studies. The IEA and EPA marginal abatement cost curve studies include an incredible amount of technical and geographic detail that we had to exclude in favor of elucidating the capital cost component in a transparent manner. Some studies (ICF International, 2014, 2015) effectively report capital costs alongside the marginal abatement cost curves, but lack global data.

Another chief limitation of our model is the lack of an integrated trajectory for the methane emissions from the oil and gas sector. Our use of the natural gas share in electricity generation as a proxy for the trajectory of sector emissions as a whole is likely not representative. It could be improved by accounting for the use of natural gas and oil across the entire Project Drawdown framework. It could furthermore be informed by exogenous trajectories, like we attempted in alternative scenario 2. An issue in some studies in the literature is that baseline emissions for the sector are assumed to increase in all cases, which seems increasingly unlikely given a global acknowledgment of policy aims like net-zero, and risks leading to overestimates of emissions savings. Accounting in absolute emissions, not savings, may overcome this.

4.3 BENCHMARKS

The two main data sources compiled in our analysis – EPA and IEA – present very disparate views of the issue. They differ significantly in the total abatement opportunity, the costs to achieve it, the amount that can be done at no lifetime cost, and the amount of abatement that is technically feasible. We have attempted below to extract some comparable indicators from these datasets and others, based on our own calculations, in order to contextualize our own findings.

Figure 18: Benchmarking comparison of some key indicator results

Source	Technical mitigation possible in 2020 ($Mt\ CH_4$)	Annualized cost of achieving total possible mitigation (USD)	Average annualized abatement cost ($USD / t\ CH_4$)	Average annualized abatement cost ($USD / t\ CO_2e$)
This study – PDS2 scenario	36.53	(Not calculated)	339.36	12.12
(IEA, 2021b)[15]	50.57	8.48 billion[b]	187.88	6.71
(US EPA, 2019b)[16]	22.51[a]	1.49 trillion	66193.80[a]	2647.71
(US EPA, 2019b)[17] – excluding measures above $500/t CO_2e	17.52[a]	27.3 billion	1558.21[a]	62.32
(Harmsen et al., 2019) – Oil sector in 2050	48[a,c]	34 billion	708[a]	28.33
(Harmsen et al., 2019) – Gas sector in 2050	40[a,c]	9 billion	225[a]	9.00

[15] Based on data from International Energy Agency (2021) Methane Tracker Database – Data product – IEA; as modified by Project Drawdown.

[16] Based on data from US Environmental Protection Agency (2019) Global Non-CO2 Greenhouse Gas Emissions Projections & Mitigation 2015-2050 – Data product – EPA; as modified by Project Drawdown.

[17] Same as above; as modified by Project Drawdown to exclude measures exceeding $500/t$CO_2e$

(ICF International, 2014) – USA onshore oil and gas	-	-	34.5[a]	1.38
(Climate and Clean Air Coalition, 2021)[18]			520	18.57

[a]Methane global warming potential of 25, for consistency with source.

[b]All cost calculations and dependent values from this source are based on a conversion 52.7 MBTU/tCH_4.

[c]For year 2050

The wide range of results represented in this benchmarking analysis gives insight into the challenge of arriving at a global estimate for emissions reductions and costs. Our central result (PDS2) is within the range of literature values for average abatement cost and technical mitigation possible. The comparison of data calculated out of marginal cost curve studies is a tenuous exercise, given the differing assumptions upon which these studies rely. The lack of a central tendency for key indicators in the above benchmarking analysis indicates that though there ostensibly is rich data about the technologies and practices to abate emissions in this sector, there is not agreement on how much can be realized and at what costs.

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours