Opportunities to Tackle Short-lived Climate Pollutants and other Greenhouse Gases for China

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About the California-China Climate Institute

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Executive Summary

In addition to carbon dioxide (CO_2), reducing a particular group of non-CO_2 greenhouse gases (GHGs) and precursors, short-lived climate pollutants (SLCPs), including emissions of black carbon, methane (CH_4), tropospheric ozone, and fluorinated gases such as hydrofluorocarbons (HFCs), is increasingly recognized as critical and necessary to limit global temperature increase to below 1.5°Celsius (C). While SLCPs remain in the atmosphere for shorter periods of time than CO_2, they trap heat more efficiently than CO_2 on a per-unit basis making them potent climate forcers with the potential to significantly warm the atmosphere and ocean. In addition, SLCPs also have exacerbated other climate change-related impacts – including disrupting seasonal rain patterns, accelerating Arctic melting, and contributing to deadly air pollution. Combined, black carbon from fossil-fuel combustion; methane from agriculture and fossil fuel operations; HFCs from cooling, refrigeration and other industrial uses; and tropospheric ozone formed from air pollutants are responsible for up to 45% of current global warming. In addition, the longer-lived non-CO_2 GHG, nitrous oxide (N_2O), is a potent GHG and ozone depleting substance. N_2O is approximately 300 times more potent than CO_2 and contributes the equivalent of about 10% of today's CO_2 warming. Indeed, N_2O is the third most damaging GHG, after CO_2 and CH_4.

The Intergovernmental Panel on Climate Change has recognized that reducing SLCPs is crucial to limit global temperature rise to below 1.5°C which is key to slowing the devastating impacts of climate change. Recent studies have also pointed out that reducing SLCPs is critical to reducing the short-term warming trend by more than half over the next few decades and slowing down self-reinforcing feedbacks such as the loss of Arctic sea ice, methane release from permafrost thaw, and avoiding climate tipping points. These studies have also shown that fast reductions in SLCPs could avoid up to 0.6°C of warming by 2050, and up to 1.2°C by 2100. Reducing black carbon and tropospheric ozone has additional near- and long-term co-benefits in improved air quality and health, and increased crop production. There is currently a window of opportunity for global cooperation in reducing SLCPs as global efforts advance toward universal implementation of the Kigali Amendment on HFCs under the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) and as countries continue to update their Nationally Determined Contributions (NDCs).

As SLCPs gain global recognition regarding their important role in meeting global climate targets, more and more countries and regions have adopted a variety of mitigation policies and programs. These moves demonstrate that policymakers around the world are considering multiple policy strategies and mitigation options to target reducing different SLCPs and non-CO_2 greenhouse gases, thereby highlighting successes from different experiences. More recently, selected countries have also announced quantitative reduction targets for methane, F-gases, black carbon and SLCPs that reflect high ambition based on both technical feasibility and cost-effectiveness, as shown in Table ES-1. A few best practices emerging from these successful experiences include:

1. Addressing multiple gases across sectors provides a means to create synergies across policies and integrate SLCPs into existing climate plans. It also highlights the benefits for coordination across scales, sectors, and policies, as well as the various roles for multilateral, national, and subnational mitigation actions.

    a. Examples of policies addressing multiple gases across sectors and integration into climate plans include the European Union covering 7 GHGs, Canada covering SLCPs and total GHGs, and the U.S. covering total GHGs in their climate/SLCP strategies and targets

    b. Examples of coordination across multilateral and national actions include the Kigali Amendment on HFC phasedown, the Climate and Clean Air Coalition on SLCPs, the Arctic Council's Expert Group on Black Carbon and Methane, and Canada's SLCP strategy on national and subnational coordination

2. Developing a quantitative target with a baseline sets the stage for developing effective implementation strategies.

a. Examples include the U.S. national-level oil and gas methane reduction target-setting plus more stringent California, Colorado and New Mexico regulations, and Canada national-level oil and gas methane reduction target-setting plus supporting regulations in British Columbia, Alberta, and Saskatchewan

3. A combined and inclusive approach, using a mix of policy tools, provides a means to overcome the various barriers to action. Such approaches include policies, strategies, regulations, economic instruments such as taxes or subsidies, capacity building and knowledge sharing.

   a. Examples of multi-pronged approach used include the E.U. and California on reducing high-GWP HFCs through a mix of regulations, bans, taxes, and incentives

4. Monitoring, reporting and verification systems are essential. These policies and regulations are only effective if there is a way to ensure compliance. There is evidence that many of these approaches are working to meet our climate goals; the key is to adapt them to the local context and continue to learn from our efforts.

   a. Examples of tracking and data reporting include the Kigali Amendment on HFC phasedown and the U.S. EPA voluntary partnership programs' reporting requirements

China will be a critical player in global efforts to reduce SLCPs as the largest emitter of CH_4 and second largest emitter of HFCs. In 2014, China's non-CO_2 greenhouse gas emissions[1] totaled 2.0 gigatons of carbon dioxide equivalent ($GtCO_2e$), which exceeded the national GHG emissions from all countries other than the United States, India, and Russia – accounting for more than 20% of global non-CO_2 emissions. China also emits more than 1 million tons of black carbon, a potent SLCP and precursor to air pollutants such as fine particulate matter 2.5 microns or less in width (PM2.5). China's actions to reduce the key group of non-CO_2 GHGs—SLCPs and N_2O—can help protect China's population and economy from the effects of devastating climate change and meet global climate mitigation goals while supporting China's decarbonization targets and the newly announced targets for 2030 carbon peaking and 2060 carbon neutrality. Selecting a pathway that reduces both CO_2 and SLCPs as fast as possible, along with other fast mitigation strategies, is essential for achieving near-term and long-term climate targets and provides the most avoided warming in the shortest period of time. It can also help mitigate the risk of catastrophic economic costs of extreme climate disaster events that may have low probability of occurring compared to general climate damage, but causes much greater damage once it happens. Recent analysis found that if the possibility of this "fat tail effect" of extreme results and impacts of disaster risk loss is considered, then the social cost of carbon could be nearly three times higher than the median social cost of carbon.

In a virtual summit with President Macron of France and Chancellor Merkel of Germany on April 16, 2021, Chinese President Xi Jinping announced China will accept the Kigali Amendment to the Montreal Protocol, and strengthen the control of non-CO_2 greenhouse gases, including hydrofluorocarbons that are scheduled for phasedown under the Kigali Amendment. President's Xi announcement and China's subsequent ratification of the Kigali Amendment set the stage at the leadership level for China to adopt strategies and targets to reduce SLCPs and N_2O. Additionally, the 14th Five-Year Plan provides that China will "strengthen the control of other GHGs, such as methane, HFCs and PFCs." Finally, China announced that its 2060 carbon neutrality pledge includes non-CO_2 greenhouse gases. These references provide the policy authority for inclusion of detailed requirements and targets for SLCPs in environmental protection and GHG reduction plans that the Ministry of Ecology and Environment, for example, is currently drafting.

Indeed, China has issued a series of policies and guidelines to control SLCPs with notable success during the last 10 years. Chinese industries have also responded to global technological and policy trends in adopting alternative solutions such as low-global warming potential (GWP) refrigerants in room air conditioners (AC). Based on the cost-effective mitigation potential identified in this study, which is consistent with mitigation potential identified in a late 2020 Tsinghua study, China can and should consider reduction targets for SLCPs in its ministerial and sectoral action plans that cover the 14th Five-Year Plan period (2021-2025) to support its 2060 carbon

1 Reported non-CO_2 emissions include CH_4, N_2O, F-gases including HFCs, PFC and SF_6

neutrality target and commitment to the Paris Agreement in its 2030 and 2060 long-term planning. Further, in certain areas, China is in the unique leadership position to spur global action, such as simultaneously improving energy efficiency and transitioning to low-GWP refrigerants in room ACs, where China's share of global production is greater than 80%. Thus, China's early actions could have a large spill-over effect globally, and in other emerging economies in particular.

When considering specific targets and mitigation regulations, China should aim to harmonize, to the extent possible, its regulations with global best practices and norms, including addressing multiple gases across sectors with quantitative targets and specific implementation timelines. Table ES-1 summarizes the national or regional quantitative targets that have been set internationally for overall GHGs (including SLCPs), and for methane, F-gases, and black carbon specifically. For overarching GHG emission reduction targets that also cover SLCPs, The European Union (E.U.) and California have both set reduction targets relative to 1990 levels, ranging from 55% to 40% reduction by 2030. Canada's reduction target is slightly lower with 40-45% reduction by 2030 relative to a higher 2005 baseline level, the equivalent of 27% reduction from 1990 levels. For methane, California is the only jurisdiction to have set an overarching reduction target of 40% below 2013 levels by 2030, but North American countries have committed to an oil and gas sector methane emission reduction target of 40-45% from 2012 levels by 2030. For F-gases, both the E.U. and California have set F-gas and HFCs emission reduction targets for 2030, with 67% reduction and 40% reduction from 2014 and 2013 levels, respectively. California is also the only jurisdiction to have set a black carbon emission reduction target of 50% below 2013 levels by 2030. In the Arctic Council's Reykjavik Declaration on the Climate Change Crisis adopted in May 2021, the Arctic States and Observer states (including China) are encouraged to support a collective and aspirational goal to reduce black carbon emissions by 25-33% below 2013 levels by 2025, and to adopt similar reduction goals for their jurisdictions.

Table ES-1. Comparison of International SLCP Reduction Targets Framing High Ambition, Technical Feasibility and Current Cost-Effectiveness

	OVERARCHING GHG (INCLUDING SLCP) REDUCTION TARGETS	METHANE REDUCTION TARGETS	F-GASES REDUCTION TARGETS	BLACK CARBON REDUCTION TARGETS
E.U.	By 2030, reduce net GHG emissions by 55% from 1990 levels (51% from 2005).		By 2030, phase-down F-gas emissions by 67% compared with 2014 levels.	
CANADA	By 2030, reduce GHG emissions by 40-45% below 2005 levels. (27% from 1990).	By 2025, reduce methane emissions *from oil and gas* by 40-45% from 2012 levels.	Under Kigali Amendment (ratified), phase-down HFC consumption by 40% in 2024, 70% in 2029, 80% in 2034, and 85% in 2036 from calculated baseline.	
U.S.	By 2030, reduce GHG emissions by 50-52% below 2005 levels. (43% from 1990).	By 2025, reduce methane emissions *from oil and gas* by 40-45% from 2012 levels.	AIM Act requires 85% phase-down in production and consumption of HFC by 2036 from baseline.	
CALIFORNIA	By 2030, reduce GHG emissions by 40% below 1990 levels.	By 2030, reduce methane by 40% below 2013 levels.	By 2030, reduce HFCs emissions by 40% below 2013 levels.	By 2030, reduce black carbon emissions by 50% below 2013 levels.
CHINA			By 2020 and 2025, 35% and 67.5% reduction, respectively, in production of HCFC-22 for controlled uses compared to 2010 levels. Under Kigali Amendment (ratified), freeze HFC production and consumption in 2024, with an 80% reduction by 2045.	

These quantitative reduction targets reflect existing international ambition on reducing key SLCPs, and represent technical feasibility and today's cost-effectiveness. Greater ambition can be achieved, given that technologies and their cost-effectiveness will further improve over time, and will be needed to slow global climate change. As seen with the dramatic and rapid cost reductions of solar and wind power and battery technologies over the past decade, societal push for increased adoption of GHG mitigation measures can accelerate learning curves and achievement of economies of scale. Based on existing international ambition in committing to quantitative reduction targets with a defined implementation timeline for different SLCPs, and our analysis of China's specific cost-effective reduction potential for different non-CO_2 GHGs across different sources and sectors, China could adopt ambitious yet technically and economically feasible reductions for SLCPs and N_2O in the near, mid- and long-term.

In consideration of possible target-setting for China for 2030, this analysis has identified cost-effective reduction potential of 35%-40% for methane, 30% for F-gases, and 40% for N_2O, relative to 2015 levels for China under the Deep Non-CO_2 Mitigation scenario, with a total reduction potential of 1080 million metric tons of carbon dioxide equivalent ($MtCO_2e$) by 2030. This is comparable to the total non-CO_2 reduction potential of 1,096 $MtCO_2e$ identified by 2030 in a 1.5°C scenario published by Tsinghua's Institute of Climate Change and Sustainable Development in late 2020. There are also opportunities for China to take early actions in the next five years to reduce HFC-23, N_2O, and other HFCs related to cooling.

For methane, this analysis has identified cost-effective reduction potential of 35-40% relative to 2015 levels by 2030 for China, which is comparable to the lower range of existing 2030 reduction targets in the U.S., Canada and California. In the near-term, China could consider adopting or harmonizing with the emerging international protocols in preventing leakage in the oil and gas industries and consider setting a target for 25% reduction of methane leakage associated with the coal mining process. These energy sector mitigation measures have been demonstrated to be feasible for use around the world and in China at a reasonable cost (see mitigation potential section for details).

In the mid-term to 2030, methane emissions in the energy sector could be reduced about 55% by adopting cost-effective mitigation measures and reducing coal production. Methane emissions in agriculture could be reduced 20% by adopting better practices in irrigation and animal feeds, and those in the waste sector could be reduced 19% by adopting best available technologies and potential waste reduction strategies (reducing landfills).

For F-gases, this analysis has identified cost-effective reduction potential of 30% relative to 2015 levels by 2030 for China, which is lower than the current 2030 E.U. and California reduction targets. The Chinese cooling industry is currently transitioning to lower-GWP refrigerants, with an estimated market share of ~40%-50% according to industry estimates for 2020. Furthermore, in the Global Cooling Prize—which aims to lower the climate impact of cooling by 5X compared to today's baseline—two of the eight finalists are led by Chinese companies. Gree Electric Appliances Inc, in partnership with Tsinghua University, is one of the two winners of the Global Cooling Prize. By accelerating this transition to low-GWP refrigerants while adopting enhanced energy efficiency, Chinese air conditioning companies will be well positioned as global leaders in this field.

As part of the Kigali Amendment to the Montreal Protocol, which China has just ratified on June 17, 2021, China could potentially reduce almost all HFC-23 emissions associated with HCFC-22 production for non-controlled feedstock use during the 14th Five-Year Plan Period. The mitigation technologies have been demonstrated successfully over the past 10 years in China and around the world, and the cost of mitigation is also low (under \$1/tonCO_2e).

By 2030, China could accelerate the adoption of low-GWP refrigerants and reduce all other HFC emissions at least 50% for the room air conditioning and mobile air conditioning industries and 30% for commercial air conditioning and refrigeration industries. Considering China's significant share of the export markets, China can also play a leader's role for the global HFC transition, as well as AC efficiency improvement, which can take place simultaneously with the refrigerant transition.

For N_2O emissions, this analysis has identified cost-effective reduction potential of 40% relative to 2015 levels by 2030 for China. In the near-term, China could adopt cost-effective reduction measures to the maximum extent as practically feasible in industrial processes, since these measures have widely been adopted elsewhere in the world. For the agricultural sector, China could potentially set a 10% reduction target through reducing overuse of fertilizers by 2025.

By 2030, N_2O emissions from industrial processes could be reduced almost completely by adopting existing mitigation measures in the production of nitric and adipic acid production processes, where costs of mitigation are also relatively low (about \$5/tonCO_2e). For the agricultural sector, China could reduce N_2O emissions by more than 22% through reducing over-use of fertilizers.

For black carbon, this analysis has identified a technically feasible reduction potential of 35% by 2030 relative to 2015 levels for China. China has already implemented emission standards for industrial boilers, coking ovens, and automobiles, all of which will lead to significant black carbon reduction. In the near and mid-term to 2030, China could consider expanding such emission standards for diesel-power vehicles to other off-road vehicles.

Further, China could expand its clean heating and cooking program for rural households to the extent that is technically feasible and economically viable.

Looking at PFCs and sulfur hexafluoride (SF_6), the mitigation measures are also very cost effective, and could potentially be fully adopted by China in the near to mid-term.

Table ES-2 below outlines potential China goals for the near-term and for 2030 for different gases and sectors for consideration, based on our cost-effectiveness analysis and comparable existing international targets.

Table ES-2. Potential Near-term and 2030 Goals for China Involving Specific Climate Pollutants/Non-CO_2 GHGs

<table>
<tr><th rowspan="2">CLIMATE POLLUTANT/ NON-CO_2 GHG</th><th colspan="2">POTENTIAL CHINA GOALS</th></tr>
<tr><th>2025</th><th>2030

(TOTAL 1080 MILLION METRIC TONS OF CARBON DIOXIDE EQUIVALENT ($MTCO_2e$)</th></tr>
<tr><td>METHANE</td><td>Consider adopting Oil and Gas Methane Protocol

Coal mines: 25% emissions reduction compared to 2015 levels</td><td>Consider 35-40% methane emissions reduction compared to 2015 levels across all sectors, including:

• Energy: 55% reduction
• Agricultural: 20% reduction
• Waste: 19% reduction</td></tr>
<tr><td>F-GASES</td><td>HFC-23: near complete destruction of HFC-23 associated with HCFC-22 production for non-controlled feedstock use to the extent feasible

Aim for 50% new Room AC and 90% new mobile AC units to adopt low-GWP refrigerants

Power: consider 30% SF_6 emissions reduction compared to 2015 levels

Perfluorocarbons (PFCs): consider 15% emissions reduction compared to 2015 levels</td><td>Consider 30% emissions reduction compared to 2015 levels across all HFCs (excluding HFC-23), including:

• Room and mobile ACs: 50% reduction
• Commercial ACs and Refrigeration, Industrial Refrigeration: 30% reduction

Power: consider 58% SF_6 emissions reduction</td></tr>
<tr><td>N_2O</td><td>Agricultural: consider 10% emissions reduction (fertilizer usage) compared to 2015 levels

Industrial: adopt cost-effective reduction measures as practically feasible</td><td>Consider 40% emissions reduction compared to 2015 levels, including:

• Industrial: 94% reduction
• Agricultural: 22% reduction</td></tr>
<tr><td>BLACK CARBON</td><td>Consideration of the following measures:

• Residential heating: expand clean heating as much as technically and economically feasible</td><td>Consider 35% emissions reduction compared to 2015 levels and the following measures:

• New standards for off-road diesel vehicles
• Accelerate retirement of small capacity coal boilers</td></tr>
</table>

Note: The 2030 total reduction potential of 1080 $MtCO_2e$ does not include reduction potential in manure management, which has more uncertain costs, but includes reduction potential from agricultural soils, commercial ACs, commercial and industrial refrigeration beyond measures shown in the cost-curve.

For the long-term targets, progress made on SLCPs could help China to reach its carbon neutrality target by 2060. While there are still some uncertainties regarding the long-term mitigation potential in SLCPs, current analyses suggest that fast adoption of cost-effective technologies available today could allow China to reduce its non-CO_2 greenhouse gases by 56% by 2050. Tsinghua identified a similar 2050 reduction level of 60% in its recently published 1.5°C scenario. Further reduction could come from a variety of technological and behavioral solutions such as dietary changes, further reduction in fossil energy usage, as well as newer technologies. These opportunities will be explored further in future research.

1 Introduction

In addition to carbon dioxide (CO_2), reducing a particular group of non-CO_2 greenhouse gases (GHGs) and precursors, short-lived climate pollutants (SLCPs), including emissions of black carbon, methane (CH_4), tropospheric ozone, and fluorinated gases such as hydrofluorocarbons (HFCs), is increasingly recognized as critical and necessary to limit global temperature increase to below 1.5°Celsius (C). While SLCPs remain in the atmosphere for shorter periods of time than CO_2, they trap heat more efficiently than CO_2 on a per-unit basis making them potent climate forcers with the potential to significantly warm the atmosphere and ocean. In addition, SLCPs also have exacerbated other climate change-related impacts – including disrupting seasonal rain patterns, accelerating sea level rise and Arctic melting, and contributing to deadly air pollution. Combined, black carbon from fossil fuel combustion; methane from agriculture and fossil fuel operations; hydrofluorocarbons (HFCs) from cooling, refrigeration and other industrial uses; and tropospheric ozone formed from air pollutants are responsible for up to 45% of current global warming.[1], [2] In addition, the longer-lived non-CO_2 GHG, nitrous oxide (N_2O), is a potent GHG and ozone depleting substance. N_2O is approximately 300 times more potent than CO_2 and contributes the equivalent of about 10% of today's CO_2 warming.[3] Indeed, N_2O is the third most damaging GHG, after CO_2 and CH_4.

The Intergovernmental Panel on Climate Change has recognized that reducing SLCPs is crucial to limit global temperature rise to below 1.5°C which is key to slowing the devastating impacts of climate change.[4] Recent studies have also pointed out that reducing SLCPs is critical to reducing the short-term warming trend by more than half over the next few decades and slowing down self-reinforcing feedbacks such as the loss of Arctic sea ice, methane release from permafrost thaw, and avoiding climate tipping points.[5] These studies have also shown that fast reductions in SLCPs could avoid up to 0.6°C of warming by 2050, and up to 1.2°C by 2100.[6] The latest research has shown that strategies exist to cut global methane emissions from human activities in half within the next decade, with half of these strategies currently incurring no net cost.[7] Pursuing readily available methane mitigation measures can deliver nearly 0.3°C of avoided warming by the 2040s while simultaneously reducing ground-level ozone concentrations.[8] Reducing black carbon and tropospheric ozone has additional near- and long-term co-benefits in improved air quality and health, and increased crop production. Fast SLCP reduction can also decrease the rate of sea level rise by 24-50% and reduce cumulative sea level rise by 22-42% by 2100, which has significant implications for many of China's eastern coastal cities.[9] There is currently a window of opportunity for global cooperation in reducing SLCPs as global efforts advance toward universal implementation of the Kigali Amendment on HFCs under the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) and as countries continue to update their Nationally Determined Contributions (NDCs).

China will be a critical player in global efforts to reduce SLCPs as the largest emitter of methane and second largest emitter of HFC gases. In 2014, China's non-CO_2 greenhouse gas emissions[2] totaled 2.0 gigatons of carbon dioxide equivalent ($GtCO_2e$), which exceeded the national greenhouse gas emissions from all countries other than the United States, India, and Russia – accounting for more than 20% of global non-CO_2 emissions.[10],[11] Reducing SLCPs and N_2O in China can help meet global climate mitigation goals while supporting its domestic decarbonization targets and the newly announced targets for 2030 carbon peaking and 2060 carbon neutrality target. China also emits more than 1 million tons of black carbon, a potent SLCP and precursor to air pollutants such as PM2.5.[12] China's actions to reduce the key group of non-CO_2 GHGs—SLCPs and N_2O—can help protect China's population and economy from the effects of devastating climate change and meet global climate mitigation goals. Selecting a pathway that reduces both CO_2 and SLCPs as fast as possible, along with other fast mitigation strategies, is essential for achieving near-term and long-term climate targets and provides the most avoided warming in the shortest period of time. It can also help mitigate the risk of catastrophic economic costs of extreme climate disaster events that may have low probability of occurring compared to general climate damage, but causes much greater damage once it happens. Recent analysis found that if the possibility of this "fat tail effect" of extreme results and impacts of disaster risk loss is considered, then the social cost of carbon could be nearly three times higher than the median social cost of carbon.[13]

2 Reported non-CO_2 emissions include CH_4, N_2O, F-gases including HFCs, PFC and SF_6

This White Paper aims to provide a review of leading international experiences with SLCP reduction target-setting and identify global best practices in gas-specific sectoral policies and programs. For China, similar policy actions on non-CO_2 greenhouse gases are reviewed and additional potential for future reductions under different techno-economic scenarios is analyzed. Drawing on international lessons learned and remaining barriers in China for faster reductions, this paper provides near, mid- and long-term policy recommendations for China.

2 International Policy Review and Best Practices

As SLCPs gain global recognition regarding their important role in meeting global climate targets, more and more countries and regions have adopted a variety of mitigation policies and programs. These moves demonstrate that policymakers around the world are considering multiple policy strategies and mitigation options to target reducing different SLCPs and non-CO_2 greenhouse gases, thereby highlighting successes from different experiences. To understand how existing international policy experiences can inform and support action in China and other countries, this paper highlights specific policy and program examples that demonstrate leadership and effectiveness in both design and implementation. More specifically, policies and programs are reviewed that successfully exhibit:

- Leadership in committing to quantitative targets with a defined timeline;
- Comprehensiveness in policy scope and mitigation strategy development encompassing multiple gases and sectors;
- A multi-pronged approach to applying different types of policies, programs, and tools to support mitigation efforts;
- Coordination and complementarity between multilateral, national, and subnational mitigation actions; and
- Reporting and data tracking to quantify both baseline emissions and emission reduction impacts of mitigation measures.

These examples not only provide detailed insights into how different SLCP mitigation efforts can be realized through effective policy design and implementation, but also help to identify common best practices from existing international experiences with SLCP mitigation.

Comprehensive Climate Policy Development and Target-Setting

There are limited instances of comprehensive policies and strategies that address multiple SLCPs across multiple sectors to date, with the state of California in the U.S., Canada, and the European Union (E.U.) standing out as examples of best practices in their attempts to develop comprehensive SLCP reduction strategies and consider synergies across gases and sectors.

California has set a standard for other jurisdictions in its policy structure. In California, the non-CO_2 policies are directly connected to its overall greenhouse gas emission reduction target of 40% below 1990 levels by 2030. The state built on this overall framework to address various SLCPswith specific quantitative targets with dates and a clear baseline. Using legislation, the state made 2030 targets for reducing black carbon by 50%, methane by 40%, and HFCs by 40% against a 2013 baseline.[14] This policy only included regulations for landfills and agricultural operations. These general targets were further elaborated with a detailed SLCP Reduction Strategy in 2017. This strategy lays out regulation, incentives, and market-supporting activities to reduce black carbon, methane, and F-gases. For example, the SLCP Reduction Strategy includes additional specific goals for reducing methane from different sectors and an incentive program for promoting the adoption of new low-global warming potential (GWP) refrigerants.

Additionally, the E.U.,[15] Canada, and the U.S. have taken a comprehensive approach by considering SLCPs in their overall greenhouse gas emission reduction goals. The European Union's 2018 regulation defines greenhouse gas emissions to include CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride, and sulphur hexafluoride.[16] This definition ensures that SLCPs are included in its proposed 55% reduction by 2030 target. Similarly, SLCPs are included in the *Pan-Canadian Framework on Clean Growth and Climate Change*[17] as part of its initial goal to reach or exceed a 30% reduction below 2005 levels by 2030. Building on this goal and its Mid-Century Long-Term Low-Greenhouse Gas Development Strategy,[18] Environment & Climate Change Canada developed a detailed strategy for short-lived climate pollutants. This strategy provides a coordinated and complementary response across its climate policies and provided a mechanism for explicitly considering and quantifying the multiple benefits of SLCP mitigation. It also recognized the large role that subnational governments play in addressing SLCPs and the need to collaborate on areas where there are shared jurisdictions, ensure consistency in emission inventories, and align reporting requirements. On April 22, 2021, Canadian President Trudeau committed Canada to a strengthened NDC target of 40-45% GHG emissions reduction below 2005 levels by 2030 while U.S. President Biden committed the U.S. to a NDC target of 50-52% net GHG emissions reduction below 2005 levels by 2030.[19]

Gas-Specific Policies

As the impacts of SLCPs become more widely known, more countries and regions have adopted gas-specific policies targeting specific sources of methane and F-gases.

Methane

The primary sources for methane are oil and gas production, coal mining, wastewater, landfills and agriculture – providing an avenue to a comprehensive approach to tackle gas reduction. The European Union[20] has taken the opportunity to develop a comprehensive strategy that addresses cross-sectoral and sectoral methane emissions in the energy, agriculture, and waste sectors. California also recently adopted a comprehensive policy package to address methane, targeting multiple energy- and non-energy-related sectors through regulatory and legislative actions that include reduction targets, market-based mechanisms through the state's cap and trade program, emissions monitoring, and research, development and deployment funding. In some cases, a comprehensive strategy has been combined with a sector-based approach, while other countries and subnational jurisdictions have taken a predominately sector-based approach. A selection of sector-specific policies is presented below.

Oil and Gas Sector Methane

Significant policy attention has focused on methane emissions from the oil and gas sector given that it is the largest source of industrial emissions. The International Energy Agency estimates that the oil and gas sector emitted more than 5% of global energy-related greenhouse gas emissions.[21] In 2016, North American leaders from Canada, Mexico, and the United States pledged to reduce methane leakage from oil and gas production by 40-45% from 2012 levels by 2025.[22] This was followed by supporting regulations adopted in the United States and Canada, with draft rules pending in Mexico. These regulations include both technology standards that prescribe the use of certain technologies and performance standards that provide more flexibility to users to determine how to meet a prescribed emission reduction goal. Canadian regulations are expected to reduce greenhouse gas emissions in Canada by 15 $MtCO_2e$ each year, beginning in 2023.[23]

The United States introduced revised performance and technology standards for methane reduction in the oil and gas industry. Measures included in the 2016 regulations, and the ones passed in 2012, would have led to the avoidance of up to 75% of oil and gas methane emissions. Additionally, it was found that this could be done at little or no net cost.[24] According to the U.S. Environmental Protection Agency (EPA) estimates, these standards would reduce methane emissions by 510,000 tons in 2025 from new, reconstructed, and modified sources. Additionally, significant reductions in volatile organic compounds and hazardous air pollutant emissions, providing significant public health co-benefits are estimated.[25]

These standards were weakened and modified by the Trump administration in 2020, but a 2021 executive order by President Biden calls for review of the rollback of these standards by September 2021. The Biden executive order also requests the U.S. EPA to consider proposing new comprehensive standards for performance and emission guidelines for exploration and production, transmission, processing, and storage elements in the oil and gas sector by September 2021.[26] Proposed legislation and budget line items have also been introduced for cleaning up abandoned oil and gas wells, which could create new jobs for oil and gas workers.[27]

In the absence of comprehensive and stringent national standards in the United States, states have proactively taken on leadership roles in developing specific regulations to reduce methane from oil and gas operations within state boundaries. Colorado's 2014 regulation represents the first state regulation in the U.S. to require additional emissions control devices and implementation of leak detection and repair programs to address volatile organic compound (VOCs) and methane emissions.[28] Its follow-on 2019 regulations mandated additional mitigation measures, including adding semi-annual leak detection and repair and storage tank controls for low-producing wells, a statewide find and fix program for pneumatic devices, performance-based standards for transmission segments, and annual requirements for reporting pollution including methane.[29] In February 2021, Colorado also approved a new rule that requires oil and gas operators to install zero-bleed or zero-emission pneumatic devices for both new and existing operations.[30]

Similarly, California introduced greenhouse gas standards for crude oil and natural gas facilities in 2017 that require specific mitigation options in support of its target to achieve at least 45% of its overall methane reduction by reducing fugitive emissions from the oil and gas sector. These regulations include new and old facilities, improving on the EPA regulations. New Mexico also finalized proposed state rules to eliminate routine gas venting and flaring in oil fields, with oil and gas producers required to capture 98% of methane they produce by 2026.[31]

Canada has allowed provinces to develop their own regulations, with the important caveat that the emissions reductions are equivalent or surpass the national goal. Canada's three major oil and gas provinces, British Columbia, Alberta, and Saskatchewan, have each developed their own regulations. This includes setting a methane reduction target of 45% by 2025, compared to 2014 (the national baseline is 2012). In 2020, Alberta developed detailed regulations focused on flaring, incinerating, and venting[32] and on measurement, accounting, and reporting.[33] British Columbia released new regulations reducing methane emissions by 10.9 metric tons of carbon dioxide equivalent ($MtCO_2e$) during a 10-year period, and has aligned the regulations with its overall climate plan.[34]

Landfill Methane

Outside of the energy sector, the United States has also seen some federal and state action reducing methane emissions from landfills. In 2010, the California Air Resources Board adopted a rule requiring methane controls on all landfills with more than 450 tons of waste in place, restricting flares, and requiring ongoing monitoring and reporting mandates for all landfills.[35] California's 2015 SLCP Bill (SB-1383) also included quantitative goals for diverting organic waste from landfills with the intention of reducing methane emissions.[36] In 2016, the U.S. EPA announced updates to the federal New Source Performance Standards to reduce emissions of methane-rich landfill gas from municipal solid waste landfills. These updates were reconsidered and modified in 2017 and 2019, but the Biden Administration challenged these changes in court and the U.S. Environmental Protection Agency issued a final rule in May 2021 giving landfill operators 30 months to install appropriate systems to meet methane emission standards.[37] In the European Union, recent changes to waste legislation (2018) introduced an obligation to collect biodegradable waste separately by 2024, and set a new target of a maximum 10% landfilling of waste by 2035 in order to reduce methane emissions.[38]

F-Gases

Kigali Amendment to the Montreal Protocol

The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) was agreed in October 2016. The Kigali Amendment entered into force on 1 January 2019, and its initial schedule will achieve over an 80% reduction in HFC consumption by 2047. As with previous refrigerant transitions, the Montreal Protocol is driving a transparent and organized global market transition away from HFCs through a stepwise phasedown. Most developed countries begin in 2019, whereas a majority of developing countries will freeze consumption and production in 2024 and begin the phasedown five years later. Developing countries susceptible to high ambient temperatures will freeze at 2028 and begin to phase down in 2032.[39] As of June 2021, the Kigali Amendment has been ratified by 122 parties, with China as the latest country to ratify on June 17, 2021.

The Kigali Amendment and subsequent decision recognize the importance of addressing energy efficiency in the cooling sector while phasing down HFCs. Indeed, as of 2017, approximately 80% of the climate impact of cooling equipment was from the indirect emissions (CO_2 and black carbon emissions from fossil-fuel electricity generation) and 20% was from the direct emissions of the refrigerants.[40]

Prior to the adoption of the Kigali Amendment to the Montreal Protocol, national and state governments had also adopted regulations to limit the total volume of HFCs used, implement containment strategies for use and disposal phases, and impose taxes on high-GWP refrigerants or fiscal incentives for alternative, low-GWP refrigerants. The European Union and California represent two successful examples of an integrated approach to control and phase out high-GWP HFCs while incentivizing containment and use of low-GWP HFCs through multiple policy strategies to meet explicit HFC emission reduction targets.

European Union

The European Union led the adoption of an F-gas regulation for controlling fluorinated gases from stationary sources in 2006, and substantially strengthened that rule in 2015.[41] The European Union measure is the most stringent regulation in the world, phasing down F-gases in a brisk 15 years with many equipment-specific bans along the way where feasible alternatives exist. One specific example that has been effective is E.U. Directive 2006/40/EC, which gradually bans the use of high GWP refrigerants in mobile air conditioning systems – specifically R134a with 100-year GWP of 1300, for passenger cars and light commercial vehicles.[42] In phase 1, effective June 2008, car manufacturers can no longer obtain approval for a new vehicle if it uses gases with GWP higher than 150 or if it exceeds designated limits on refrigerant leakage. In phase 2, effective January 2011, new vehicles must fill their air conditioning systems with refrigerant with GWP of lower than 150. In phase 3, effective January 2017, all new vehicles that use refrigerant gases with GWP higher than 150 are banned from the European Union market. Under the current European Union F-gas regulation, European Union's F-gas emissions will be cut by two-thirds by 2030 compared with 2014 levels.[43] The European Union ratified the Kigali Amendment in 2018 and is currently reviewing its F-gas regulation.[44] The European Commission is expected to release the proposal for a new Regulation by the end of 2021 in view of various issues including the HFC phasedown obligations under the Kigali Amendment.[45]

At the European Union member state level, HFC containment strategies focused on containing leaks during use and disposal have been adopted in countries such as Sweden and The Netherlands, while other countries, such as Denmark, have focused on phase-out strategies that include bans on products with HFCs as well as taxes.[46] Taxes or emissions fees based on weight or GWP of HFCs have also been adopted by many countries, including Belgium, Poland, Slovenia, Spain, Norway, and New Zealand.[47]

Combined, the multi-pronged regulatory approaches to controlling F-gases have steadily lowered the European Union's consumption of HFCs covered under the Montreal Protocol since 2010. As a result, the European Union reached its 2024 commitment of a 40% reduction from baseline under the Kigali Amendment six years early, in 2018.[48]

California

California is leading integrated efforts in promoting both containment and phase out of HFCs through a three-pronged approach that includes the state's Refrigerant Management Program, the California Significant New Alternatives Policy (SNAP) regulation, and newly planned incentives for adoption of new refrigerant technologies.[49] Together, these programs and measures are expected to help support the state's 2016 target of 40% HFCs emission reduction below 2013 levels by 2030.

California's Refrigerant Management Program was created in 2009 and includes leak detection and monitoring, repair, system retrofit and retirement, and proper refrigerant cylinder use, sale, and disposal from stationary sources. In 2018, California adopted a California SNAP Regulation after the U.S. EPA's ability to regulate high-GWP HFCs under the federal SNAP became limited in 2017. The California SNAP includes a new California Air Resources Board (CARB) HFC regulation and the California Cooling Act (Senate Bill 1013), and covers all of the end-use specific HFC prohibitions covered under the U.S. EPA SNAP Rules 20 and 21. The California SNAP program prohibits the use of high-GWP refrigerants in new and retrofit stationary refrigeration equipment and certain HFCs used as blowing agents in foam end uses. The California Cooling Act also establishes the Fluorinated Gases Emission Reduction Incentive Program, which authorizes state funding and requires coordination between multiple state agencies to increase adoption of low-GWP refrigerant technologies in the supermarket and industrial sector. For 2019-2020, the state authorized $1 million to fund the incentive program. The funding was allocated in early 2021 to help pay for new, innovative low-GWP refrigerants and refrigeration technologies at 14 grocery stores and 2 retrofits.[50]

Black Carbon Reductions and Co-Benefits: Air Quality Strategies

For black carbon, a SLCP and key air pollutant, strategies focused on improving air quality (including vehicle emission standards and residential fuel switching programs) have been shown to be effective in also reducing related black carbon emissions.

According to an assessment by the International Council on Clean Transportation, policies that have been adopted or implemented since 2015 are projected to avoid 2 metric ton (Mt) of black carbon emissions from 2015 to 2030.[51] China, India, Europe, Japan, Canada, South Korea and the United States have adopted filter-based standards for new diesel cars and for heavy duty diesel trucks, which will significantly cut black carbon emissions by >95% (along with other forms of ultrafine particulates). These policies are also cost-effective.

Besides national vehicle emission standards, California's clean air rules have also reduced black carbon emissions by 90% since the 1960s, despite a five-fold increase in diesel consumption.[52] California is expected to completely eliminate black carbon emissions from on-road diesel engines over the next decade, and has also set a goal of reducing black carbon emission by 50% from its 2013 levels by 2030. Other recent efforts in California to reduce black carbon emissions have focused on off-road mobile vehicles, fuel combustion in industry and power generation, and wood-burning stoves and fireplaces.

In subnational jurisdictions in Canada, there have been a range of transportation programs and policies including vehicle inspections and scrappage programs, emission standards for new wood-burning appliances, and wood stove change-out programs in some provinces and territories. These have been promoted through regulations and incentives for using improved technologies.[53]

For the residential sector, India appropriated $1.1 billion U.S. dollars for propane fuel subsidies via its Ujjwala program in 2015 to protect poor households from the health impacts of cooking with solid biomass, thereby substantially reducing black carbon. By September 2019, the program has increased the coverage of liquefied petroleum gas (LPG) connections in households to over 94% (compared with 56% in 2015) by providing 80 million poor households with LPG connections.[54]

Regional and Voluntary Initiatives

The earliest methane reductions in the United States were achieved through voluntary public-private partnership programs started by the U.S. EPA that provided technical assistance and technology transfer to industry partners to encourage the adoption of cost-effective mitigation measures and technologies. Today, these programs continue to help reduce methane emissions from multiple sectors, particularly where regulations are lacking.

The earliest example is the U.S. EPA Natural Gas STAR program started in 1993, which helped 100 oil and gas companies to voluntarily adopt methane reduction technologies across four oil and gas subsectors. Since its initiation, the program has evolved into the NG STAR Methane Challenge Program, which provides flexible performance-based mechanisms beyond technology-only recommendations for companies to meet emission reduction targets.[55] This program has helped its partners reduce 1.7 trillion cubic feet of methane emissions cumulatively by implementing 153 cost-effective measures. Similarly, the U.S. EPA Coalbed Methane Outreach Program has helped reduce coal mine methane emissions by 199 $MtCO_2e$ since 1994.[56] Other voluntary programs have targeted the landfill and agriculture sectors. The U.S. EPA Landfill Methane Outreach Program successfully promoted biogas recovery and use from municipal solid waste through 682 projects, reducing 510 $MtCO_2e$ cumulatively through 2000.[57] The U.S. EPA and U.S. Department of Agriculture (USDA) AgSTAR program achieved annual reductions of 4.27 $MtCO_2e$ in 2018 using biogas recovery from livestock waste.[58]

Recent oil and gas protocols have been developed to support governments to act. The International Energy Agency's (IEA) focus is on developing regulations for oil and gas.[59] Another protocol developed by Project Climate at the University of California at Berkeley is focused on tracking, managing, and reducing methane emissions at the subnational level, and builds on the regulatory approach of California as well as other subnational jurisdictions like Colorado and Alberta. It is a six-step framework for inventorying emission sources, inventorying emissions, setting an emission reduction target, requiring leak detection and repair, implementing performance standards, and information and technology sharing for jurisdictions to require facility-level action to cost-effectively minimize emissions.

Multilateral voluntary programs have also emerged to play an important role in bringing together different governments to help address reducing SLCPs from multiple sectors in the absence of any mandatory policies or programs. Two specific examples include:

- The Climate and Clean Air Coalition (CCAC), which is a voluntary partnership led by governments focusing on SLCPs (i.e., methane, HFCs, black carbon, and tropospheric ozone) mitigation. The CCAC has established black carbon and methane initiatives to identify quick-start actions and ensure rapid scale-up of emissions reduction. These initiatives facilitate communication, information exchange, partnership establishment, and network building and expansion among governments, implementing agencies, and other related organizations.[60]

- The Arctic Council has an Expert Group on Black Carbon and Methane to identify measures to reduce black carbon and methane emissions and make policy recommendations. The Expert Group identified that reducing black carbon and methane emissions could help address both climate change and air quality concerns in 2015[61] and established a pan-Arctic goal of reducing black carbon emissions by 25% to 33% below 2013 levels by 2025 in 2017.[62] Four sectors were recommended as priorities to reduce emissions and include: diesel-powered mobile sources; oil and gas methane leakage, venting and flaring; residential biomass combustion appliances; and solid waste disposal.

Lastly, for controlling N_2O emissions, adipic acid plants in western industrialized countries voluntarily installed catalyzed abatement chambers in the 1990s when they became aware of the climate impacts and low costs of mitigation.[63] Voluntary projects under the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism spread that technology to Asia and Latin America, but only temporarily.

Summary of Best Practices from International Experiences

There are various policy and voluntary initiatives that have been applied around the globe to address SLCPs. A few best practices emerge from this analysis:

- While still not applied widely, addressing multiple gases across sectors provides a means to create synergies across policies and integrate SLCPs into existing climate plans. It also highlights the various roles for multilateral, national, and subnational mitigation actions and the benefits for coordination across scales, sectors, and policies.

- Developing a quantitative target with a baseline sets the stage for developing effective implementation strategies.

- There are a range of approaches including policies, strategies, regulations, economic instruments such as taxes or subsidies, capacity building and knowledge sharing, and monitoring, and verification (M&V). A combined approach, using a mix of policy tools, provides a means to overcome the various barriers to action.

- Monitoring, reporting and verification systems are essential. These policies and regulations are only effective if there is a way to ensure compliance. There is evidence that many of these approaches are working to meet our climate goals; the key is to adapt them to the local context and continue to learn from our efforts.

3 China Policy Review

Since the "12th Five-Year Plan" (2011-2015), China's policy documents related to climate change have mentioned some non-CO_2 greenhouse gas emissions control requirements, but they have generally been qualitative rather than quantitative. These qualitative requirements include, among others, encouraging related industries to apply mitigation measures and technologies to reduce emissions. More specifically, in 2012, the State Council published the "Work Plan for Greenhouse Gas Emission Control during the 12th Five-Year Plan Period," which emphasized the necessity to effectively control non-energy CO_2 emissions as well as methane (CH_4), nitrous oxides (N_2O), HFCs, perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and other greenhouse gas emissions. In 2016, the "Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period" (2016-2020) reemphasized this point and also required further strengthening of the control of emissions of greenhouse gases such as HFCs, CH_4, N_2O, PFCs, and SF_6.

In a virtual summit with President Macron of France and Chancellor Merkel of Germany on April 16, 2021, Chinese President Xi Jinping announced China will accept the Kigali Amendment to the Montreal Protocol, and strengthen the control of non-CO_2 greenhouse gases, including hydrofluorocarbons that are scheduled for phasedown under the Kigali Amendment. President's Xi announcement and China's subsequent ratification of the Kigali Amendment set the stage at the leadership level for China to adopt strategies and targets to reduce SLCPs and N_2O. Additionally, the 14th Five-Year Plan provides that China will "strengthen the control of other GHGs, such as methane, HFCs and PFCs."[64] Finally, China recently announced that its 2060 carbon neutrality pledge includes non-CO_2 greenhouse gases. These references provide the policy authority for inclusion of detailed requirements and targets for SLCPs in environmental protection and GHG reduction plans that the Ministry of Ecology and Environment, for example, is currently drafting.

At the gas and sector-specific levels, national climate change policies have included some qualitative requirements and a few quantitative targets. For example, methane emission reduction in the agricultural and household waste sectors as well as N_2O and F-gases control in the industrial sectors are mentioned in the "National Plan for Tackling Climate Change" (2014-2020) and the "Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period." Quantitative reduction targets for HFC-23 are raised in the "Enhanced Actions on Climate Change: China's 2016 Nationally Determined Contributions." Other policies and recommendations are more scattered, reflected in sector-specific development plans or action plans and closely linked with China's industry policies, including reducing overcapacity, safe production, and comprehensive utilization. Since black carbon emissions are closely linked with air pollution and public health risks, reduction in black carbon emissions is often a co-benefit of the national air quality improvement policies, including fuel switching, industrial boiler and coking emission standards, and transportation fuel standards and emission standards.

Methane

Energy Sector

China announced a goal to make efforts to peak its methane emissions from energy activities by 2020 in its Second Biennial Update Report on Climate Change.[65] Policies on methane emission control in the energy sector have been associated with the control and reduction of coal capacity plans. In 2016, the State Council put forward "Opinions on Resolving Excess Capacity in the Coal Industry for Development Out of Difficulty," which suggests a 3- to 5-year period to withdraw production capacity by about 500 million tons, and to reduce and restructure by about 500 million tons, as well as to control the methane emissions from coal mining with backward production capacity from the source.[66]

Methane control in the energy sector is also closely linked with production safety issues in China. In 2014, the National Energy Administration put forward the "Guiding Opinions on Promoting Safe and Green Development, Clean and High-Efficiency Utilization of Coal," and proposed that China's coalbed methane (coal gas) output will be 40 billion cubic meters by 2020. Of this 40 billion, 20 billion cubic meters are ground development, basically all used and 20 billion cubic meters are underground drainage, with a utilization rate of more than 60%.[67] This goal was reemphasized in the Action Plan for Coal Bed Methane Exploration and Development published in 2015. However, the 13th Five-Year Plan for the Development and Utilization of Coalbed Methane (Coal Mine Gas) (2016) provided an updated set of targets that "by 2020, the coalbed methane (coal mine gas) extraction volume shall reach 24 billion cubic meters, within which the production of on-ground coalbed methane shall reach 10 billion cubic meters with a utilization rate of over 90%; the extraction of coal mine gas shall reach 14 billion cubic meters with a utilization rate of over 50%."[68]

China's national regulatory system on coal mine emissions include national emission standards, supported by government financial incentives such as subsidies and tax benefits. China's Ministry of Ecology and Environment first issued the Emission Standard of Coalbed Methane/Coal Mine Gas (on trial) in 2008. This standard provides a major exemption, indicating that coal mines are not required to carry out flaring and utilization measures if the drained gas has a methane content <30%. Additionally, this standard only covers new and existing coal mines, but it is not clear with regard to the abandoned coal mines.[69] The China Ministry of Ecology and Environment recently announced plans to revise the emission standards for coalbed methane and coal mine gas.

China has also promoted gas recovery and recycling in the oil and gas sector, which could contribute to methane emissions reduction in this sector. The "12th Five-Year Development Plan for Natural Gas" (2012) promotes associated gas and gas recovery technology field trials as well as natural gas and other energy-saving technologies.[70] It also provided policy guidance to strengthen the methane venting recycling from mining activities in the oil and gas industry. These measures were re-emphasized in the "13th Five-Year Development Plan for Natural Gas" (2016). In 2013, the National Development and Reform Commission amended the Catalogue for Guiding Industrial Restructuring (Version 2011) to encourage methane recovery and utilization in the oil and gas industry and to lay the foundation for reducing methane venting from oil and gas production. The latest version of the Catalogue for Guiding Industrial Restructuring (Version 2019) also included the recovery technologies of oilfield associated gas and natural gas leakage during storage and transportation, as well as extraction and utilization technologies of coalbed methane and coal mine gas, in its category of recommended technologies.

Waste and Wastewater Sector

There have been no specific targets for reducing methane emissions in the waste and wastewater sector, but the application of mitigation measures has been promoted in various government policies. For example, the "National Plan for Tackling Climate Change" (2014-2020) requires various measures, including: accelerating the construction of non-hazardous treatment facilities for residential waste; developing a domestic waste treatment classification system; improving the collection and transfer system of domestic waste; resource utilization and non-hazardous treatment; conducting unified collection and centralized treatment of domestic waste; promoting food waste disposal and resource utilization; encouraging the production of fertilizer using post-treatment residue; carrying out CH_4 collection and utilization and reprocessing work at landfills with CH_4 collection value; and encouraging the development of waste incineration power generation in areas where conditions permit.

In 2017, the State Council forwarded the Implementation Plan of the Household Waste Classification System, which requires that, by the end of 2020, compulsory classification of domestic waste shall be implemented in the urban areas of some key cities according to the principles of minimization, valorization and environmentally sound management and the recycling and utilization rate in cities with mandatory domestic waste classification system shall reach 35% or more.[71]

In the wastewater sector, the Action Plan for Prevention and Control of Water Pollution required all counties and key towns across the country to have sewage collection and treatment capabilities by 2020. County and city sewage treatment rates are required to reach 85% and 95% or so, respectively, by 2020. They must promote wastewater and sludge anaerobic digestion processes and the development of biogas recycling and other technologies.[72]

Most recently, the "Outline of the 14th Five-Year Plan" (2021-2025) released in 2021 requires the development of an environmental infrastructure system that integrates treatment and disposal facilities and monitoring and supervision capabilities for sewage, garbage, solid waste, hazardous waste, and medical waste. It also promotes centralized sludge incineration and requires that the rate of harmless treatment of urban sludge reach 90%, and the utilization rate of sewage sludge in water-scarce cities to exceed 25%.

Agricultural Sector

For the agricultural sector, recent national plans have promoted methane mitigation in farming and livestock management practices and laid out some quantitative targets focused primarily on increasing utilization of animal waste and manure treatment facilities. The "National Plan for Tackling Climate Change" (2014-2020) encouraged the use of organic fertilizers, promoted low-carbon recycling production methods (such as "pig - methane - fruit" biogas production) according to local conditions, and developed large-scale breeding. It also required promoting the comprehensive utilization of crop straw, resource utilization of agricultural and forestry waste, comprehensive utilization of livestock manure, and actively promoting the application of geothermal energy in agriculture and aquaculture facilities.

The "Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period" includes requirements to control farmland CH_4 emissions, such as by selecting high-yield and low-emission varieties and improving water and fertilizer management, and encourages the construction of large and medium-sized biogas projects for livestock and poultry farms. China's 2016 Nationally Determined Contributions further emphasize the need to control methane emissions from rice fields.

In 2017, the General Office of the State Council issued the "Opinions on Accelerating the Resource Utilization of Livestock and Poultry Farming Waste," that included specific targets of reaching over 75% comprehensive utilization of livestock and poultry waste and equipping more than 95% of large-scale farms with manure treatment facilities by 2020.[73]

Nitrous Oxide

China announced a goal to make efforts to peak its N_2O emissions from the industrial and agricultural sources by 2020 in its Second Biennial Update Report on Climate Change.[74]

Industrial Sectors

The key industrial sectors that emit N_2O are nitric acid and adipic acid production. China has focused on two main areas to mitigate N_2O emissions in these sectors. The first focus is to reduce backward capacities in the nitric acid production sector by adding outdated processes to the Restricted List, which are expected to be gradually phased out in the Industrial Structure Adjustment Guidelines published by the National Development and Reform Commission in 2011. The second area of policy focus is on industrial pollution standards and regulations, which set N_2O emission limits from flue gas in the nitric acid production sectors.

More recently, the "National Plan for Tackling Climate Change" (2014-2020) mentioned improving the production process of adipic acid and nitric acid and applying emission control techniques to significantly reduce N_2O emissions. In 2016, the Ministry of Industry and Information Technology published its "Industry Green Development Plan (2016-2020)" which requires improving the production processes of fertilizer, adipic acid, nitric acid, caprolactam and other industries and reducing N_2O emissions in industrial production processes.[75]

Agricultural Sector

Although no specific sector-wide reduction targets for N_2O have been set, a quantitative requirement for limiting fertilizer use was set in 2015 by the Ministry of Agriculture, and the 13th Five-Year Work Plan on Greenhouse Gas Emission Control (2016) includes targets to "reduce farmland N_2O emissions and peak farmland N_2O emissions by 2020." Specifically, the "Action Plan for Zero-Growth in Chemical Fertilizer Use by 2020" proposed to limit the annual growth rate of fertilizer use to less than 1% from 2015 to 2019 and zero growth in fertilizer use in major crops by 2020, which will significantly limit the N_2O emissions from fertilizer use in the agricultural sector.[76]

F-Gases

For F-gases, it is important to distinguish between substances that are controlled under the Montreal Protocol Annex F and byproduct emissions, such as HFC-23, which are not included in baseline calculations for the Kigali Amendment phase-down schedule. China has set a specific reduction schedule for the byproduct HFC-23 emissions with quantitative reduction targets for HCFC-22 for controlled uses. It also limits emissions by promoting emission control technologies in the production processes, as well as by reducing overcapacity in the electrolytic aluminum sector. However, emissions of HFC-23 have risen significantly in recent years.[77]

Since 2014, in order to effectively achieve the reduction commitments above, relevant authorities have actively organized key actions to control HFCs, issued annual circulars on the organization of HFC disposal-related work, and arranged for investment and financial subsidies within the central budget to support the destruction and disposal of HFC-23. The "2014-2015 Energy Saving, Emission Reduction and Low Carbon Development Action Plan" included strengthening emissions control of HFCs, accelerating destruction and replacement of HFCs and achieving cumulative emissions reduction of 0.28 gigatons of carbon dioxide equivalent (Gt CO_2-eq) during the 12th Five-Year Period. The "13th Five-Year Work Plan on Greenhouse Gas Emission Control" (2016) set a cumulative HFC-23 reduction target of over 1.1 Gt CO_2-eq during the 13th Five-Year Period. Additionally, China's 2016 Nationally Determined Contributions further includes quantitative targets "to phase down the production and consumption of HCFC-22 for controlled uses, with its production to be reduced by 35% from the 2010 level by 2020, and by 67.5% by 2025." Effective control on emissions of HFC-23 must also be achieved by 2020.[78]

For other F-gases, specifically, Sulphur Hexafluoride (SF_6), the state issued standards for "Use and Handling of Sulphur Hexafluoride (SF_6) in High-Voltage Switchgear and Controlgear" in June 2012.[79] The requirements for SF_6 treatment during installation and handover of high-voltage switching equipment and control equipment, treatment of SF_6 during normal service life, and SF_6 recovery during maintenance are specified. The "National Plan for Tackling Climate Change" (2014-2020) also aims to improve the production process of the hydrochlorofluorocarbons (HCFCs) industry by using control techniques to significantly reduce HFC emissions, increase investment in research and development of HFC alternative technologies and substitutes, and encourage the use of SF_6 mixed gas and recovery of SF_6.

The production of primary aluminum by the Hall-Heroult process periodically produces small amounts of perfluorinated carbon compounds (PFCs). The State Council, the Ministry of Industry and Information Technology (MIIT), and the National Development and Reform Commission issued guidelines to resolve severe overcapacity problems in electrolytic aluminum and other industries in October 2013, which contributes to reducing PFC emissions from aluminum production.[80] In 2015, the National Development and Reform Commission and MIIT jointly issued a notice on the issuance of clean-up opinions on non-compliance projects in the steel, electrolytic aluminum, and marine industries to rectify the electrolytic aluminum industry violations. In June 2018, the State Council issued a three-year action plan to win the battle for a blue sky, proposing that key areas such as Beijing-Tianjin-Hebei and surrounding areas, the Yangtze River Delta, and the Fenwei Plain are strictly prohibited from adding new electrolytic aluminum production.

Black Carbon

Black carbon emissions have primarily been addressed through air pollution measures to date. In the residential sector, China's clean heating programs to phase-out dispersed coal heaters/boilers and promote residential fuel switching to natural gas and electricity have been effective in reducing related black carbon emissions. For example, China took extraordinary steps to change out six million small coal boilers for heating in the run-up to the nation's 2017 deadline for achieving major reductions in ambient particulate matter 2.5 microns or less in width (PM2.5), substantially reducing black carbon emissions at the same time.[81]

Industrial black carbon emission control focuses on industrial boilers and the coking industry. China has adopted the "Emission Standard of Air Pollutants for Boilers" (GB 13271-2014), which requires all new coal-fueled boilers to install high-efficiency (>99%) emission control technologies.[82] The "Emission Standard of Pollutants for Coking Chemical Industry" (GB 16171-2012) sets strict standards for PM emissions from each stage of coking.[83] Successful implementation of these standards will yield significant black carbon emission reductions of >90% for coal boilers and >40% for coking ovens. In addition, the "Action Plan for Clean and Efficient Utilization of Coal in the Industrial Sector (2015-2020)" focuses on improving the technical capacities of high energy-consuming and polluting industrial process equipment in coking, industrial furnaces, coal chemicals, and industrial boilers, which can help reduce black carbon emissions. It also calls for accelerating the pace of elimination of backward kilns and boilers, with the goal of saving more than 160 million tons of coal consumption and reducing smoke and dust emissions by one million tons by 2020.[84]

In the transportation sector, China has taken efforts to control emissions from mobile vehicles and from shipping through shore power. For example, China has published the "Limits and Measurement Methods for Emissions from Light-Duty Vehicles (CHINA 6)" and "Limits and Measurement Methods for Emissions from Diesel Fueled Heavy-Duty Vehicles (CHINA VI)," [85,86,87] both of which set strict standards for particulate matter emissions from vehicles. The VI emission standards mandate that vehicles marketed after July 2021 be fitted with diesel particulate filters.[88] Full compliance with these standards, together with additional early retirement programs for polluting diesel vehicles, can achieve ~70% reduction of black carbon emissions in the transportation sector. China has also issued policies to promote development of the electric vehicle industry, including the "New Energy Automobile Industry Development plan (2021-2035)," which can help further reduce black carbon emissions by accelerating the transition away from diesel vehicles.

Shore power is the provision of shoreside electrical power to a ship at berth while its main and auxiliary engines are shut down. Shore power saves consumption of fuel that would otherwise be used to power vessels while in port, and eliminates the air pollution associated with consumption of that fuel. The Ministry of Transport promotes the use of shore power by ships at ports, for the purpose of reducing air and noise pollution from ships in the port area. By the end of 2019, more than 5,400 port shore power facilities have been built across the country, covering more than 7,000 berths (service areas above water), of which 76% are located in inland river ports. The utilization rate varies by region but remains generally low due to cost and docking capacity constraints, with shore power use ranging from 1.7% of berths in the Yangtze River Delta region to 6% in Southern ports.[89] Data from 1088 berths in 29 coastal ports and 19 inland ports revealed an increase in shore power use in 2019 (60,000 times the energy use) – with a total connection time of about 740,000 hours and total electricity consumption of about 45 million kilowatt hours (kWhs). A total of more than 710 tons of nitrogen oxides, sulfur oxides, and particulate matter emissions have been reduced, thereby also reducing black carbon emissions from shipping fuel use while docked at ports.

Voluntary Initiatives

Under the guidance of relevant national policies and related initiatives in the international oil and gas field to address climate change, China's major oil and gas producers and suppliers have carried out a series of methane emission reduction actions. China National Petroleum Corporation (CNPC) participated in the development of "OGCI-2040 Low Emission Roadmap" to carry out a statistical survey of methane emissions in the oil and natural gas industry supply chain under its jurisdiction and to take actions on methane recovery and utilization. Sinopec Group issued a green enterprise action plan in April 2018, requiring oil and gas companies to strengthen methane recovery and emission reduction by promoting methane recovery and utilization from oil and gas testing, crude oil gathering, and the transportation system.

On January 15, 2021, 17 petroleum and chemical companies, chemical parks and the China Petroleum and Chemical Industry Federation signed and jointly issued the "China Petroleum and Chemical Industry Carbon Peaking and Carbon Neutrality Declaration" in support for green and low-carbon development actions for the industry but did not include specific industry targets.[90] Separately, China's two largest oil and gas companies, Sinopec and China National Petroleum Corporation, have also announced targets to reduce their own methane emissions intensity by 50% and 62.3%, respectively, by 2025 and to achieve carbon peaking by or before 2030.

On May 18, 2021, seven Chinese oil and gas companies including Sinopec Group, PetroChina Company Limited, China National Offshore Oil Corporation, PipeChina, Beijing Gas Group, China Resources Gas and ENN Energy Holdings jointly launched the China Oil and Gas Methane Alliance in Beijing. Member companies under this alliance are committed to reduce the average methane emission intensity of natural gas production to less than 0.25% by 2025 and strive to reach the world's leading level by 2035.[91]

4 China Potential Analysis

A bottom-up energy model and scenario analysis was used in this study to assess the possible growth in China's non-CO_2 emissions (i.e., methane, N_2O, F-gases) and reduction potential through different technologies, measures, and strategies under plausible trajectories for total greenhouse gas emissions. To inform the development of the mitigation scenarios, cost-curve analysis for non-CO_2 mitigation measures were conducted for key sectors for 2030 and 2050. Table 1 summarizes the scenarios considered in the potential analysis as well as linkage to cost-curve analysis.

Table 1. Summary of Greenhouse Gas Scenarios for China Potential Reduction Analysis

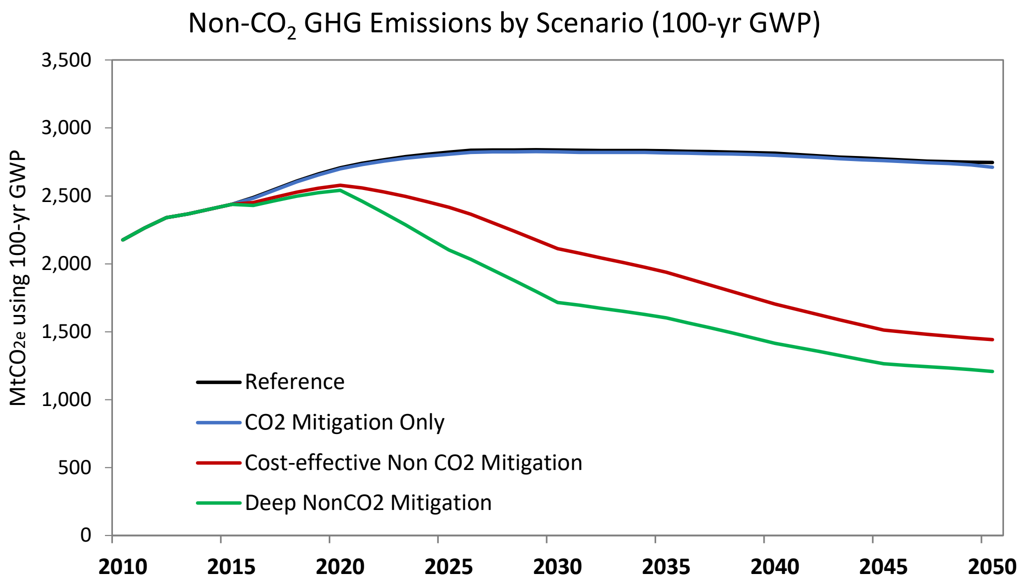
SCENARIO	SCENARIO BASIS	SECTORAL MEASURES CONSIDERED
Reference	A counterfactual baseline scenario that reflects continuous energy efficiency improvement and adoption of cost-effective low carbon technologies to reduce CO_2 emissions in energy sector	Energy sector only, plus HCFC-22 phase out underway under the Montreal Protocol
CO_2 Mitigation Only	A deep CO_2 decarbonization scenario that considers energy-consuming activity reductions, faster and greater adoption of low-carbon fuels (including some in pilot stages) and electrification, to reduce CO_2 emissions in energy sector	Energy sector only
CO_2 and Non-CO_2 Mitigation	Full adoption of key cost-effective (i.e., generally below annualized costs of $7/t$CO_2$e reduction) technologies to reduce non-CO_2 emissions by 2050, based on measures evaluated in the cost-effectiveness analysis	Energy sector, plus agriculture, waste, industrial processes [1]
Deep Non-CO_2 Mitigation	Application of additional technically feasible mitigation measures that are generally below $100/t$CO_2$e and accelerate the full adoption of all current mitigation measures by 2030	Additional measures in oil industry, wastewater, industrial processes [2]

Notes:

[1] Measures modeled include methane oxidation and methane recovery from ventilation air in coal mining; green completions; plunger lift systems; leak monitoring and repair; low-bleed, no-bleed, or air pneumatic controllers for natural gas; methane collection, flaring, and recovery of landfill gas for energy use for landfills; humid and intermittent irrigation; improving livestock productivity, manure composting, and reducing nitrogen fertilization in agriculture; thermal oxidation in HCFC-22 production; replacing high-GWP refrigerant with low-GWP refrigerant for room and mobile air conditioners; improved leakage control for commercial air conditioners; commercial and industrial refrigeration; upgrading process control systems in aluminum production and SF_6 recycling; leak detection and repair; equipment refurbishment; and improved SF_6 handling in power systems.

[2] Additional measures modeled include best practices to reduce unintended leakage; recovery and use of vented associated gas for the oil sector; open sewer to aerobic wastewater treatment for wastewater; thermal decomposition and secondary abatement for adipic and nitric acid production, and thermal abatement for semiconductors.

A potential 56% reduction in non-CO_2 greenhouse gases was identified by 2050 in a Deep Non-CO_2 Mitigation scenario where technically feasible mitigation measures are implemented at an accelerated pace compared to a reference scenario without any non-CO_2 mitigation measures. This reduction potential is comparable to the 60% reduction potential identified in Tsinghua's recent 1.5°C scenario (relative to 2020 level)[92]. This scenario reached a cumulative reduction of 35 GtCO_2e of non-CO_2 greenhouse gases between 2015 and 2050. Almost 50% reduction in non-CO_2 greenhouse gases is possible by 2050 compared to the reference scenario, if only cost-effective mitigation measures are implemented. A cumulative reduction of 27 GtCO_2e between 2015 and 2050 is found using cost-effective measures.



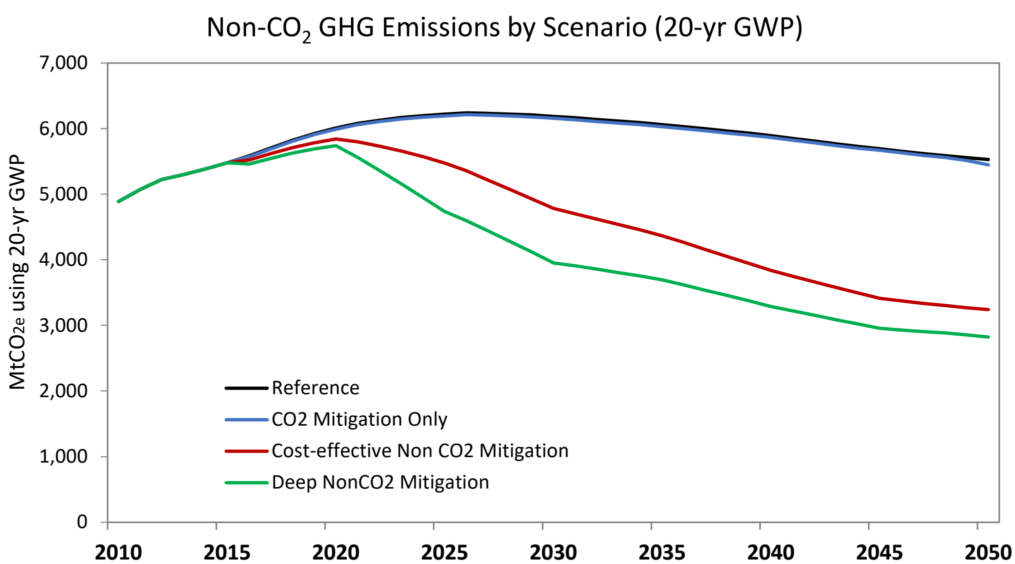


Figure 1. Total Non-CO_2 Greenhouse Gas Emissions by Scenario, in 100-yr and 20-yr GWP

By 2030, techno-economic potential reductions of 35%-40% (compared to 2015 levels) are identified for methane, 30% reduction in F-gases, and 40% reduction in N_2O based on the cost-curve analysis and applicability of mitigation measures evaluated in the Deep Non-CO_2 Mitigation Scenario. This results in a total annual reduction potential of 1,080 $MtCO_2e$ (excluding manure management) in 2030 compared to our Reference scenario, comparable to 1,096 $MtCO_2e$ reduction potential under Tsinghua's 1.5°C scenario. By sector, the largest reduction potentials are in HCFC-22 production and room and mobile ACs for F-gases; energy (particularly coal mining) and agriculture for methane; and industrial and agricultural sectors for N_2O, as seen in Figure 2.

By 2050, under the deep mitigation scenario, the largest mitigation potential by gas is in F-gases (particularly HFC-125 and HFC-23), followed by lower methane reduction potential due to decreased fossil fuel demand. By sector, cooling (room and commercial ACs), HCFC-22 production and agricultural sectors account for 70% of deep mitigation potential in 2050.

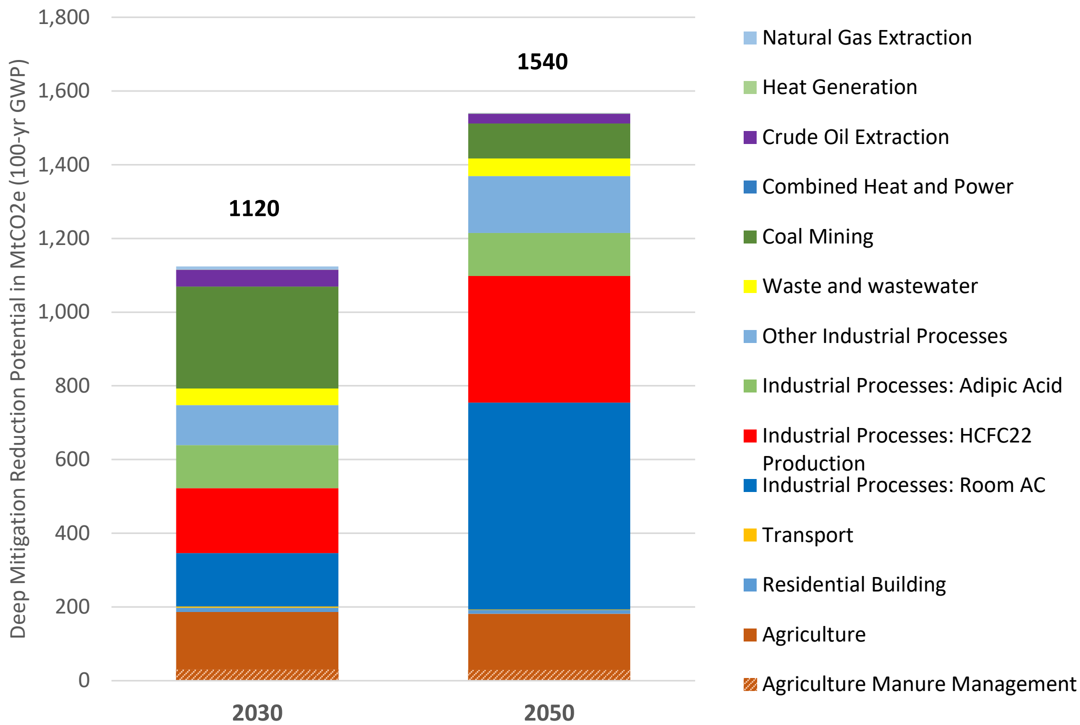


Figure 2. Deep Non-CO_2 Mitigation Reduction Potential by Subsector for 2030 and 2050

*Note: Manure management in agriculture has highly uncertain abatement costs and are not considered in the reduction potential for possible target-setting.

After the application of deep mitigation non-CO_2 greenhouse gas measures, 1,209 $MtCO_2e$ of non-CO_2 greenhouse gas emissions still remains in 2050 (comparable to 1271 $MtCO_2e$ in Tsinghua's 1.5°C scneario), including 780 $MtCO_2e$ of methane, 264 $MtCO_2e$ of N_2O, 120 $MtCO_2e$ of HFC gases, 32 $MtCO_2e$ of SF_6, and 12 $MtCO_2e$ of PFCs. The sectors where these non- CO_2 greenhouse gases are found are shown in Figure 3, below.

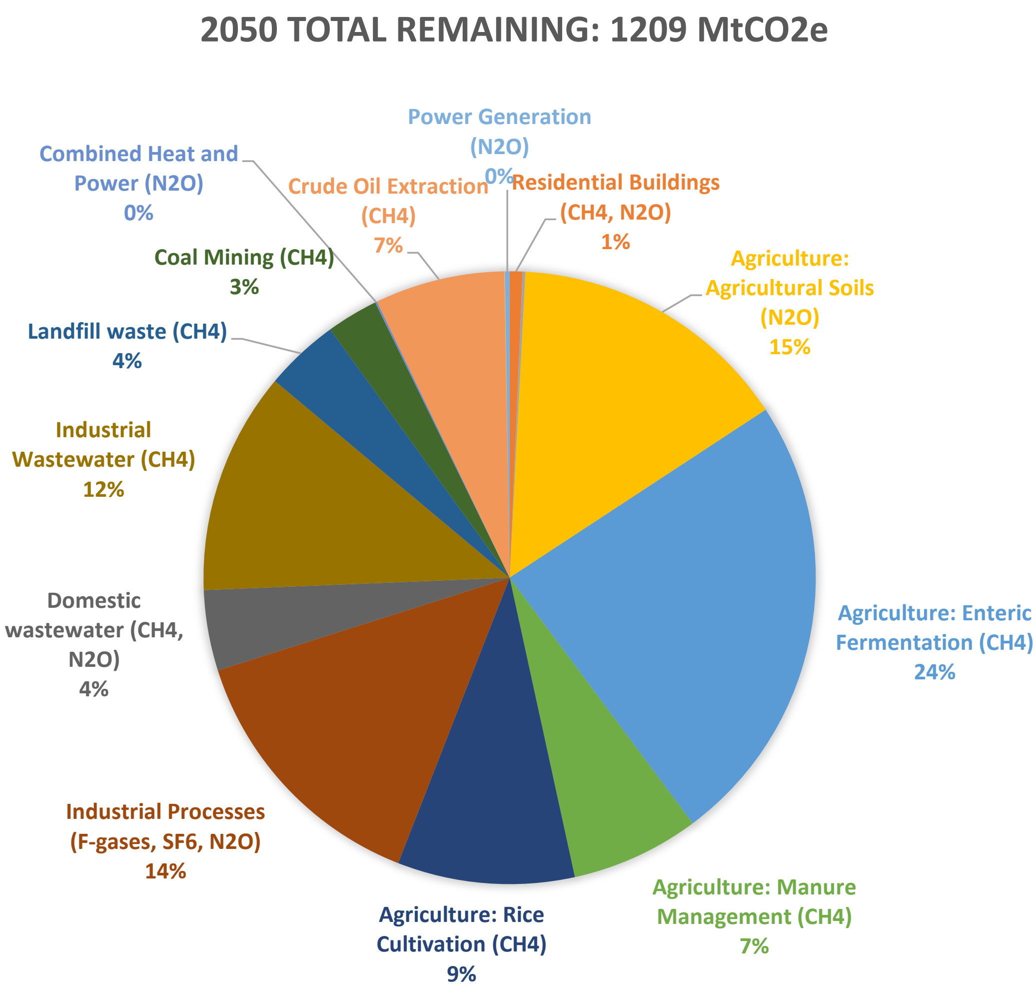


Figure 3. 2050 Remaining Non-CO_2 GHG by Sector after Deep Mitigation Measures

Beyond the Deep Mitigation Scenario, additional non-CO_2 GHG reductions are technically feasible at today's significantly higher costs for additional measures in some sectors (e.g., landfill waste and wastewater, and aluminum production), along with adoption of potential breakthrough technologies and behavioral change such as dietary changes that were not considered in this analysis.

Cost-Effectiveness Analysis

Based on literature review, including two U.S. EPA reports,[93, 94] one study from the International Institute for Applied System Analysis,[95] one from China,[96] and the International Energy Agency's methane tracker,[97] cost curves were developed in key years (i.e., 2030 and 2050) with mitigation potential under the deep mitigation scenario. The costs shown in Figures 4 and 5 represent the average (not marginal) abatement cost across multiple measures for a given gas in a given subsector.

With an average abatement cost of US\$10/tCO_2e across all sectors and gases, an estimated 970 MtCO_2e of non-CO_2 emissions can be reduced by 2030 with a maximum abatement cost of less than US\$100/tCO_2e for most (but not all) of the measures included in the deep mitigation scenario.

By 2050, 1375 MtCO_2e non-CO_2 emissions reductions can be achieved with an average cost of US\$8.5/tCO_2e across all sectors and gases. By gas, F-gases can achieve greater than 80% reduction at an average cost of less than US\$6/tCO_2e in room ACs, the power sector, and industrial sectors – and an average cost of US\$34/

tCO_2e for mobile ACs (see Figure 4). Methane reduction reaches close to 26%; about half of the reduction is in the energy sector, with negative average abatement cost in the gas sector, an average abatement cost of US$7/ tCO_2e in coal mining, and an average abatement cost of US$71/$tCO_2e$ in the oil sector.

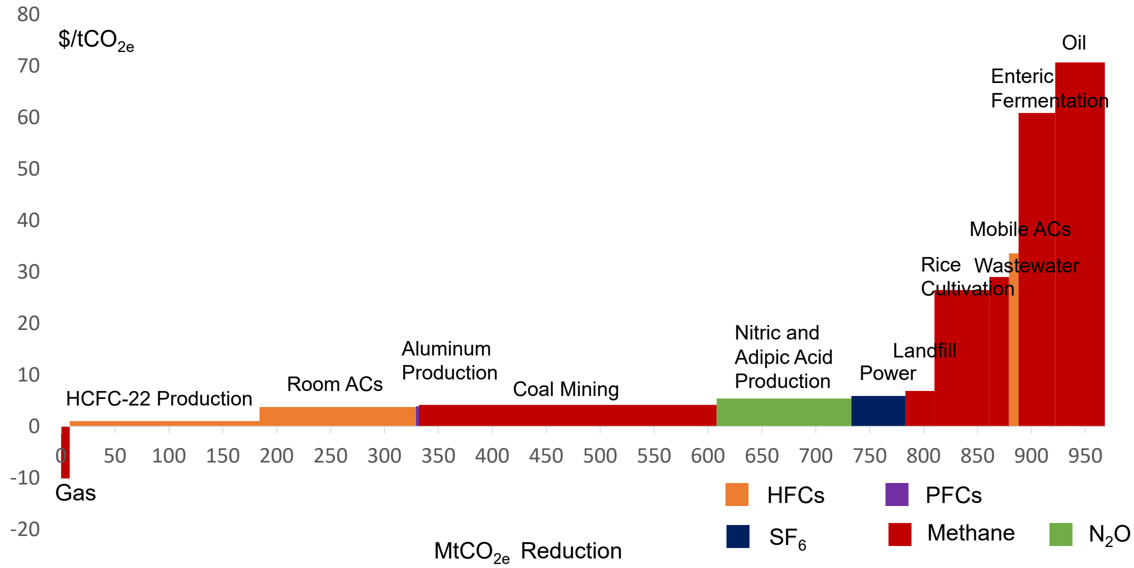


Figure 4. 2030 Cost-Curve of Non-CO_2 Mitigation Measures in China

Note: agricultural soil and manure management and commercial air conditioning and commercial and industrial refrigeration measures are not included in the cost curve above, but may have additional reduction potential with relatively low costs.

By 2050, 69 $MtCO_2e$ of N_2O can be eliminated from agricultural soil by reducing nitrogen fertilizer use at a potentially low cost (see Figure 5). Moreover, 54 $MtCO_2e$ of HFCs can be eliminated from commercial and industrial air conditioning and refrigeration.

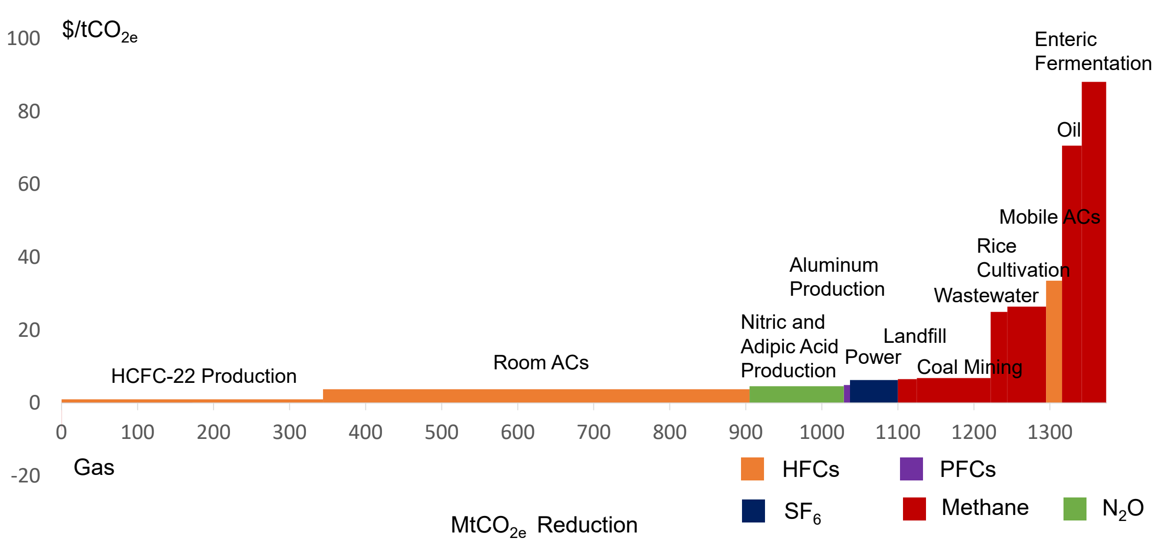


Figure 5. 2050 Cost-Curve of Non-CO_2 Mitigation Measures in China

Note: agricultural soil and manure management and commercial air conditioning and commercial and industrial refrigeration measures are not included in the cost curve above, but may have additional reduction potential with relatively low costs.

5 Policy Recommendations

During the last 10 years, China has issued a series of policies and guidelines to control SLCPs with notable success, as discussed in the China Policy Review section, above. Chinese industries have also responded to global technological and policy trends in adopting alternative solutions such as low-GWP refrigerants in room ACs. Based on the cost-effective mitigation potential identified in this study, which is consistent with mitigation potential identified in a late 2020 Tsinghua study, China can and should consider reduction targets for SLCPs in its ministerial and sectoral action plans governing the 14th Five-Year Plan period (2021-2025) to support its 2060 carbon neutrality target and commitment to the Paris Agreement in its 2030 and 2060 long-term planning. Further, in certain areas, China is in the unique leadership position to spur global action, such as simultaneously improving energy efficiency and transitioning to low-GWP refrigerants in room ACs, where China's share of global production is greater than 80%. Thus, China's early actions could have a large spill-over effect globally, and in other emerging economies in particular.[98]

When considering specific targets and mitigation regulations, China should aim to harmonize, to the extent possible, its regulations with global best practices and norms, including addressing multiple gases across sectors with quantitative targets and specific implementation timelines. Table 2 summarizes the national or regional quantitative targets that have been set internationally for overall GHGs (including SLCPs), and for methane, F-gases, and black carbon specifically. For overarching GHG emission reduction targets that also cover SLCPs, the E.U. and California have both set reduction targets relative to 1990 levels, ranging from 55% to 40% reduction by 2030. Canada's reduction target is slightly lower with 40-45% reduction by 2030 relative to a higher 2005 baseline level, the equivalent of 27% reduction from 1990 levels. For methane, California is the only jurisdiction to have set an overarching reduction target of 40% below 2013 levels by 2030, but North American countries have committed to oil and gas sector methane emission reduction target of 40-45% from 2012 levels by 2030. For F-gases, both the E.U. and California have set F-gas and HFCs emission reduction targets for 2030, with 67% reduction and 40% reduction from 2014 and 2013 levels, respectively. California is also the only jurisdiction to have set a black carbon emission reduction target of 50% below 2013 levels by 2030. In the Arctic Council's Reykjavik Declaration on the Climate Change Crisis adopted in May 2021, the Arctic States and Observer states (including China) are encouraged to support a collective and aspirational goal to reduce black carbon emissions by 25-33% below 2013 levels by 2025, and to adopt similar reduction goals for their jurisdictions.[99]

Table 2. Comparison of International SLCP Reduction Targets Framing High Ambition, Technical Feasibility and Current Cost-Effectiveness

	OVERARCHING GHG (INCLUDING SLCP) REDUCTION TARGETS	METHANE REDUCTION TARGETS	F-GASES REDUCTION TARGETS	BLACK CARBON REDUCTION TARGETS
E.U.	By 2030, reduce net GHG emissions by 55% from 1990 levels (51% from 2005).		By 2030, phase-down F-gas emissions by 67% compared with 2014 levels.	
CANADA	By 2030, reduce GHG emissions by 40-45% below 2005 levels. (27% from 1990).	By 2025, reduce methane emissions *from oil and gas* by 40-45% from 2012 levels.	Under Kigali Amendment (ratified), phase-down HFC consumption by 40% in 2024, 70% in 2029, 80% in 2034, and 85% in 2036 from calculated baseline.	
U.S.	By 2030, reduce GHG emissions by 50-52% below 2005 levels. (43% from 1990).	By 2025, reduce methane emissions *from oil and gas* by 40-45% from 2012 levels.	AIM Act requires 85% phase-down in production and consumption of HFC by 2036 from baseline.	
CALIFORNIA	By 2030, reduce GHG emissions by 40% below 1990 levels.	By 2030, reduce methane by 40% below 2013 levels.	By 2030, reduce HFC emissions by 40% below 2013 levels.	By 2030, reduce black carbon emissions by 50% below 2013 levels.
CHINA			By 2020 and 2025, 35% and 67.5% reduction, respectively, in production of HCFC-22 for controlled uses compared to 2010 levels. Under Kigali Amendment (ratified), freeze HFC production and consumption in 2024, with an 80% reduction by 2045.	

These quantitative reduction targets reflect existing international ambition on reducing key SLCPs, and represent technical feasibility and today's cost-effectiveness. Greater ambition can be achieved, given that technologies and their cost-effectiveness will further improve over time, and will be needed to slow global climate change. As seen with the dramatic and rapid costs reductions of solar and wind power and battery technologies over the past decade, societal push for increased adoption of GHG mitigation measures can accelerate learning curves and achievement of economies of scale. Based on existing international ambition in committing to quantitative reduction targets with a defined implementation timeline for different SLCPs, and our analysis of China's specific cost-effective reduction potential for different non-CO_2 GHGs across different sources and sectors, China could adopt ambitious yet technically and economically feasible reductions for SLCPs and N_2O in the near, mid- and long-term.

In consideration of possible target-setting for China for 2030, this analysis has identified cost-effective reduction potential of 35%-40% for methane, 30% for F-gases, and 40% for N_2O, relative to 2015 levels for China, with a total reduction potential of 1080 million metric tons of carbon dioxide equivalent ($MtCO_2e$) by 2030. This is comparable to the reduction potential of 1,096 $MtCO_2e$ identified in Tsinghua's recent 1.5°C scenario. There are also opportunities for China to take early actions in the next five years to reduce HFC-23, N_2O, and HFCs related to cooling.

For methane, this analysis has identified cost-effective reduction potential of 35-40% relative to 2015 levels by 2030 for China, which is comparable to the lower range of existing 2030 reduction targets in the U.S., Canada and California. In the near-term, China could consider adopting or harmonizing with emerging international protocols in preventing leakage in the oil and gas industries and consider setting a target for 25% reduction of methane leakage associated with the coal mining process. These energy sector mitigation measures have been demonstrated to be feasible for use around the world and in China at a reasonable cost (see mitigation potential section for details).

In the mid-term to 2030, methane emissions in the energy sector could be reduced about 55% by adopting cost-effective mitigation measures and reducing coal production. Methane emissions in agriculture could be reduced 20% by adopting better practices in irrigation and animal feeds, and those in the waste sector could be reduced 19% by adopting best available technologies and potential waste reduction strategies (reducing landfills).

For F-gases, this analysis has identified cost-effective reduction potential of 30% relative to 2015 levels by 2030 for China, which is lower than the current 2030 E.U. and California reduction targets. The Chinese cooling industry is currently transitioning to lower-GWP refrigerants, with an estimated market share of ~40%-50% according to industry estimates for 2020. Furthermore, in the Global Cooling Prize—which aims to lower the climate impact of cooling by 5X compared to today's baseline—two of the eight finalists are led by Chinese companies. Gree Electric Appliances Inc, in partnership with Tsinghua University, is one of the two winners of the Global Cooling Prize. By accelerating this transition to low-GWP refrigerants while adopting enhanced energy efficiency, Chinese air conditioning companies will be well positioned as global leaders in this field.

As part of the Kigali Amendment to the Montreal Protocol, which China has just ratified on June 17, 2021, China could potentially reduce almost all HFC-23 emissions associated with HCFC-22 production for non-controlled feedstock use during the 14th Five-Year Plan Period. The mitigation technologies have been demonstrated successfully over the past 10 years in China and around the world, and the cost of mitigation is also low (under $1/ton CO_2e).

By 2030, China could accelerate the adoption of low-GWP refrigerants and reduce all other HFC emissions at least 50% for the room air conditioning and mobile air conditioning industries and 30% for commercial air conditioning and refrigeration industries. Considering China's significant share of the export markets, China can also play a leader's role for the global HFC transition, as well as AC efficiency improvement, which can take place simultaneously with the refrigerant transition.

For N_2O emissions, this analysis has identified cost-effective reduction potential of 40% relative to 2015 levels by 2030 for China. In the near-term, China could adopt cost-effective reduction measures to the maximum extent as practically feasible in industrial processes, since these measures have widely been adopted elsewhere in the world. For the agricultural sector, China could potentially set a 10% reduction target through reducing overuse of fertilizers by 2025.

By 2030, N_2O emissions from industrial processes could be reduced almost completely by adopting existing mitigation measures in the production of nitric and adipic acid production processes, where costs of mitigation are also relatively low (about $5/ton CO_2e). For the agricultural sector, China could reduce N_2O emissions by more than 22% through reducing over-use of fertilizers.

For black carbon, this analysis has identified a technically feasible reduction potential of 35% by 2030 relative to 2015 levels for China. China has already implemented emission standards for industrial boilers, coking ovens, and automobiles, all of which will lead to significant black carbon reduction. In the near and mid-term to 2030, China could consider expanding such emission standards for diesel-power vehicles to other off-road vehicles. Further, China could expand its clean heating and cooking program for rural households to the extent that is technically feasible and economically viable.

Looking at PFCs and sulfur hexafluoride (SF_6), the mitigation measures are also very cost effective, and could potentially be fully adopted by China in the near to mid-term.

Table 3, below, outlines potential China goals for the near-term and for 2030 for different gases and sectors for consideration, based on our cost-effectiveness analysis and comparable existing international targets.

Table 3. Potential Near-term and 2030 Goals for China Involving Specific Climate Pollutants/Non-CO_2 GHGs

POTENTIAL CHINA GOALS	2025	2030 (TOTAL 1080 $MtCO_2e$)
METHANE	Consider adopting Oil and Gas Methane Protocol Coal mines: 25% emissions reduction compared to 2015 levels	35-40% methane emissions reduction compared to 2015 levels across all sectors, including: • Energy: 55% reduction • Agricultural: 20% reduction • Waste: 19% reduction
F-GASES	HFC-23: near complete destruction of HFC-23 associated with HCFC-22 production for non-controlled feedstock use to the extent feasible 50% new Room AC units and 90% new mobile AC adopt low-GWP refrigerants Power: 30% SF_6 emissions reduction compared to 2015 levels PFCs: 15% emissions reduction compared to 2015 levels	30% emissions reduction compared to 2015 levels across all HFCs (excluding HFC-23), including: • Room and mobile ACs: 50% reduction • Commercial ACs and Refrigeration, Industrial Refrigeration: 30% reduction Power: 58% SF_6 emissions reduction
N_2O	Agricultural: 10% emissions reduction (fertilizer usage) compared to 2015 levels Industrial: adopt cost-effective reduction measures as practically feasible	40% emissions reduction compared to 2015 levels, including: • Industrial: 94% reduction • Agricultural: 22% reduction
BLACK CARBON	Consideration of the following measures: • Residential heating: expand clean heating as much as technically and economically feasible	Consideration of the following measures: • New standards for off-road diesel vehicles • Accelerate retirement of small capacity coal boilers

Note: The 2030 total reduction potential of 1080 $MtCO_2e$ does not include reduction potential in manure management, which has more uncertain costs, but includes reduction potential from agricultural soils, commercial ACs, commercial and industrial refrigeration beyond measures shown in the cost-curve.

For the long-term targets, progress made on SLCPs could help China to reach its carbon neutrality target by 2060. While there are still some uncertainties regarding the long-term mitigation potential in SLCPs, current analyses suggest that fast adoption of cost-effective technologies available today could allow China to reduce its non-CO_2 greenhouse gases by 56% by 2050. Further reduction could come from a variety of technological and behavioral solutions such as dietary changes, further reduction in fossil energy usage, as well as newer technologies. These opportunities will be explored further in future research.

Technical Appendices

A1. Measures included in cost-curve analysis

SECTOR	GAS	TECHNICAL MEASURES
Coal Mining	CH_4	Gas collection and flaring; Gas collection for energy use
Coal Mining	CH_4	Ventilation air methane (VAM) oxidation
Natural Gas	CH_4	Green completions and plunger lift systems
Natural Gas	CH_4	Leak monitoring and repair (production, processing & transmission)
Natural Gas	CH_4	Replace or retrofit high-bleed pneumatic devices or air pneumatic controllers (using low-bleed or no-bleed pneumatic controllers)
Oil	CH_4	Good practice to reduce unintended leakage
Oil	CH_4	Recovery and utilization of vented gas
Landfill Waste	CH_4	Gas collection and flaring; Gas collection for power generation
Wastewater	CH_4	Upgrade to anaerobic treatment with gas recovery and utilization; Open sewer to aerobic WWTP
Manure Management	CH_4	Converting manure to compost
Livestock Enteric Fermentation	CH_4	Improving nutritional balance of livestock feed and improving feed digestibility
Rice Cultivation	CH_4	Changing irrigation practices (humid and intermittent irrigation)
Adipic Acid	N_2O	Thermal/catalytic decomposition
Nitric Acid	N_2O	Secondary abatement: catalytic N_2O decomposition in the oxidation reactor
Agricultural Soils	N_2O	Reduced fertilizer application; improved fertilizer use efficiency, such as splitting nitrogen fertilization
Aluminum	PFCs	Upgrading process control systems (automated extinguisher and automated controls for the electrolytic processes)
Power	SF_6	SF_6 recycling
Power	SF_6	Leak detection and leak repair
Power	SF_6	Equipment refurbishment
Power	SF_6	Improved SF_6 handling
Light Duty Vehicles MVACs	HFCs	Replacing HFC-134a with HFO-1234yf
New Room AC Equipment	HFCs	Replacing HCFC-22/HFC-410a with alternative refrigerants, particularly propane (R290)
Commercial Air Conditioners	HFCs	Leakage control
Commercial and Industrial Refrigeration	HFCs	Leakage control

SECTOR	GAS	TECHNICAL MEASURES
HCFC-22 Production	HFCs	Thermal oxidation
Semiconductor	PFCs	Thermal abatement

A2. International Policy and Programs

SECTOR	GAS	COUNTRY/STATE	NAME OF POLICY OR PROGRAM
Multiple sectors	SLCPs: black carbon, methane, HFCs	California	Senate Bill No.1383 Short-lived climate pollutants reduction strategy
Multiple sectors	CO_2, CH_4, N_2O, HFCs, PFCs, NF_3, SF_6	European Union	Regulation on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (E.U.) No 525/2013
Multiple sectors	SLCPs: black carbon, methane, tropospheric ozone, HFCs	Canada	Pan-Canadian Framework on Clean Growth and Climate Change
Multiple sectors	SLCPs: black carbon, methane, tropospheric ozone, HFCs	Canada	Environment and Climate Change Canada (ECCC) Strategy on Short-Lived Climate Pollutants
Energy, agriculture and waste sectors	CH_4	European Union	European Commission: E.U. strategy to reduce methane emissions Brussels, 14.10.2020 COM(2020) 663 final
Oil and Gas	CH_4	Canada, Mexico, and the United States	North American Climate, Clean Energy, and Environment Partnership
Oil and Gas	CH_4	United States	Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Review, 85 Fed. Reg. 57018 (Final Rule)
Oil and Gas	CH_4	United States	Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Reconsideration, 85 Fed. Reg. 57398 (Reconsideration Rule) (final rule)
Oil and Gas	CH_4	United States	Notice Regarding Withdrawal of Obligation to Submit Information, 82 Fed. Reg. 12817
Oil and Gas	CH_4	Colorado	Colorado's Air Quality Control Commission Rule on Air Emissions from Oil and Gas
Oil and Gas	CH_4	California	California Code of Regulations, Title 17, Division 3, Chapter 1, Subchapter 10 Climate Change, Article 4 Subarticle 13: Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities

SECTOR	GAS	COUNTRY/STATE	NAME OF POLICY OR PROGRAM
Oil and Gas	CH_4	New Mexico	New Mexico Oil Conservation Division Rules to Eliminate Routine Gas Venting and Flaring in Oil Fields
Oil and Gas	CH_4	British Columbia	British Columbia Oil and Gas Commission Regulations to Reduce Methane Emissions from Upstream Oil and Gas Operations: The Amendments to the Drilling and Production Regulation
Oil and Gas	CH_4	Alberta	Directive 060 Upstream Petroleum Industry Flaring, Incinerating, and Venting
Oil and Gas	CH_4	Alberta	Directive 017 Measurement Requirements for Oil and Gas Operations
Oil and Gas	CH_4	Saskatchewan	The Oil and Gas Emission Management Regulations (OGEMR)
Landfill	CH_4	United States	Final Rule: Federal Plan Requirements for Municipal Solid Waste Landfills (86 FR 27756)
Landfill	CH_4	California	The California Air Resources Board Landfill Methane Regulation
Multiple sectors	HFCs, HCFC	122 countries (as of June 2021)	The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer
Stationary sources	F-gas	European Union	Regulation (E.U.) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 Text with EEA relevance
Mobile Air Conditioning	HFCs	European Union	E.U. Directive 2006/40/EC
Cooling, refrigeration, industrial applications	HFCs	Austria	Regulations Prohibiting the Import and Use of HFCs in Specified Circumstances
Refrigeration	HFCs	Belgium	Subsidy for Replacing HFCs with Natural Refrigerants, in Existing and New Installations
Stationary sources	HFCs	Denmark	Bans and Taxes to Inhibit the Use of HFCs
HFC producers and emitters	HFCs (as well as CFCs and HCFCs)	Poland	Emission Fees for “Using the Environment” Applies to HFCs
Stationary equipment	F-gases	Slovenia	An Environmental Tax on the Use of HFCs (and Other F-gases)
Consumption of F-gases with GWPs above 150	F-gases	Spain	A Tax on F-gases, including HFCs
Refrigeration	HFCs	Sweden	Limits on Permitted HFC Refrigerant Charges
Stationary sources	HFCs	California	California’s Refrigerant Management Program

SECTOR	GAS	COUNTRY/STATE	NAME OF POLICY OR PROGRAM
Refrigeration, Cooling except mobile air conditioning	HFCs	California	the California Significant New Alternatives Policy (SNAP) Regulation: California Air Resources Board (CARB) HFC regulation and the California Cooling Act (Senate Bill 1013)
Refrigerants in supermarket and industrial sectors	HFCs	California	Fluorinated Gases Emission Reduction Incentive Program
Transportation, residential, commercial, agriculture	Black Carbon	California	California's Clean Air Rules
Transportation	Black Carbon	China, India, Europe, Japan, Canada, South Korea and the United States	Filter-based Standards for New Diesel Cars and for Heavy Duty Diesel Trucks
Transportation	Black Carbon	California	The In-Use Off-Road Diesel-Fueled Fleets Regulation
Residential	Black Carbon	Canada	The Code of Practice for Residential Wood Burning Appliances (2012)
Residential	Black Carbon	Subnational Jurisdictions in Canada	Emission Standards for New Wood-Burning Appliances
Residential	Black Carbon	Subnational Jurisdictions in Canada	Wood Stove Change-out Programs
Transportation	Black Carbon	Subnational Jurisdictions in Canada	Vehicle Inspections and Scrappage Programs
Residential	Black Carbon	India	Ujjwala Program

Endnotes

1 Institute for Governance and Sustainable Development. (2013). *Primer on Short-lived Climate Pollutants.* https://www.ccacoalition.org/en/resources/primer-short-lived-climate-pollutants

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