WORLD RESOURCES INSTITUTE

WORKING PAPER

OPPORTUNITIES TO ADVANCE MITIGATION AMBITION IN CHINA: NON-CO_2 GREENHOUSE GAS EMISSIONS

RANPING SONG

EXECUTIVE SUMMARY

Highlights

- Non–carbon dioxide (CO_2) greenhouse gas (GHG) emissions are a substantial driver of climate change and have significant negative impacts on air quality, human health, and food production. In 2014, the last year with official data, non-GHG emissions in China were greater than total GHG emissions in Japan or Brazil.

- China's policy development since 2015 has led to a significantly lower non-CO_2 GHG emissions trajectory than expected under policies as of 2015. This paper estimates that non-CO_2 GHG emissions will grow modestly until 2030 under current policies, remain flat between 2030 and 2040, and then begin a more significant decline.

- There is significant potential to further reduce non-CO_2 GHG emissions beyond the effects of current policies. With additional actions, China could further mitigate 1.5–3.0 billion tons of carbon dioxide equivalent (Gt CO_2e) cumulative emissions between 2020 and 2030. The country's non-CO_2 emissions can stabilize as early as 2020 at a level lower than expected under the current policies trajectory.

- Key mitigation prospects include reducing hydrofluorocarbons, methane emissions from coal mines, as well as nitrous oxide from nitric and adipic acid production.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

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- China does not have a quantitative top-line target for non-CO_2 GHGs in its nationally determined contribution (NDC). The country should enhance its NDC in 2020 by establishing ambitious and precise targets for non-CO_2 GHG reduction and implement actions correspondingly. The country should also identify additional ways to further reduce non-CO_2 emissions by 2025.

Context

China is on track to meet its international climate targets. By 2017, China had beat its carbon intensity reduction target for 2020 established in 2009, three years ahead of schedule. The country is also well on track to meet its NDC targets committed in 2015.

However, for the world to have a chance at meeting the goal of the Paris Agreement, China and other countries must accelerate efforts beyond current targets. Even when fully implemented, NDCs collectively will place the world on a trajectory to experience a 3.2˚C temperature rise, far exceeding the Paris Agreement goal of limiting temperature rise to between 1.5˚C and 2˚C. As the world's top emitter, it is especially important for China to demonstrate climate leadership.

A special report by the United Nation's Intergovernmental Panel on Climate Change (IPCC) notes it will be impossible to limit global warming to 1.5˚C without acting right away to reduce highly potent, non-CO_2 climate pollutants like methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs) in addition to carbon dioxide. Fast and immediate action on these non-CO_2 GHG emissions is particularly important to decrease the chances of triggering dangerous climate tipping points.

Non-CO_2 GHG emissions also have significant negative impacts on air pollution, human health, and food production. Methane, the largest precursor to background tropospheric (at ground level and up to 15 km) ozone, causes 79–121 million tons of crop production loss and is linked to around 1 million premature deaths per year globally. Nitrous oxide destroys the ozone layer at the stratosphere level, and therefore threatens human and ecological systems with harmful ultraviolet radiation from the sun.

Box 1 | **About This Working Paper**

- This working paper is the first of a two-part study conducted by World Resources Institute (WRI) to analyze whether and how China is able to enhance its mitigation ambition by 2020.
- This paper focuses on non-CO_2 GHG emissions, including future trends, mitigation potential, and policy recommendations. The second part of the study will make more comprehensive recommendations on China's NDC update, including targets related to CO_2 emissions.

Non-CO_2 GHG emissions reduction represents an important opportunity for China to enhance its mitigation ambition when communicating and updating its NDC. According to the government's most recent data, in 2014 China's non-CO_2 GHG emissions accounted for 16 percent of the country's total GHG emissions, exceeded the total GHG emissions of Japan or Brazil, and this paper estimates the emissions will continue to increase. Non-CO_2 GHGs are not included in the top-line NDC targets China submitted in 2015. Nevertheless, China has made concrete efforts to mitigate this category of emissions. Various studies show there are cost-effective measures that can result in further emissions reductions, making non-CO_2 GHG a signifiant opportunity for China as it looks to strengthen its migitation ambition.

Methodology and Scenario Description

This paper identifies 30 major sources of non-CO_2 GHG emissions and synthesizes multiple studies to project China's future non-CO_2 GHG emissions prospects under various scenarios. It examines government documents, studies by reputable organizations, peer-reviewed literature, industrial research, and experts' opinions in order to develop three scenarios of emissions trajectories.

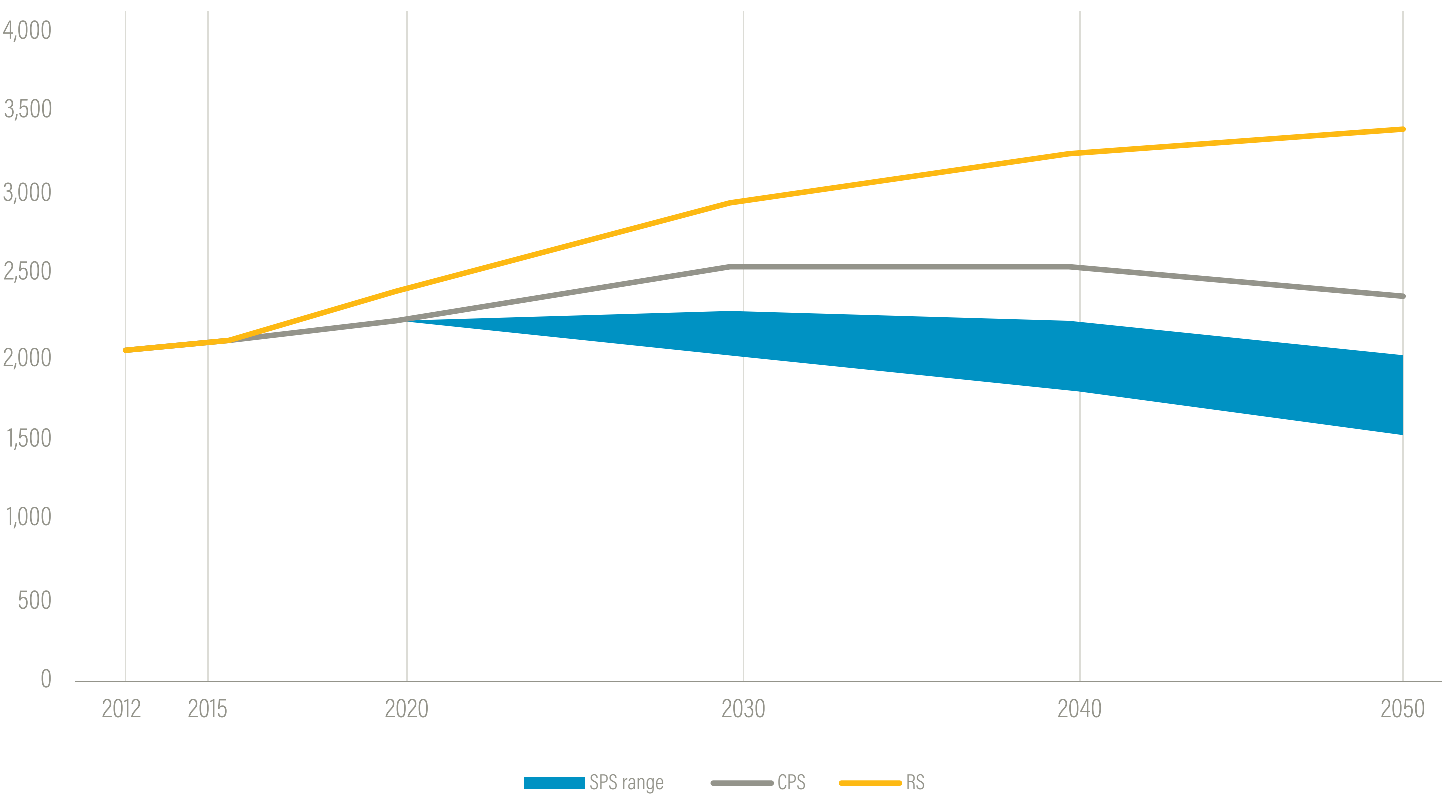
This paper uses a spreadsheet to project emissions until 2050 under the three scenarios. Appendix A describes the methodology and assumptions in more detail, while Appendix B provides the full spreadsheet with data.

The Reference Scenario (RS) represents policies and trends as of 2015. In this scenario China would implement policies to meet targets committed to by the end of 2015, including targets and policies articulated in its existing NDC. However, it would not pursue additional policies to mitigate non-CO_2 GHGs. It serves as a reference to assess the progress China has made with regard to non-CO_2 GHGs since 2015.

The Current Policies Scenario (CPS) represents policies and trends as of 2018. In this scenario China would implement policies and targets communicated by the end of 2018, including an HFC phasedown target based on the Kigali Amendment of the Montreal Protocol; the zero growth target for nitrous oxide emissions from industrial processes, based on China's First Biennial Update Report on Climate Change; and its targets relating to coal mine methane utilization, rural biogas development, and municipal solid waste (MSW) treatment, as specified in relevant sectoral 13th Five-Year-Plans (13th FYPs). The CPS serves as a reference to assess whether and by how much future policies will further reduce emissions compared to 2018 policies.

The Strengthened Policies Scenario (SPS) represents a range of non-CO_2 GHG emissions pathways for feasible mitigation ambition enhancement that go beyond the CPS. The SPS focuses on the top seven emission sources that add up to 76 percent of China's non-CO_2 GHG emissions in 2030 under CPS. All measures incorporated in the upper bound of emissions for the SPS have a low cost—less than US$14/per ton of carbon dioxide equivalent (t CO_2e), which is the average expected carbon price for China in 2025, based on 317 surveyed stakeholders that follow China's carbon market development. The lower bound of emissions for the SPS incorporates more amibitous but still feasible assumptions, including a higher penetration

Figure ES-1 | **Projected Non-CO_2 GHG Emissions under Various Scenarios (Mt CO_2e)**



Source: WRI.

rate of low-cost measures and additional measures with higher costs. Assumptions on measures' penetration rate and their mitigation potential are informed by literature, practices in other countries, and expert consultations.

Key Findings

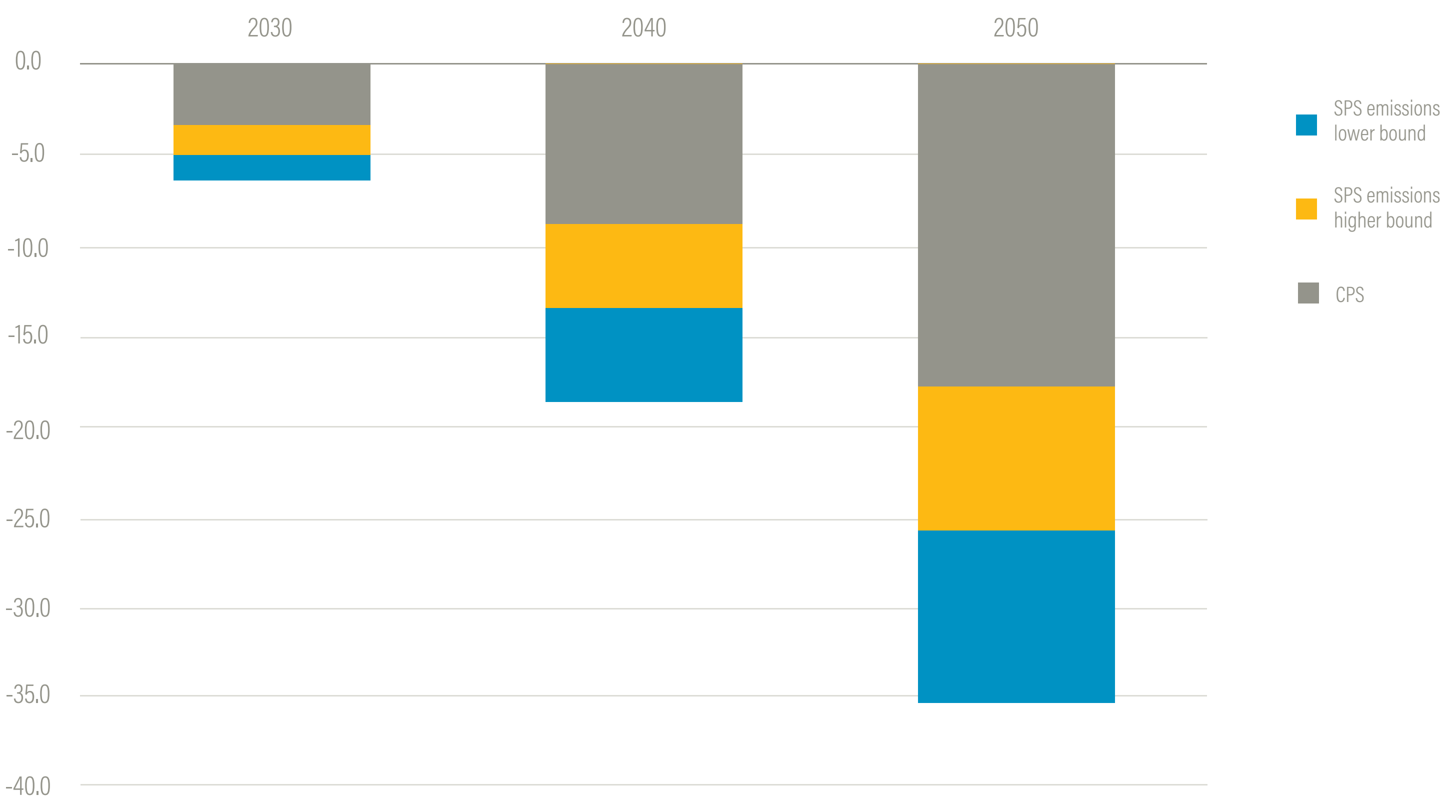
Under the RS, China's non-CO_2 GHG emissions would grow significantly. Between 2012 and 2030, emissions would increase by around 44 percent, and would continue to grow another 15 percent between 2030 and 2050. Most emissions emanate from industrial processes, given that use of HFCs increases as hydrochlorofluorocarbon (HCFC) consumption and production phases out. Emissions from nitric and adipic acid production are also a significant factor.

Since 2015 policy development has fundamentally changed the trend of non-CO_2 GHG emissions in China. Under the CPS, while emissions will grow modestly between 2020 and 2030, they will remain flat between 2030 and 2040 before a more evident decline after 2040.

Other actions would further reduce non-CO_2 GHG emissions significantly below the trajectories expected under current policies. As Figure ES-1 shows, with strengthened action, China's non-CO_2 emissions could stabilize as early as 2020, a decade earlier and at a lower level than under the current policies trajectory. Annual non-CO_2 GHG emissions could return to the 2012 level as early as 2030.

Strengthened action would significantly lower cumulative emissions. Figure ES-2 demonstrates that while current policies will reduce 3.5 Gt CO_2e cumulative emissions by 2030 and 17.8 Gt CO_2e cumulative emissions by 2050 compared to the RS, strengthened actions will further reduce 1.5–3.0 Gt CO_2e cumulative emissions by 2030 and 7.9–17.5 Gt CO_2e cumulative emissions by 2050.

Figure ES-2 | Cumulative Emissions Reduction since 2015 Compared with the Reference Scenario (Gt CO_2e)



Source: WRI.

China is able to mitigate around 280 Mt CO_2e per year from non-CO_2 GHGs by 2030 at low cost. With more ambitious yet attainable action, the impact will be almost doubled. Reduction could be achieved from the top seven emission sources, which represent more than 76 percent of non-CO_2e emissions in 2030. Figure ES-3 demonstrates the range of mitigation potential for each emission source.

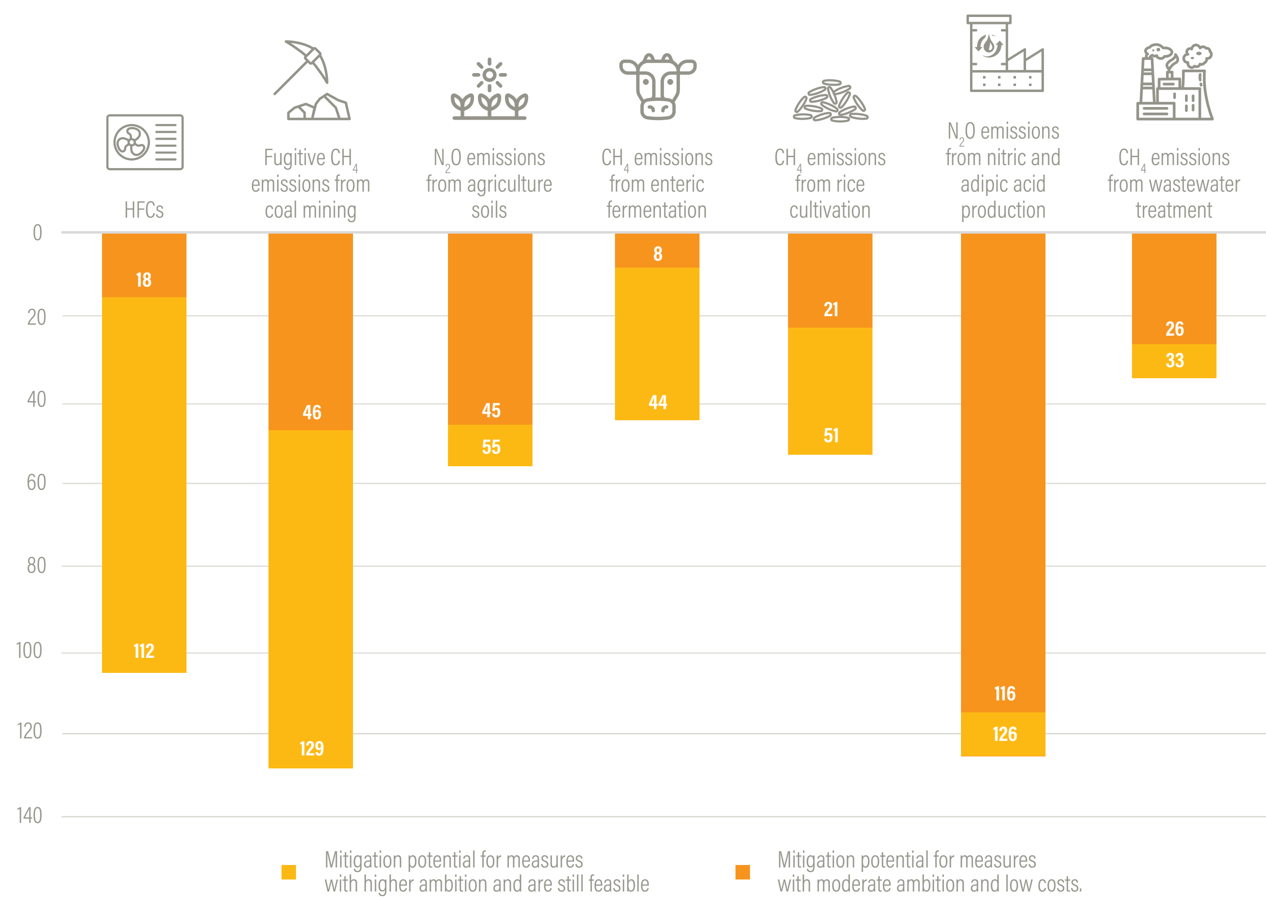
Discussion

Non-CO_2 GHG mitigation has significant development benefits. By reducing ozone generation at the ground level and preventing ozone layer destruction at the stratosphere level, methane and nitrous oxide emissions mitigation can improve air quality, reduce premature death and disease, increase food production, protect ecosystems, and enhance worker safety. Early actions for mitigating HFC emissions can reduce costs to conform to Kigali Amendment obligations.

Mitigation measures are readily available. Table ES-1 summarizes these measures along with corresponding mitigation impacts for the key emission sources.

Emissions trading schemes (ETSs) can be used to drive non-CO_2 GHG emissions reduction. Given the high global warming potential of non-CO_2 GHGs, businesses would be motivated to reduce their emissions if the gases were included in China's upcoming national ETS. Nitrous oxide emissions from nitric and adipic acid production, as well as fluorinated gases, or F-gas emissions from aluminum, integrated circuit, flat panel display, and photovoltaic manufacturing, are an especially good fit for using ETSs to regulate, as the emission sources are concentrated and relatively easy to measure, report, and verify.

Figure ES-3 | **Range of Mitigation Potential by Source under the Strengthened Policies Scenario in 2030 (Mt CO_2e)**



Source: WRI.

Table ES-1 | **Key Mitigation Measures to Support Higher Ambition**

EMISSION SOURCES	MITIGATION MEASURES
HFCs	Freeze HFC production at 90% of the allowed baseline level from 2024 to 2029 and linearly phase down HFC production to meet the Kigali Amendment commitment. Additional measures include replacing 50% of HFC-134a and HFC-410a with HFO-1234yf and propane, respectively, in 2030 and increasing the replacement rate over time.
Methane from coal mining	Require the utilization or flaring of all coal mine methane emissions beyond 9% concentration. Additional measures include reducing coal consumption to less than 2,000 Mtce by 2030.
Nitrous oxide from nitric and adipic acid production	Require nitrous oxide mitigation for all adipic acid, all major and new nitric acid manufacture facilities. Additional measures include expanding the requirement to smaller nitric acid manufacture facilities.
Nitrous oxide from agricultural soils	Promote best practices in the management of fertilizers and reduce nitrogen fertilizer application for rice, wheat, maize, and cash crops. Additional measures include setting up targets to reduce nitrogen fertilizer application linearly from 2020 to 2050, when nitrogen fertilizer application is reduced to 50% of 2015 levels.
Methane from enteric fermentation	Promote animal breeding, as well as the addition of probiotics and tea saponins in animal feed. Additional measures include improving feed digestibility and nutritional balance to increase meat and dairy production.
Methane from rice cultivation	Accelerate irrigation improvement and fertilizer use. Additional measures include piloting and promoting the use of nitrification inhibitor, slow-release fertilizer, and biochar.
Methane emissions from wastewater treatment	Require methane recovery systems for all new and major existing anaerobic wastewater treatment plants (domestic and industrial). Additional measures include expanding the requirement to smaller facilities.
Methane emissions from animal manure	Set and meet ambitious biogas development targets for rural biogas and animal farms in the 14th FYP and beyond.
Methane emissions from solid waste	Set and meet ambitious waste recycling targets in the 14th FYP and beyond.
Sulfur hexafluoride emissions from power equipment	Promote practices of SF_6 recycling, substitution, leak detection and repair, and equipment refurbishment. Additional measures include reducing electricity demand.

Source: WRI.

Recommendations

Taking action on non-CO_2 GHGs can demonstrate China's climate leadership and signal strong commitment to meeting the goals of the Paris Agreement. This paper demonstrates that it is feasible for China to reduce an additional 1.5–3.0 Gt CO_2e cumulative emissions from non-CO_2 GHGs between 2020 and 2030. Because of the development and climate benefits, China should go beyond current policies and take more actions.

Based on the findings, this paper proposes four options, which are not mutually exclusive, for China to enhance its mitigation ambition for non-CO_2 GHGs in its NDC by 2020.

Option 1: Set an ambitious economy-wide GHG target inclusive of CO_2 and non-CO_2 emissions. First, an ambitious GHG target should take into account opportunities to enhance its CO_2 mitigation beyond what is specified in the current NDC. Additionally, the GHG target should reflect a commitment that non-CO_2 GHG emissions will stabilize starting in 2020 and begin to decline as early in the decade as possible.

Option 2: Set an ambitious economy-wide non-CO_2 GHG target. An ambitious non-CO_2 GHG target should stabilize emissions starting in 2020, enabling those emissions to begin to decline as early in the decade as possible.

Option 3: Set ambitious gas-specific reduction targets. Ambitious gas-specific reduction targets should cover a majority of non-CO_2 GHGs, including 7–21 percent methane emissions reduction and 7–11 percent nitrous oxide emissions reduction by 2030 compared to 2014, and commit to taking early actions to emit less HFCs cumulatively than the limit required under the Kigali Amendment.

Option 4: Commit to implementing ambitious source-specific actions. As an initial step, policymakers should implement all the measures and targets listed in Table ES-1.

Post-2020, China's policymakers should assess early progress and identify opportunities to ramp up the country's non-CO_2 mitigation ambition by 2025. Technology development, early implementation, and new social and economic trends could unlock further mitigation potential in only a few years. As a result, in the near future China may achieve more progress than expected. It is essential for the country to evaluate these changes with the intention of boosting mitigation ambition by 2025.

ABBREVIATIONS

AC	air conditioner
AR4	IPCC Fourth Assessment Report
BUR	Biennial Update Report on Climate Change
CDM	Clean Development Mechanism
COD	chemical oxygen demand
CPS	Current Policies Scenario
EDGAR	Emission Database for Global Atmospheric Research
EPA	Environmental Protection Agency
ETS	emissions trading scheme
FYP	five-year plan
GCAM	global integrated assessment model
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
IC	integrated circuit
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
MSW	municipal solid waste
NDC	nationally determined contribution
NPS	New Policies Scenario
ODS	ozone-depleting substance
PA-Continued	Paris Agreement Continued scenario
PA-Increased	Paris Agreement Increased scenario
PFC	perfluorocarbons
PV	photovoltaic
RCP	Representative Concentration Pathway
RS	Reference Scenario
SAR	Second Assessment Report
SPS	Strengthened Policies Scenario
TPED	total primary energy demand
UNFCCC	United Nations Framework Convention on Climate Change
WEO	World Energy Outlook
WRI	World Resources Institute

INTRODUCTION

China has a record of meeting and exceeding its international commitment to mitigate climate change. By 2017, China had reduced its carbon intensity level 46 percent compared to its 2005 level, exceeding the pledge it made in 2009 to cut the rate by 40–45 percent by 2020 (Reuters 2018). China is also on track to meet its climate targets set in 2015 (UN Environment 2019) as per its nationally determined contribution (NDC). This includes reaching its maximum carbon emissions by 2030, as well as reducing its carbon intensity level 60–65 percent compared to 2005; increasing nonfossil fuels to 20 percent of primary energy consumption; and raising forest stock by around 4.5 billion cubic meters (NDRC 2015).

Nevertheless, the full implementation of countries' NDCs will lead to a mean global temperature increase of around 3.2˚C by 2100, relative to preindustrial levels (UN Environment 2019), significantly surpassing the Paris Agreement goals to keep this century's global temperature rise between 1.5˚C and 2˚C. The window of opportunity is rapidly closing to achieve the goals of the Paris Agreement (Rockstrom et al. 2017). Since countries have agreed to communicate or update their NDC targets by 2020 (UNFCCC 2016), they should take this opportunity to ramp up their ambition.

While China is a smaller contributor to greenhouse gas (GHG) emissions on a per capita basis, especially on a cumulative per capita basis, the country is currently the largest emitter and the second-largest contributor to cumulative GHG emissions between 1850 and 2016 (WRI 2018).

Given China's special role in enhancing ambition, World Resources Institute (WRI) has conducted a study to assess China's opportunities to further advance its climate action. This paper is the first installment in a two-part study that aims to identify China's potential to mitigate non-CO_2 GHG emissions and to recommend how China should enhance its mitigation ambition. The second part of the study, to be published separately, will synthesize opportunities in other areas to develop more comprehensive recommendations for China's new or updated NDC, including targets related to CO_2 emissions.

Non-CO_2 Greenhouse Gas Emissions in China

Non-CO_2 GHG refers to the six GHGs covered by the Kyoto Protocol in addition to CO_2: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Collectively, the latter four types of non-CO_2 GHGs are also called fluorinated gases (F-gases).

While CO_2 accounts for the majority of anthropogenic GHG emissions, non-CO_2 GHG emissions contribute significantly to climate change. The United Nations Intergovernmental Panel on Climate Change (IPCC) notes that for the world to have a chance of limiting global warming to 1.5˚C, countries should take immediate action to reduce highly potent, non-CO_2 climate pollutants like methane, nitrous oxide, and HFCs. Fast and immediate action on these non-CO_2 GHG emissions is particularly important to decrease the chances of triggering dangerous climate tipping points (IPCC 2018).

The emissions of methane and nitrous oxide, the two main non-CO_2 GHGs, also have significant negative impacts on human health and food production. Methane is the largest precursor to background tropospheric (at ground level and up to 15 km) ozone (UN Environment and WMO 2011), which causes 79–121 million tons (Mt) of crop production loss and is linked to around 1 million premature deaths per year globally (CCAC n.d.). At the stratosphere level, nitrous oxide destroys the ozone layer, which protects humans and the biological world from the sun's harmful ultraviolet radiation. UN Environment (2013) concludes that nitrous oxide is currently the most important ozone-depleting emission, outweighing chlorofluorocarbons since 2010.

In 2014, the latest year for which government data are available, China's non-CO_2 GHG emissions were equivalent to 2 billion tons (Gt) of CO_2, or 16 percent of the country's total GHG emissions, excluding forest and land-use change activities (GoC 2018). These emissions were more than the total GHG emissions of countries such as Brazil or Japan (WRI 2018).

China's current national development priorities already support non-CO_2 GHG mitigation efforts. While non-CO_2 GHG emissions are not among China's priority NDC quantitative targets, the country's commitment nevertheless alludes to policies and measures that would reduce these emissions. In addition, China has tested a suite of non-CO_2 GHG mitigation technologies. Adopting these will significantly further mitigate the country's non-CO_2 emissions (Lin et al. 2018; Yao et al. 2016). This paper examines various scenarios for how policies and technologies will impact China's non-CO_2 GHG emissions. It first explains the methodology used to determine projected emissions under various scenarios. This is followed by an analysis of projection results and specific recommendations for policymakers.

METHODOLOGY

Adopting a classification system similar to the one adopted by Yao et al. (2016), this paper uses a spreadsheet to project emissions. The spreadsheet first maps 30 major sources of non-GHG emissions, ranging from methane from coal mining to nitrous oxide from waste incineration. It then establishes historic emissions in 2012 using data from China's First Biennial Update Report on Climate Change (BUR) (GoC 2016)[1]. This is complemented by estimatations made by Fang et al. (2016) and EPA (2013) for emissions in 2012.

The spreadsheet then projects changes in future activity data and emission factors based on assumptions sourced from government policy targets, studies undertaken by reputable organizations, peer-reviewed literature, industrial research, and experts' opinions. This study uses official data and calibrates projected results with official data to the extent possible, given that Chinese policymakers tend to base their decisions on government data. Data from other sources, however, have been gathered to fill gaps. Appendix A details the methodology and key assumptions, while Appendix B provides the spreadsheet and data used.

All non-CO_2 GHGs, except for HFC-245fa, are converted to CO_2 equivalent, based on the global warming potential (GWP) measurement, over the 100-year timeline as per the IPCC Second Assessment Report (SAR) (IPCC 1996). The GWP for HFC-245fa is sourced from the IPCC Fourth Assessment Report (AR4) (IPCC 2007) over a 100-year scale.[2]

The paper develops three scenarios to capture the potential trajectories of China's non-CO_2 emissions until 2050:

- The Reference Scenario (RS), representing policies and trends as of 2015.
- The Current Policies Scenario (CPS), representing current policies and trends as of 2018.
- The Strengthened Policies Scenario (SPS), with upper and lower bounds for emissions that represent the range for feasible mitigation of non-CO_2 GHGs.

Reference Scenario

The RS is conditional upon China implementing only policies announced in the end of 2015, including the full implementation of the NDC, but would not pursue additional policies that have impacts on non-CO_2 GHGs. The RS is a counterfactual scenario, given that China has already announced and implemented new policies since 2015. Nevertheless, the RS can be used as a benchmark to compare if and by how much China enhances climate ambition on non-CO_2 GHGs in relation to its first NDC.

Key assumptions under the RS include the following:

- Emissions relating to fertilizers will achieve zero growth by 2020 per the action committed in the NDC (NDRC 2015).
- Energy consumption and production, except for the recovery of coal mine methane, are estimated based on NDC targets and other policies that were in place by the end of 2015, such as the Air Pollution Prevention and Control Action Plan (State Council of the PRC 2013).
- HCFC-22, as an ozone-depleting substance (ODS), will be phased out as agreed in the amended 1997 Montreal Protocol. HCFC-22 for feedstock usage and the associate HFC-23 emissions will continue to rise. There would be no regulation to limit other HFC production and consumption.
- There will be no regulation to limit nitrous oxide emissions from nitric and adipic acid production.

- Production of rural biogas, the utilization rate of coal mine methane, and the treatment rate of municipal solid waste (MSW) remain at 2015 levels, as current policies on these issues were not announced until late 2016 or early 2017.

Current Policies Scenario

The CPS corresponds to the emissions policies that China had in place until the end of 2018. The CPS is the best estimate in this paper to reflect China's future emissions trajectory in the unlikely event that it fails to take further action. The CPS can be applied as a benchmark to evaluate whether and by how much future policies will further reduce emissions.

Key assumptions under the CPS include the following:

- China will ratify the Kigali Amendment of the Montreal Protocol by 2020. Per the Kigali Amendment, HFC-23 emissions will reach near zero by 2020[3] and other HFC emissions will be phased down. While China has yet to ratify this amendment, the country nevertheless has supported it during its negotiation, and China has committed to speeding up the process of ratification (Zhao 2017). Thus, this paper assumes that the Kigali Amendment is a part of current policies.

- Nitrous oxide emissions from industrial processes will achieve zero growth by 2020 per the BUR (GoC 2016).

- China will meet policy targets on coal mine methane utilization, rural biogas development, and the rate of MSW treatment, as specified in the relevant 13th Five-Year Plan (FYP) published in late 2016 and 2017 (NEA 2017; NDRC and MOA 2017; and MOHURD 2016).

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- While China's BUR also commits to reaching zero growth of methane emissions from the energy sector (GoC 2016) by 2020, this emission source is already projected to peak under the RS projection. Therefore this policy will have no impact on the CPS projection.

- While China has announced its plan to enact a national emissions trading scheme (ETS), the specifications—including coverage and total allowance cap—are unknown. Therefore, it is not possible to estimate the reduction potential of this policy. For this reason, this study does not treat an ETS as a part of current policies.

Strengthened Policies Scenario

The SPS attempts to project the impact of feasible options above and beyond the CPS to enhance China's ambition to mitigate non-CO_2 GHGs. This paper identifies the upper and lower bounds of the emissions range under the SPS based on the strength of mitigation measures taken. The upper bound of emissions for the SPS represents a conservative estimate of mitigation potential, while the lower bound of emissions is projected based on a set of more ambitious, albeit feasible, assumptions.

Key assumptions under the SPS include the following:

- For simplicity, mitigation measures only apply to the top seven emission sources that account for around 76 percent of China's non-CO_2 GHG emissions in 2030 under the CPS.

- For the upper bound of emissions for the SPS, only measures that are proven and immediately available at a cost of less than US$14/ per ton of carbon dioxide equivalent (t CO_2e) are considered. For the lower bound of emissions for the SPS, cost of mitigation for some but not all emission sources exceeds $14/t CO_2e. The amount of $14/t CO_2e, or approximately 98 yuan/t CO_2e, is used as the benchmark for low costs since it represents the average expected carbon price in 2025 among 317 surveyed stakeholders that closely follow China's national ETS (Slater et al. 2018).

- Besides costs, the upper and lower bounds also consider the practicality of applying and scaling up measures in specific fields, and make different assumptions on choice of mitigation measure and/or its penetration rate. The assumptions are informed by the literature, practices in other countries, and consultations with experts.

Assumptions for both upper and lower bounds of emissions for the SPS for the top seven sources are summarized in Table 1. Appendix A provides a more detailed description as well as the rationale for relevant assumptions.

Table 1 | **Summary Assumptions for the Strengthened Policies Scenario**

EMISSION SOURCE	2030 EMISSIONS UNDER CPS (%)	ASSUMPTION—UPPER BOUND OF EMISSIONS FOR SPS	ASSUMPTION—LOWER BOUND OF EMISSIONS FOR SPS
HFC	18	Freeze at 90% of consumption allowable under the Kigali Amendment level from 2024 to 2029 and have linear (as opposed to step) phasedown in the following years to avoid loss of stranded assets.	In addition to assumptions under the upper bound of emissions for the SPS, replace HFC-134a and HFC-410a with HFO-1234yf and propane at 50% in 2030 and increase the replacement rate over time (Lin et al. 2018).
Fugitive methane emissions from coal mining	16	Relatively high-concentration methane (9% or more) mitigated through drainage, utilization, or flare systems by 2030. Costs range from \$0.5 to \$11 per ton of CO_2e (Yang et al. 2014).	In addition to assumptions under the upper bound of emissions for the SPS, reduce coal production after 2020 to align with coal control targets set by the China Coal Cap Plan and Policy Research Project (2016).
Nitrous oxide emissions from agriculture soils	13	Adopt three fertilizer application measures with negative costs, identified by Wang et al. (2014). Realize 70% of their mitigation potentials in 2030 and increase to 100% in 2050.	Assume nitrogen fertilizer application decreases linearly from 2020 to 2050. In 2050, the nitrogen fertilizer application will be 50% of the 2015 level. The assumption is similar to Lin et al. (2018), which was based on expert consultation at the Chinese Academy of Sciences. The feasibility is also confirmed by expert consultation conducted by the author of this paper (Li 2018).
Methane emissions from enteric fermentation	10	Adopt animal breeding, probiotics addition, and tea saponins addition measures, all of which have negative costs (Wang et al. 2014). It is assumed that 70% of these measures' potential could be realized in 2030, increasing to 100% in 2050.	It is assumed that by improving the nutritional balance of livestock feed and feed digestibility, China could mitigate 17% and 30% of emissions in 2030 and 2050, respectively. This is similar to assumptions used by Lin et al. (2018).
Methane emissions from rice cultivation	7	By adopting negative or low-cost measures such as improved irrigation and fertilizer use, 12.5% and 25% reductions are assumed in 2030 and 2050, respectively, compared to CPS emissions. The assumption is based on the literature and expert consultation (Li 2018; Lin et al. 2018; Tian et al. 2018).	It is assumed that applying nitrification inhibitor, slow-release fertilizer, or biochar on top of negative or low-cost measures could reduce emissions by 30% and 50% in 2030 and 2050, respectively, compared to CPS emissions. The assumption is based on the literature and expert consultation (Li 2018; Linquist et al. 2012; Xiao et al. 2018).
Nitrous oxide emissions from nitric and adipic acid production	6	It is assumed China could reach a 100% installation rate for mitigation systems in adipic acid production by 2030; and China's technology adaptation rate for nitric acid production (secondary treatment) would reach 20% in 2030 and increase to 80% in 2050. These assumptions are based on cost estimates and other country trends (EPA 2013; Schneider and Cames 2014; Yang et al. 2014).	It is assumed that with more proactive policies, China could reach 100% installation rate for mitigation systems in adipic acid production by 2030, and the technology adaptation rate for nitric acid production (secondary treatment) ccould reach 40% and 100% in 2030 and 2050, respectively. These assumptions are based on Chinese and international studies (EPA 2013; Schneider and Cames 2014; Yang et al. 2014).
Methane emissions from wastewater treatment	4	It is assumed that by installing methane recovery systems on top of existing anaerobic treatment plants, emissions in domestic wastewater treatment could be reduced by 20% and 30% by 2030 and 2050, respectively, while emissions from industrial wastewater treatment could be reduced by 36% and 53% by 2030 and 2050, respectively. These assumptions are based on the estimated cost of mitigation (around \$7–\$9 per ton of CO_2e) (Yang et al. 2014) and estimated emission factors for various processes, as well as the national weighted average in 2012 (Cai et al. 2015).	It is assumed that, with more proactive policies to promote installing methane recovery systems on top of existing anaerobic treatment plants, China could reduce emissions in domestic wastewater treatment by 25% and 44% by 2030 and 2050 respectively, and reduce emissions from industrial wastewater treatment by 46% and 80% by 2030 and 2050, respectively. These assumptions are developed based on studies conducted by Chinese scholars (Cai et al. 2015; Yang et al. 2014).

Source: Author.

Limitations

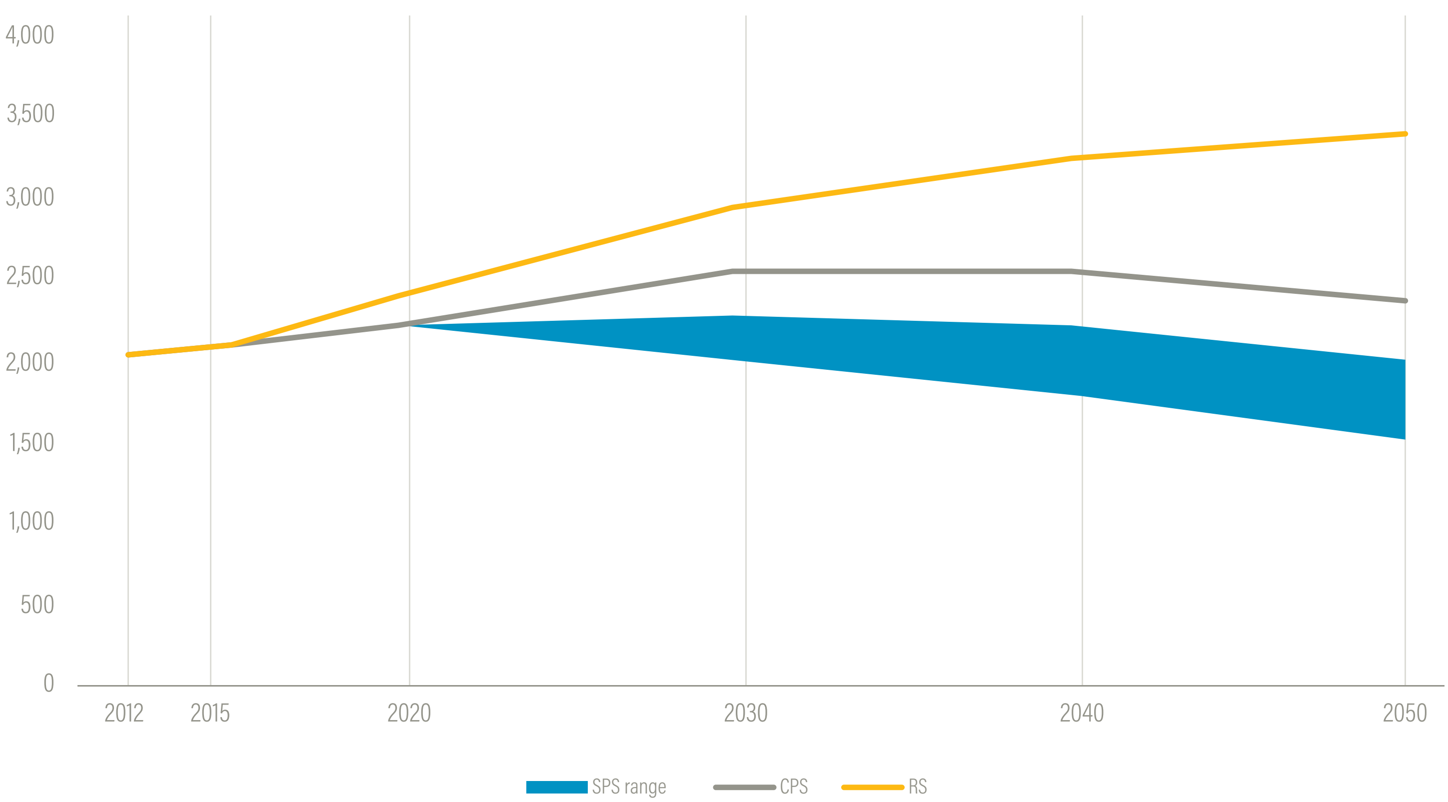
This study is based on a large number of published official data, studies, and estimates. Any uncertainties or errors in the sources will have an impact on its findings. In the absence of quantitative uncertainty information from the relevant underlying sources, this study could not quantitatively assess the uncertainty of the result.

The various underlying sources contain assumptions that are not fully consistent. For example, the projection cited for primary aluminum demand may differ in terms of gross domestic product (GDP) and population assumptions compared to the study used to project coal, oil, and gas production. To mitigate this inconsistency, where relevant information is available (e.g., in the case of SF_6 projection), this paper adjusts the projections so the results have consistent assumptions. Also, it tries to source from studies that share the most similar scenarios. That being said, assumptions about some key variables, such as GDP and population growth, in most underlying studies are not fully consistent and may result in less robust projections.

This paper projects emission sources and their mitigation potential individually without explicitly accounting for interactive effects between sources. Therefore, the aggregated results from all sources are less robust.

The relationship between emissions and their underlying drivers (e.g., activity data, production and consumption, economic growth, and population) may change, resulting in less robust projections. This is particularly true when examining post-2030 results, since relevant correlations are more likely to change over a longer period of time. Therefore, longer-term projections should be treated with more caution.

Figure 1 | **Projected Non-CO_2 GHG Emissions under Various Scenarios (in Mt CO_2e)**



Source: WRI.

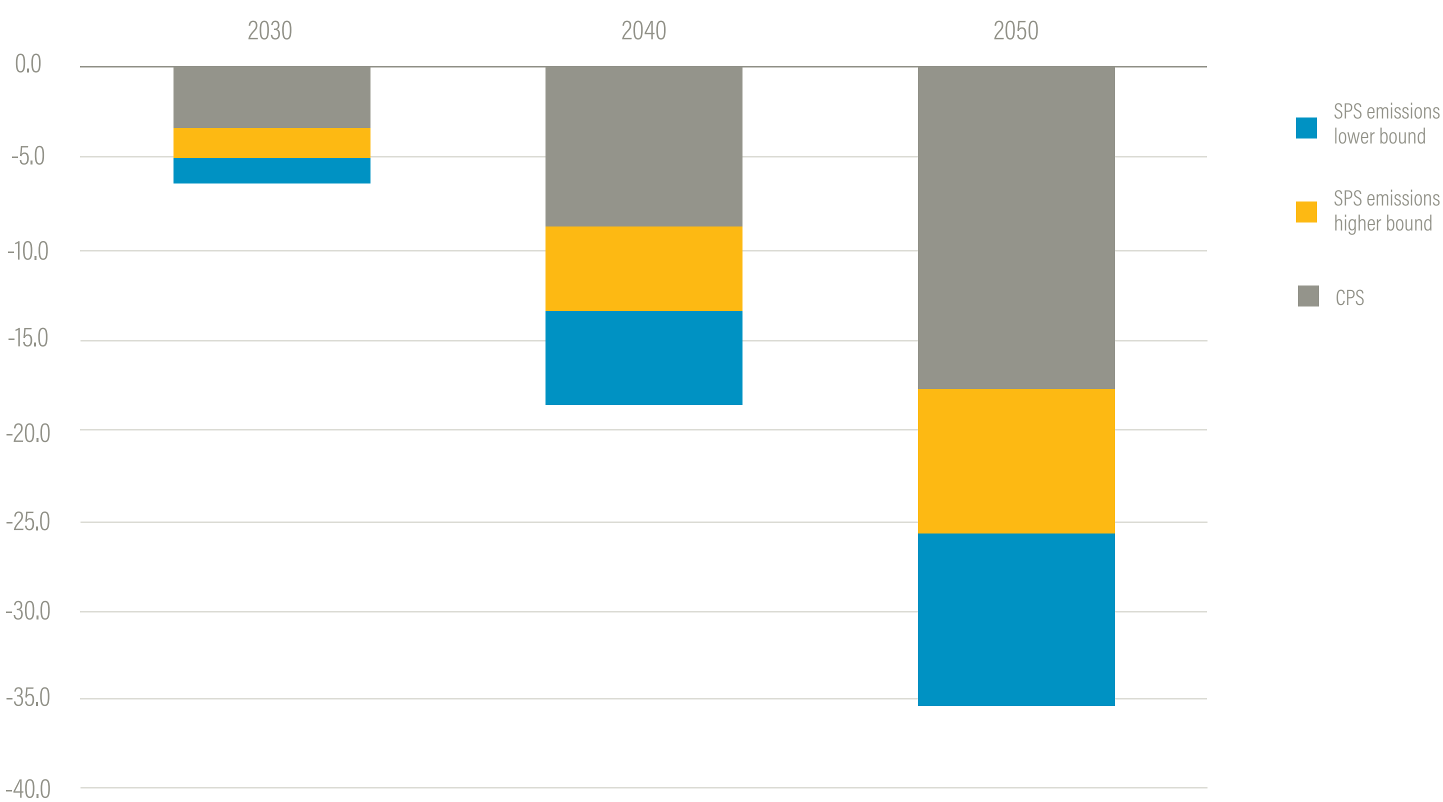
Unless there are specific policy targets, this study assumes that there is no autonomous technology improvement leading to reduced emissions over time. This may result in an overestimation of emissions.

Most important, the SPS—in particular, the upper bound of emissions—stresses feasibility rather narrowly; that is, it assumes proven technologies and measures that are immediately available at low financial cost, prior to factoring in the full economic benefits (e.g., cleaner air, improved health, less natural resource consumption, more energy security). In addition, only potential from the top seven emission sources under the CPS in 2030 is quantified, leaving many other cost-effective measures that target smaller emission sources unexplored. For example, beyond existing 2020 targets, it is feasible to further develop biogas by utilizing animal manure (NDRC and MOA 2017) and increase waste recycling to avoid methane emissions from MSW (NDRC and MOHURD 2016). It is also feasible to implement multiple measures to reduce SF_6 emissions from electrical equipment (EPA 2013; Zhou et al. 2018). As a result, the SPS does not reflect the full mitigation potential; rather, it aims to increase confidence to commit to more ambitious targets in the short term.

Even if emission targets are fully adopted, the SPS trajectory may not be sufficient to achieve the long-term goals of the Paris Agreement. As time progresses, new assessments will be necessary to inform the level of ambition in climate action.

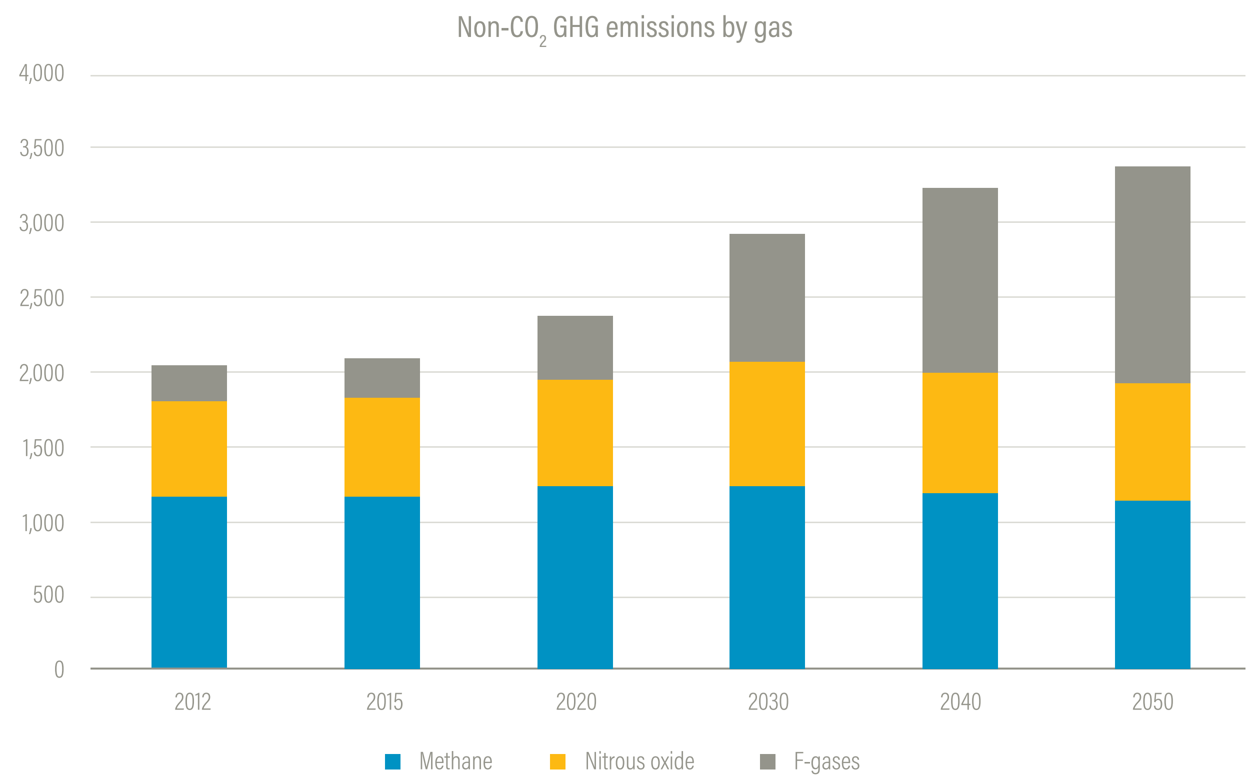
Appendices A and B present scenario assumptions, data, and quantification equations in more detail to enable a transparent assessment of results and conclusions.

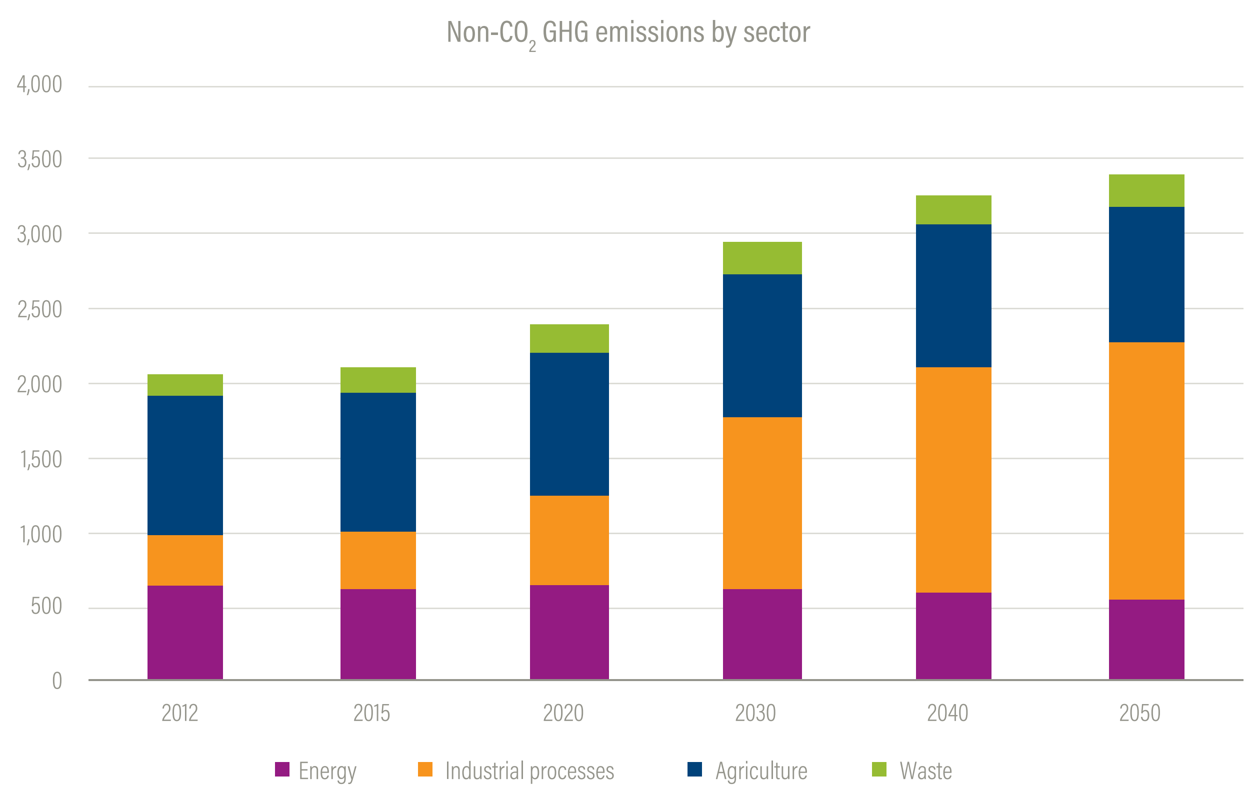
Figure 2 | **Cumulative Emissions Reduction since 2015 Compared to the Reference Scenario (Gt CO_2e)**



Source: WRI.

Figure 3 | **Non-CO_2 GHG Emissions under the Reference Scenario by Sector and by Gas (Mt CO_2e)**





Source: WRI.

FINDINGS

Summary of Trends in Non-CO_2 Greenhouse Gas Emissions

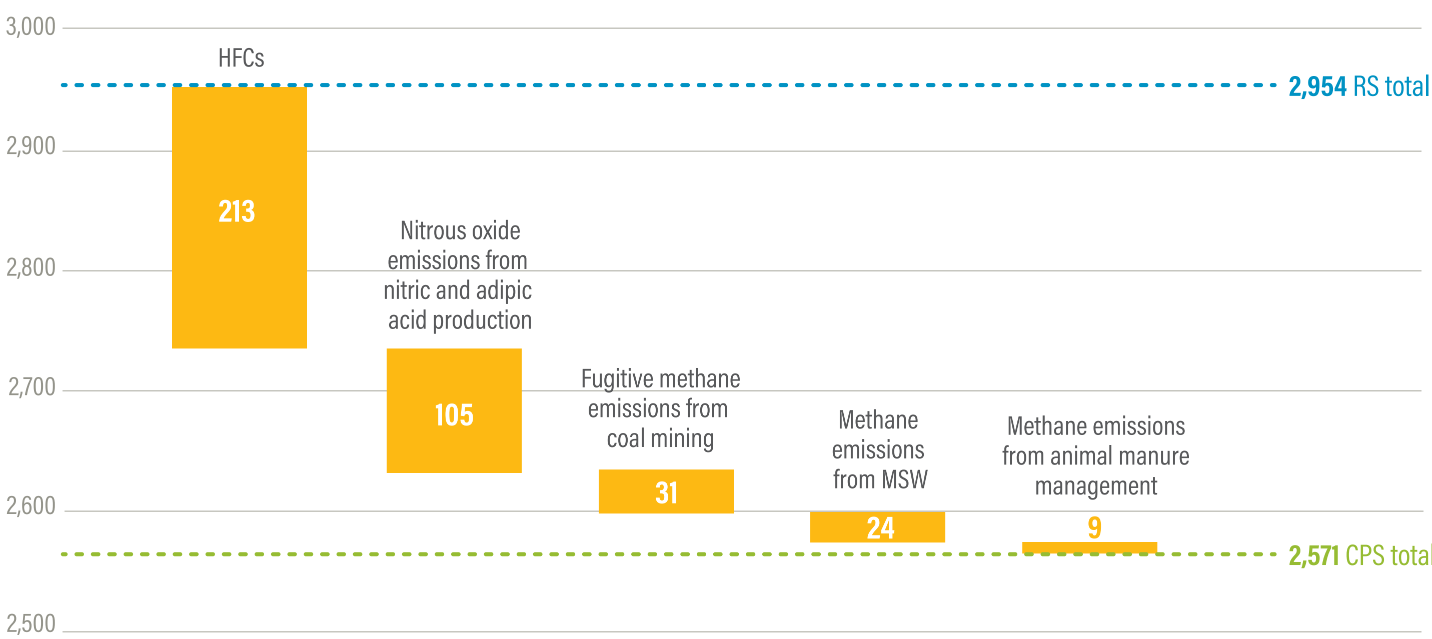
Annual emissions between 2012 and 2050 are illustrated in Figure 1. Under the RS, China's non-CO_2 GHG emissions would rise to around 2,954 Mt CO_2e in 2030 from less than 2,058 Mt CO_2e in 2012, a staggering 44 percent increase. After 2030, emissions would continue to rise another 15 percent to around 3,396 Mt CO_2e in 2050.

Policies since 2015 have fundamentally changed the trend for China's non-CO_2 GHGs. While emissions growth is projected to be around 16 percent between 2020 and 2030 under the CPS, it is estimated that non-CO_2 GHG emissions will remain flat between 2030 and 2040 at around 2,571 Mt CO_2e, followed by a more visible decline after 2040.

It is possible to reduce non-CO_2 GHG emissions beyond current policies. Under the SPS, China's non-CO_2 emissions could stabilize as early as 2020, a decade earlier, at a level that is roughly 13 percent lower than the CPS trajectory. With strengthened action, total non-CO_2 GHG emissions could return to the 2012 level sometime before 2030 (lower bound of emissions) or before 2050 (upper bound of emissions).

Climate change is casued by high concentration of GHGs in the atmosphere, which in turn is a result of cumulative GHG emissions. Therefore, the cumulative emissions should be of concern. The various scenarios also represent a significant difference in cumulative emissions since 2012, as illustrated in Figure 2. Compared with emissions under the RS, the CPS would cumulatively reduce 3.5 Gt CO_2e emissions by 2030, 9.0 Gt by 2040, and 17.8 Gt by 2050. On top of that progress, the SPS would further reduce 1.5–3.0 Gt CO_2e cumulative emissions by 2030, 4.6–9.6 Gt CO_2e by 2040, and 7.9–17.5 Gt CO_2e by 2050.

Figure 4 | **Reference Scenario and Current Policy Scenario Relating to Non-CO_2 GHG Emissions in 2030 and Sources of Mitigation (Mt CO_2e)**



Note: Numbers presented in this figure may not add up precisely due to rounding.
Source: WRI.

Trends under the Reference Scenario

Figure 3 provides a more detailed illustration of emission trends under the RS. While emissions from other sectors would either remain flat or level off over time, emissions from industrial processes would more than triple from 2012 to 2030, growing another 50 percent from 2030 to 2050. This is driven by strong projected demand for HFCs as China's cooling needs grow and while HFCs replace HCFCs at large scale as China phases out HCFCs based on its obligation under the Montreal Protocol. The projected strong demand for adipic acid, a major source of nitrous oxide emissions, also contributes significantly to the increase. The product demand for the automobile industry for the manufacturing of lightweight vehicles and the needs of the growing consumer electronics industry are the major drivers for the development of the adipic acid industry (GVR 2018).

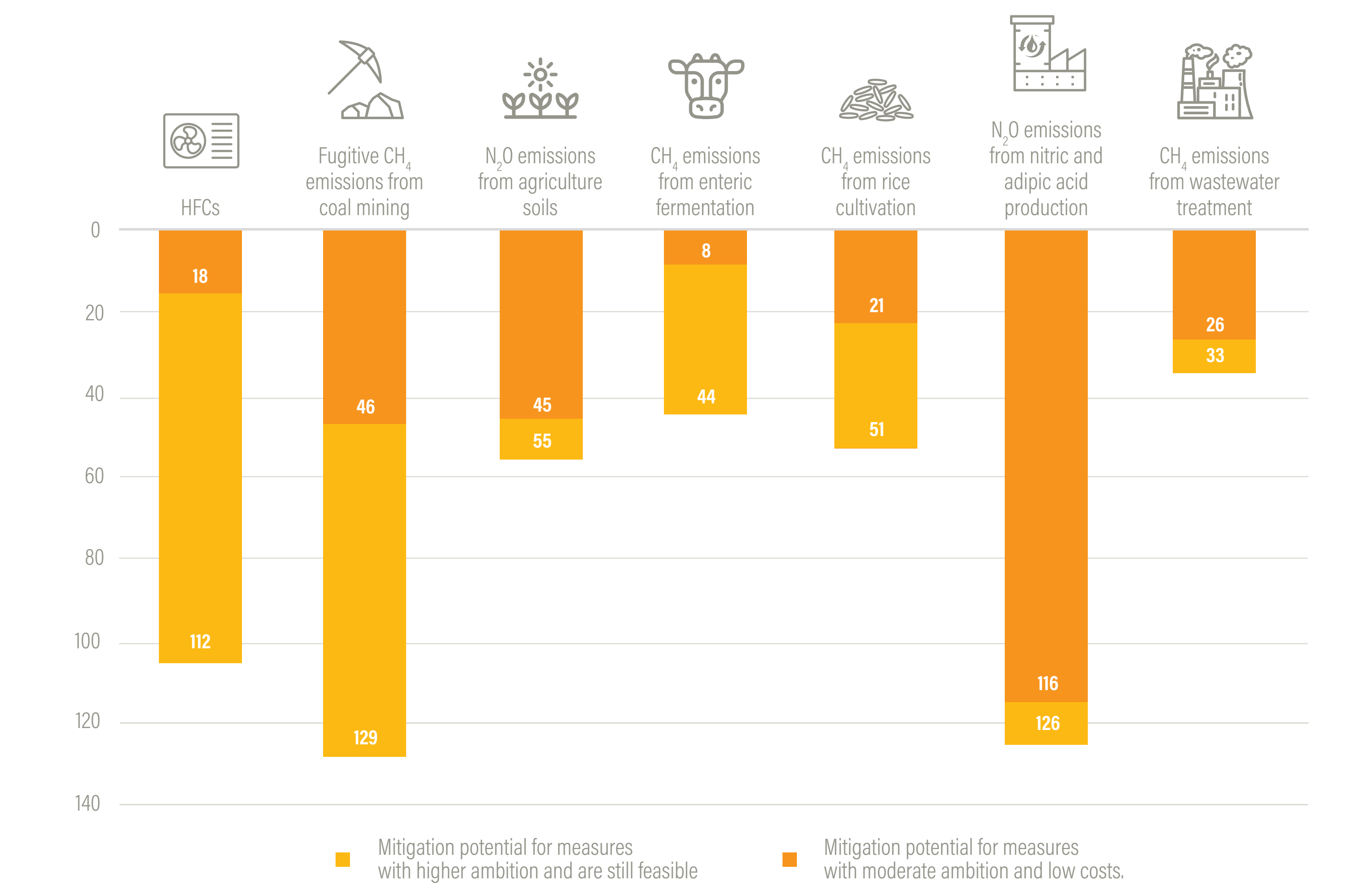
Trends under the Current Policies Scenario

Compared to emissions under the RS, the CPS would reduce around 383 Mt CO_2e in 2030, more than Ukraine's total GHG emissions in 2016 (UNFCCC n.d.b).

As illustrated in Figure 4, actions on HFCs contribute to a reduction of more than 200 Mt CO_2e, attributable to the Kigali Amendment, which reduces HFC-23 emissions to near zero by 2020 and limits the production and consumption of other HFCs in China beginning in 2024 (UN Environment Ozone Secretariat 2018). That being said, F-gases, in particular HFCs, would not stabilize until 2034 because of the effect of the delayed emissions.

China's commitment to achieving zero growth of nitrous oxide emissions from industrial processes by 2020 (GoC 2016) would also have a big impact, reducing 105 Mt

Figure 5 | **Range of Mitigation Potential by Source under the Strengthened Policies Scenario in 2030 (Mt CO_2e)**



Source: WRI.

CO_2e from nitric and adipic acid production. China's policy targets to increase coal mine methane recovery and utilization, improve MSW treatment, and develop rural biogas facilities, all stated in relevant sectoral 13th five-year plans (FYPs) after 2015, would result in reductions of 31 Mt CO_2e, 24 Mt CO_2e, and 9 Mt CO_2e, respectively.

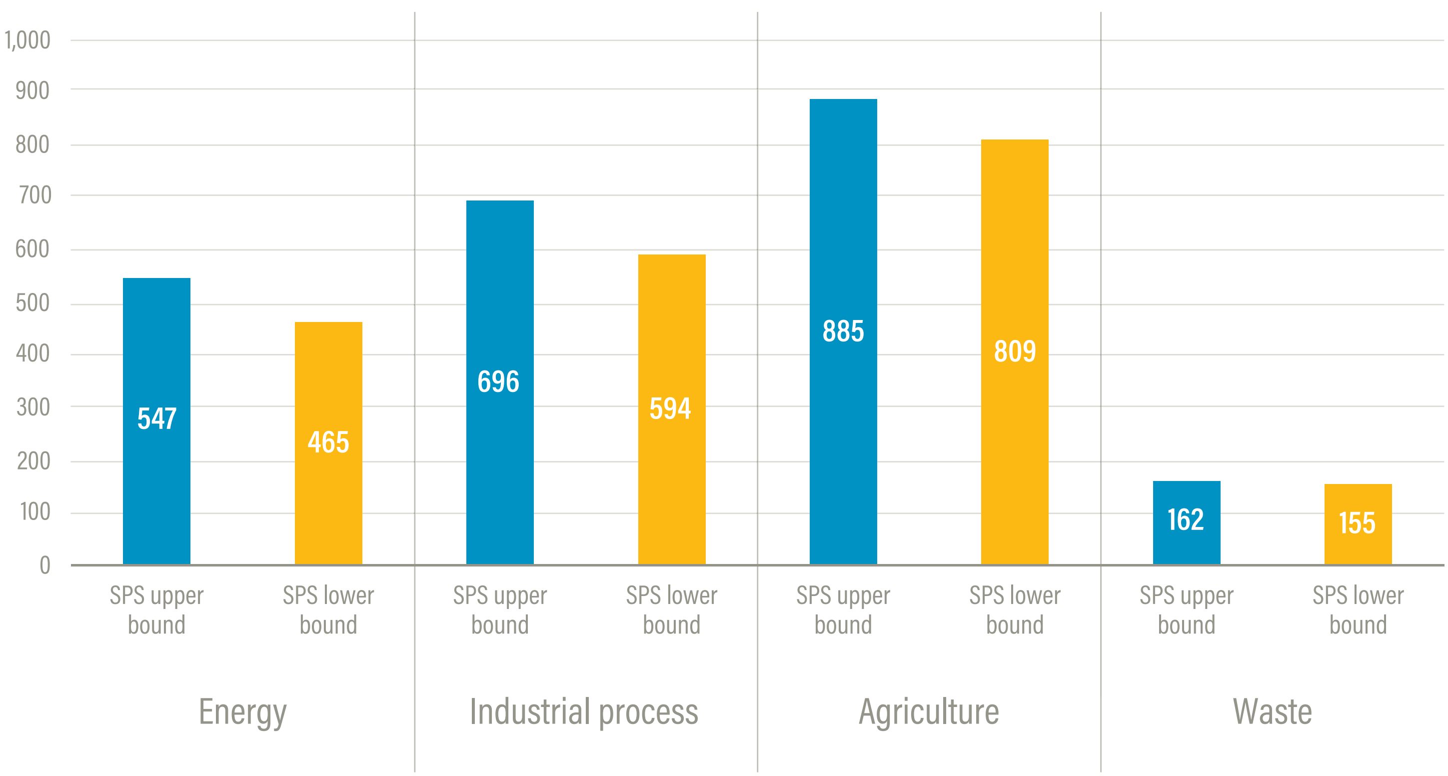
Trends under the Strengthened Policies Scenario

Figure 5 illustrates the range of mitigation potential for the top seven emission sources in 2030. Measures with the potential for greatest impact would be to accelerate the HFC phasedown; control coal production; and make mitigation of nitrous oxide from nitric and adipic acid production mandatory. If China were to only adopt those measures that have negative or modest costs under the SPS, the country would be able to reduce its emissions by 280 Mt CO_2e by 2030 compared to the CPS. With a more ambitious effort, China would almost double the impact, thus achieving 549 Mt CO_2e mitigation benefits in 2030 and maintaining its non-CO_2 emissions in 2030 at the 2012 level.

Figure 6 demonstrates the emissions in 2030 by sector. With strengthened action, agriculture and industrial processes would be the leading sectors for non-CO_2 GHG emissions in 2030.

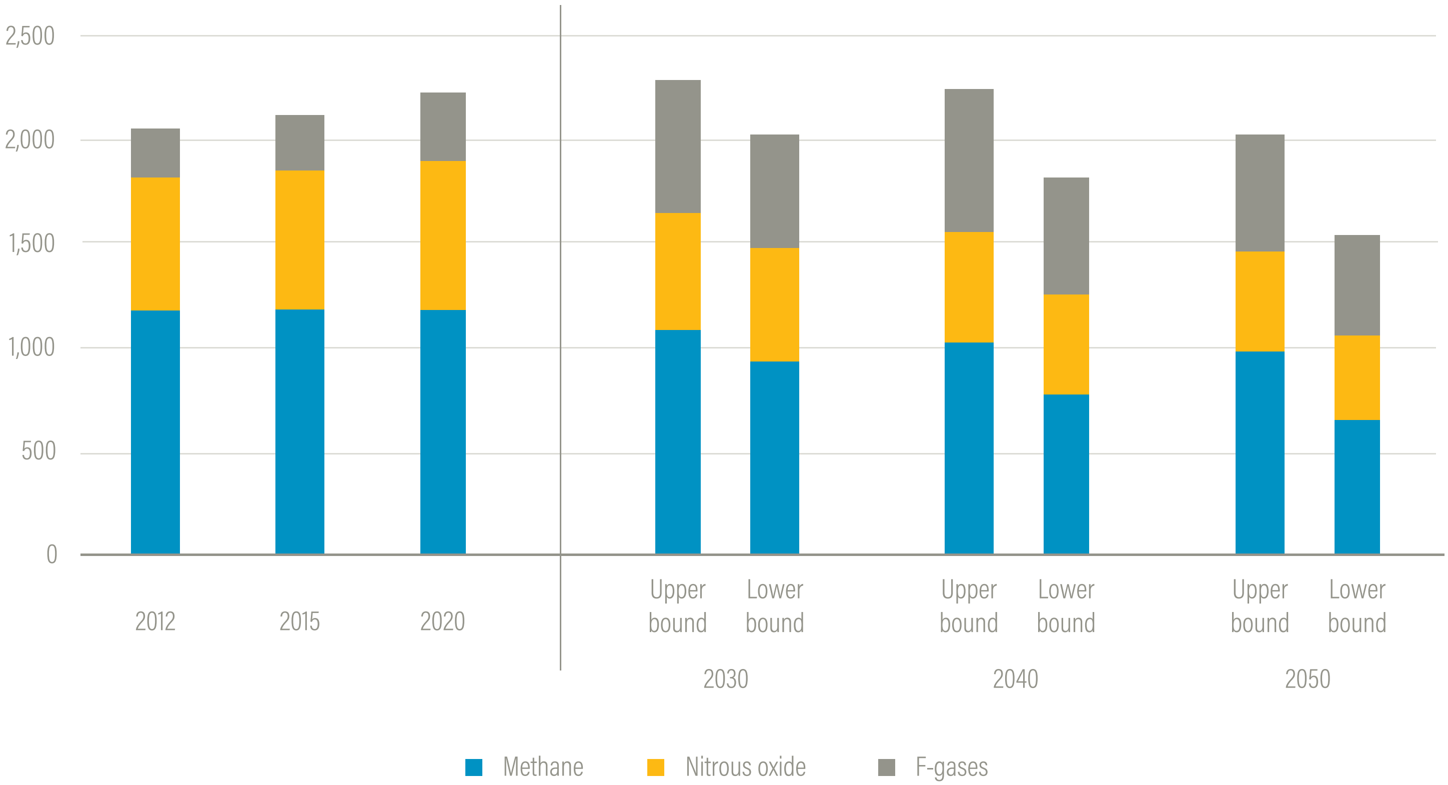
Figure 7 shows gas emissions over time. Methane would remain the largest non-CO_2 GHG, although it would stabilize by 2020. Despite an accelerated effort to phase down HFCs, however, F-gases would continue to grow by 80–128 percent (upper and lower bounds of emissions) between 2012 and 2030.

Figure 6 | **Emissions under the Strengthened Policies Scenario in 2030 by Sector (Mt CO_2e)**



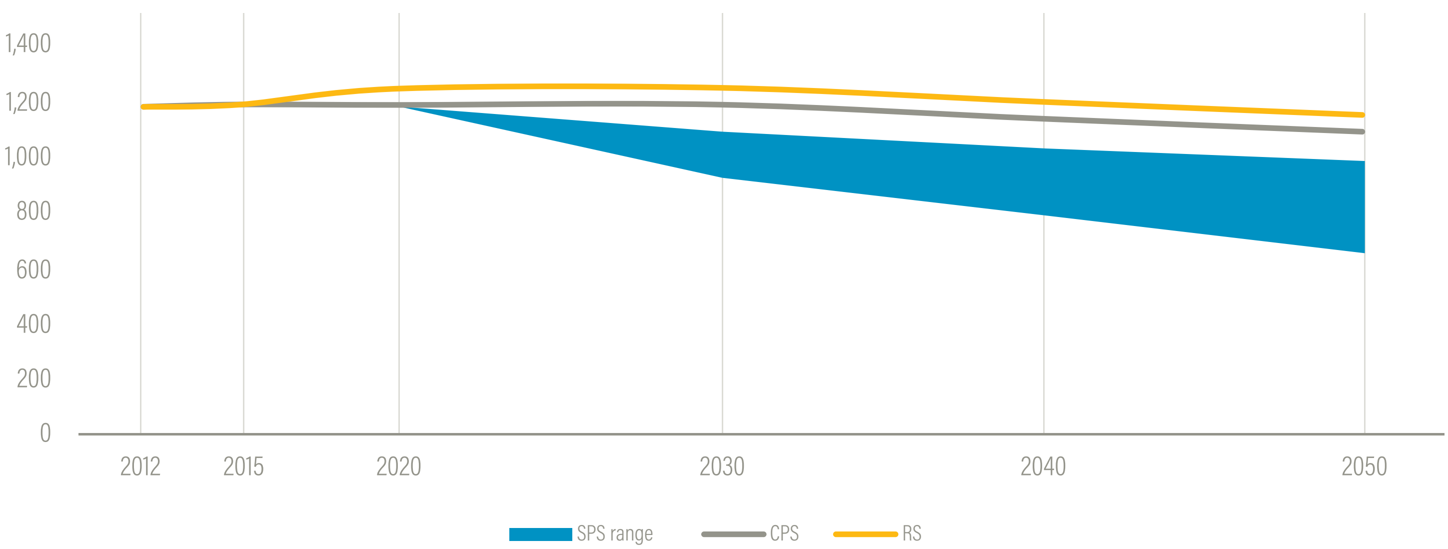
Source: WRI.

Figure 7 | Non-CO_2 GHG Emissions under the Strengthened Policies Scenario by Gas (Mt CO_2e)



Source: WRI.

Figure 8 | Methane Emissions under Various Scenarios (Mt CO_2e)



Source: WRI.

Trends for Methane Emissions

As shown in Figure 8, even under the RS, methane emissions will stabilize between 2020 and 2030 and then decline over time. The CPS would make methane stabilize one decade earlier, and then follow a trend of slow decline similar to the trend under the RS.

However, with strengthened actions, China has the potential to accelerate the decline much faster. Under the SPS, methane emissions can reduce 8–21 percent by 2030 compared to 2012. This is made possible by more ambitious and effective policies on coal mine methane, wastewater treatment, rice cultivation, and enteric fermentation.

Trends for Nitrous Oxide Emissions

Figure 9 shows that nitrous oxide emissions would continue to rise until 2030 under the RS. This is because without a policy to control industrial emissions, emissions from nitric and adipic acid production would keep growing until 2030.

Under the CPS, nitrous oxide emissions will be flat starting from 2020. On the one hand, the nitrous oxide emission zero growth target for industrial process, as set in the BUR, would reduce 105 Mt CO_2e in 2030 compared to the RS. On the other hand, the lack of additional policies and action would keep emissions at a relatively high level.

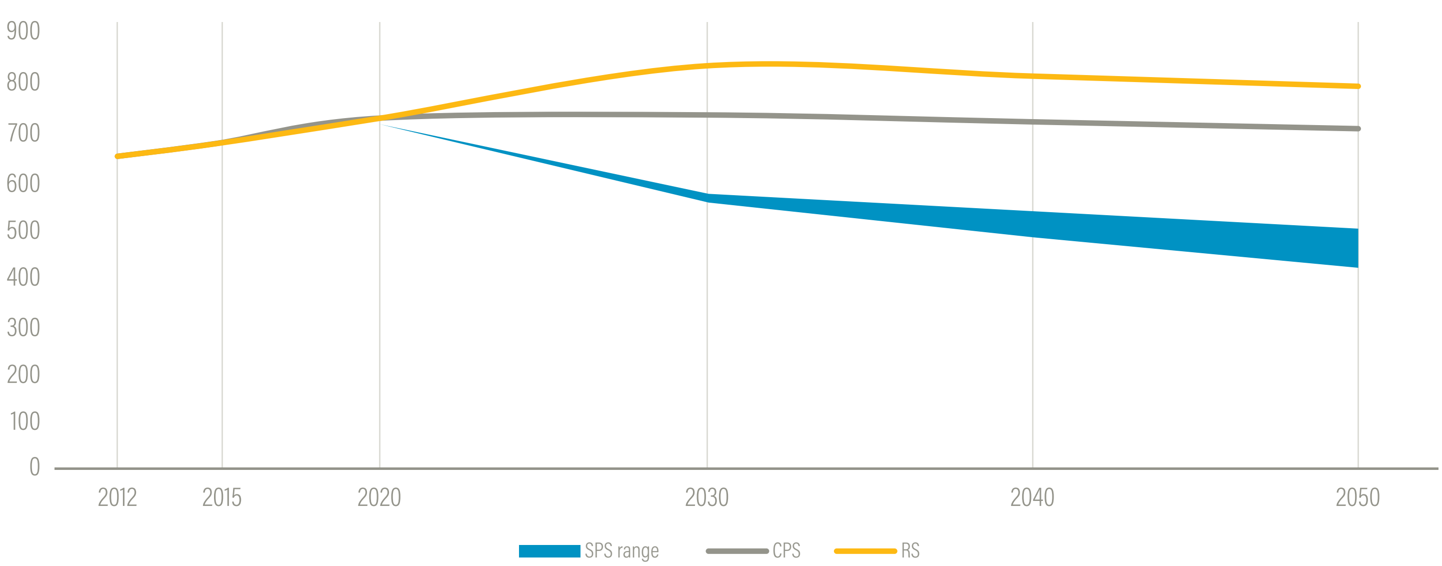
Under the SPS, nitrous oxide emissions would decrease dramatically between 2020 and 2030, and then continue to decrease over time. By 2030, nitrous oxide emissions would reduce 11–15 percent by 2030 compared to 2012. Much of the decrease is attributable to actions on nitric and adipic acid production, which would require all adipic acid production and 40 percent of the nitric acid production to mitigate emissions. Actions to reduce nitrogen fertilizer application, which enable emissions reduction from agriculture soil, would be attributable to the rest of the emissions reduction.

Trends for F-Gas Emissions

Under all scenarios F-gas emissions would grow significantly compared to 2012, as shown in Figure 10.

Under the RS, emissions would grow almost 500 percent by 2050 due to strong HFC demand and little regulation.

Figure 9 | **Nitrous Oxide Emissions under Various Scenarios (Mt CO_2e)**



Source: WRI.

Thanks to the Kigali Amendment, emissions under the CPS will rise to a much lower level, reaching 664 Mt CO_2e in 2030 and eventually declining to 588 Mt CO_2e in 2050. Although the Kigali Amendment would limit HFC consumption and production as early as 2024, the emissions would not peak until after 2030 because of the lag effect from a large amount of HFCs currently used in air conditioners and refrigeration equipment. Their emissions will be delayed until the repair or end of product life.

Under the SPS, accelerating the implementation of the Kigali Amendment could result in 18–112 Mt CO_2e emissions reduction in 2030 compared to the CPS.

The lower bound of emissions reduction can be achieved by imposing a limit on HFC consumption and production a few years earlier than the Kigali Amendment. Doing so would lower the costs of conforming to the Kigali Amendment: manufacturing equipment usually has a 10-year life cycle, and anticipating production and consumption limits and taking actions five years in advance would avoid the costs of stranded assets.

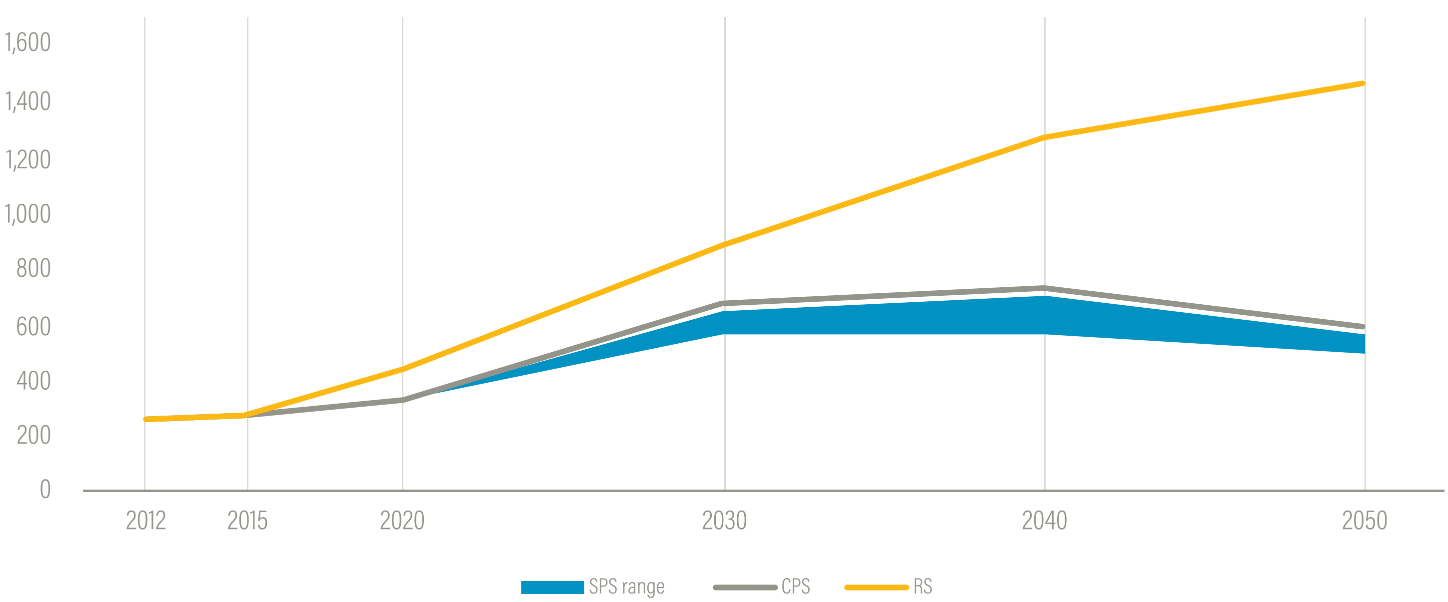
To achieve the higher end of reduction, China would need to replace 50 percent of HFC-134a and HFC-410a with HFO-1234yf and propane respectively by 2030. This is still feasible according to studies (Lin et al. 2018), which analyzes the application and patent status of HFO-1234yf as well as its production in Jiangsu Province. It also considers the use of propane and the pilot effort of the Midea Group in China.

COMPARATIVE ANALYSIS

While there are a few existing studies of China's non-CO_2 GHG emissions (EPA 2013; Fawcett et al. 2015; Lin et al. 2018; Yang et al. 2014; Yao et al. 2016; Zhang et al. 2018), only two studies have explicitly factored into China's policies as of 2015: Fawcett et al. (2015) and Lin et al. (2018).

Fawcett et al. (2015) apply a global integrated assessment model (GCAM) to develop emissions pathways for countries in relation to their 2015 national climate commitment, including China's non-CO_2 GHG emission projections. The study includes a Paris Agreement Continued scenario (PA-Continued) and a Paris Agreement Increased (PA-Increased) scenario. Both

Figure 10 | **F-Gas Emissions under Various Scenarios (Mt CO_2e)**



Source: WRI.

Table 2 | **Key Parameters of Compared Studies**

	GWP	BASE YEAR	BASE YEAR DATA SOURCE
WRI	SAR	2012	BUR data complemented by Fang et al. (2016) and EPA (2013).
LBNL	SAR	2010	Results from China 2050 Demand Resources and Energy Analysis Model. Published statistics were used to calibrate historic activity levels, and total emissions were calibrated against the BUR.
GCAM	AR4*	2010	Emission Database for Global Atmospheric Research

Note: GCAM results for methane and nitrous oxide are adjusted to SAR-GWP to enable comparison. Results for F-gases are not adjusted because of a lack of gas composition data.
Source: WRI.

scenarios assume that China will meet its NDC targets by 2030, albeit with different decarbonization rates beyond 2030. Since China's NDC does not include a top-line non-CO_2 quantitative target, the GCAM assumes equal marginal abatement costs across all sectors of the economy, including non-CO_2, and derives relevant reductions. The GCAM uses the IPCC AR4 GWP values (Fawcett et al. 2015).

Lin et al. (2018), from Lawrence Berkeley National Laboratory (LBNL), apply a bottom-up, end-use modeling approach to simulate drivers and their impact for non-CO_2 emissions from energy and nonenergy sectors alike. Lin et al. (2018) develop a reference scenario that is intended to reflect all adopted policies, including those in support of China's NDC, although they do not aim to reflect the outcome of NDC commitments or targets. The reference scenario does not assume the ratification of the Kigali Amendment, which is a part of the CPS and explains the 55 percent emissions difference between the CPS and RS. The LBNL study also develops a mitigation scenario that includes key cost-effective and currently available technologies, as well as mitigation measures that are being adopted by the Chinese market in the absence of specific policies. LBNL uses the IPCC SAR GWP values (Lin et al. 2018).

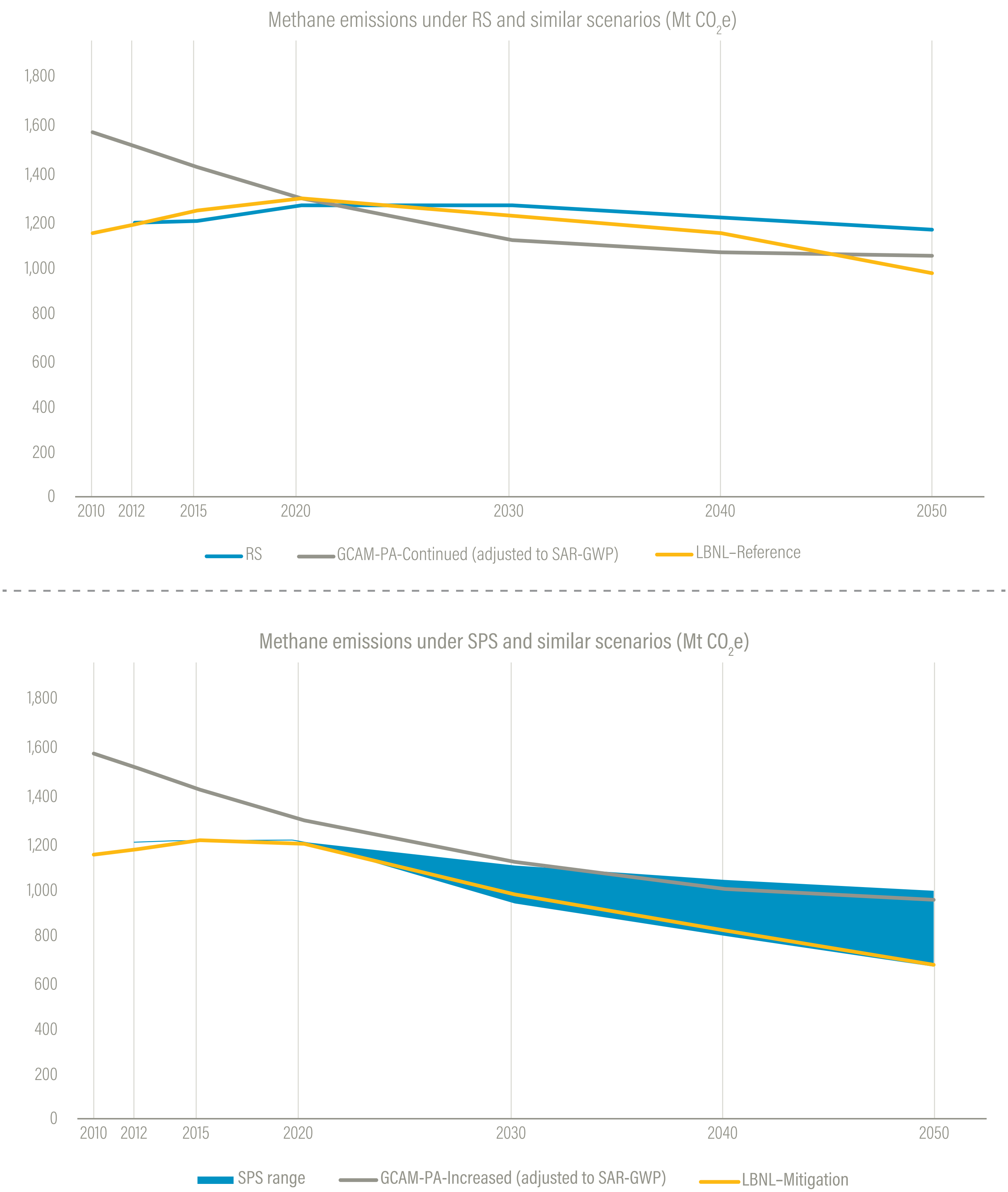
Based on scenario descriptions, the RS is most similar to the PA-Continued and Reference scenarios, while the SPS is most similar to the PA-Increased scenario and LBNL's mitigation scenario. There is no similar scenario to compare for the CPS. Table 2 summarizes the key features of the three studies.

Figure 11 compares methane emissions projections in which the GCAM's historic emissions are much higher than those of WRI and LBNL. This is because the GCAM sources sectoral data from the Emission Database for Global Atmospheric Research (EDGAR) and calibrates total emissions using the Representative Concentration Pathway (RCP), while WRI and LBNL either directly use or calibrate emissions with official data, which are known to have significant differences with EDGAR but are presumably more accurate and comprehensive.

Under all scenarios, the GCAM projects steep methane emissions reduction between 2012 and 2015, while both WRI and LBNL project a modest growth of emissions in the period. A recent study uses satellite data to conclude that coal mine methane emissions, which accounted for around 43 percent of China's total methane emissions in 2012, had a slight increase during the period (Miller et al. 2019). LBNL and WRI's projections are more aligned with the trend in Miller et al. (2019).

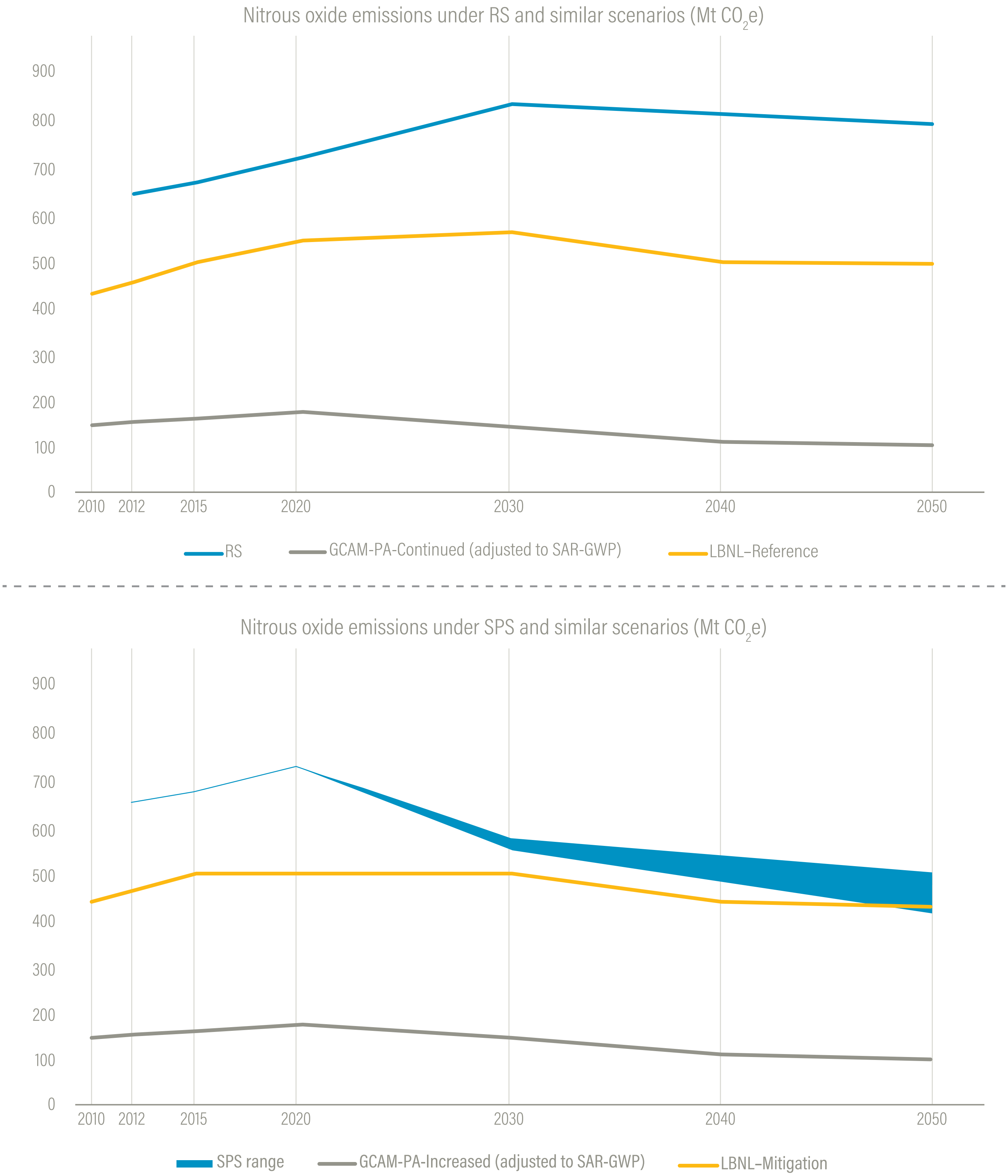
Nevertheless, under the RS and similar scenarios, emissions are projected to either stabilize or decline by 2030 in all studies. The variances in trends can perhaps be explained by the different projections for energy production, especially that of coal.

Figure 11 | **Methane Emissions Projection: A Comparison**



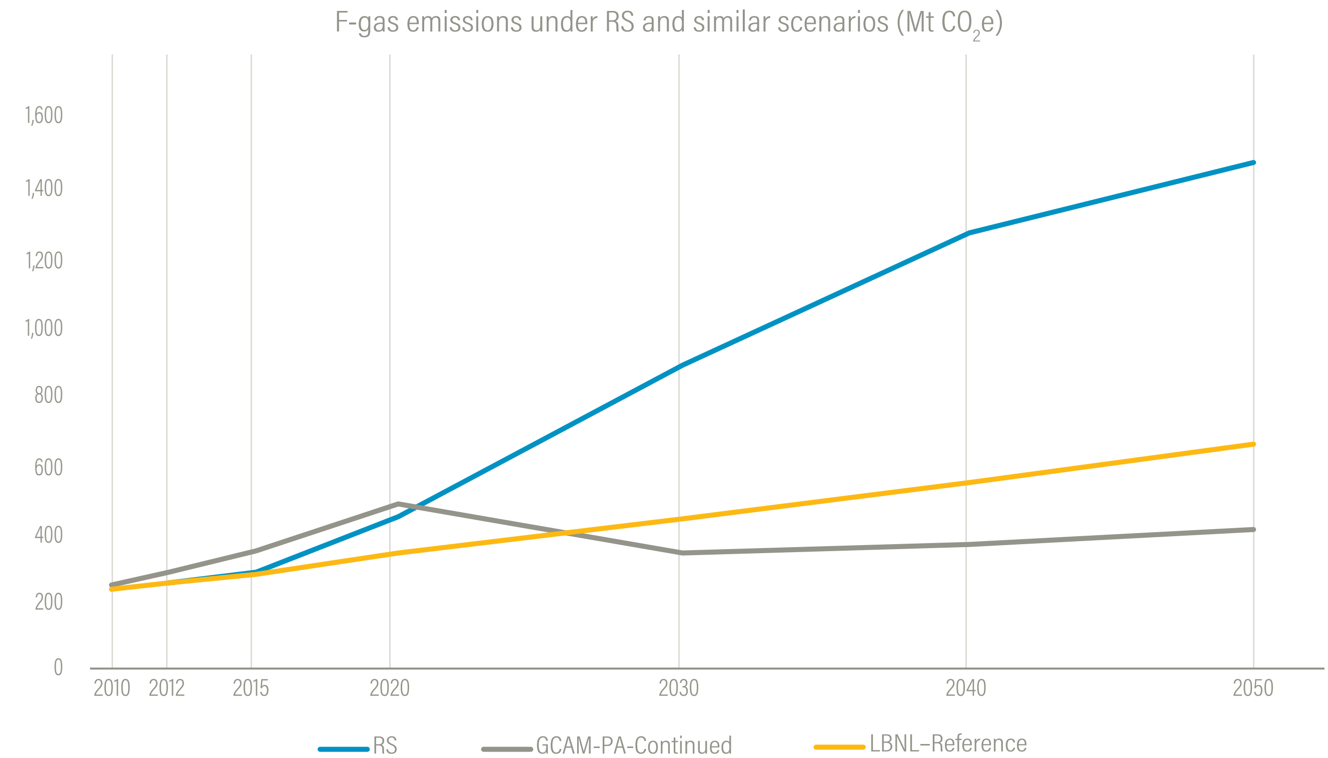
Sources: WRI based on Fawcett et al. (2015) and Lin et al. (2018).

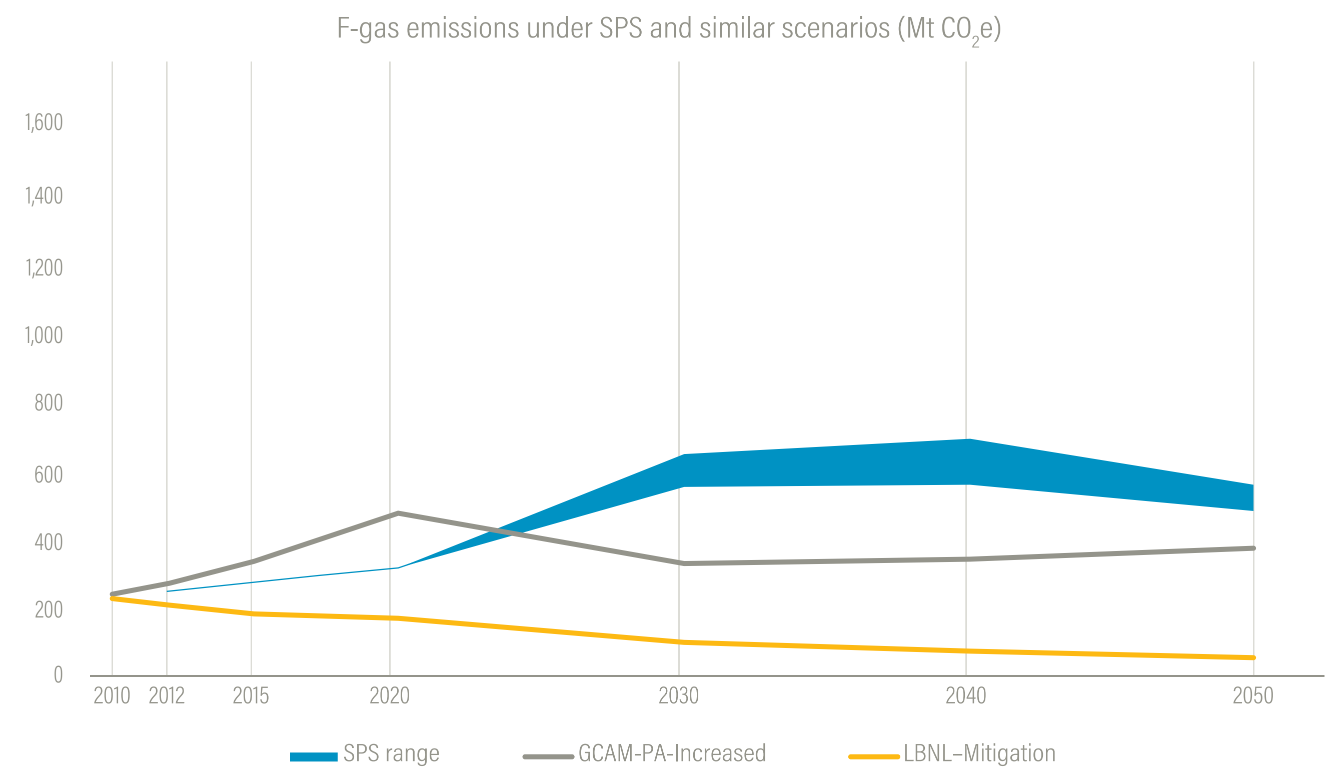
Figure 12 | Nitrous Oxide Emissions Projection: A Comparison



Sources: WRI based on Fawcett et al. (2015) and Lin et al. (2018).

Figure 13 | **F-Gas Emissions Projection Comparison**





Sources: WRI based on Fawcett et al. (2015) and Lin et al. (2018).

Under the SPS and similar scenarios, projections share a similar trend toward potential reduction. The SPS range overlaps with both the GCAM (close to the upper bound of emissions) and LBNL (close to the lower bound of emissions).

WRI,the GCAM, and LBNL have significant variances in historic emissions relating to nitrous oxide (see Figure 12). The GCAM does not include nitrous oxide emissions from agriculture sources, which account for around 59 percent of total nitrous oxide emissions in 2012. The same emission source also explains the difference between WRI and LBNL results, as LBNL has a much lower estimate than the official (and WRI) data.

Under the RS and similar scenarios, LBNL assumes that nitric and adipic acid production will peak by 2020, while WRI assumes the production will not peak until 2030, based on the 2024 global market outlook (GVR 2018). This probably explains the difference in post-2020 trends.

Under the SPS and similar scenarios, WRI and LBNL also project different mitigation potentials for nitrous oxide. This is because LBNL excludes mitigation measures for nitric and adipic acid production in its mitigation scenario based on more conservative perspectives from experts interviewed by LBNL. WRI adopts more optimistic assumptions on mitigation measures' costs and their penetration based on Chinese and international literature and other countries' practices (EPA 2013; Schneider and Cames 2014; Yang et al. 2014).

The studies have significantly different projections for F-gases, as illustrated in Figure 13. Besides using different modeling methods, the GCAM uses different data sources and GWP values than do WRI and LBNL. Differences between WRI and LBNL projections may be due to a combination of factors. First, WRI's study has more comprehensive coverage of F-gas emissions. WRI includes F-gas emissions from photovoltaic and flat panel display manufacturing, as well as emissions from HFC-143a, HFC-152a, and HFC-245fa. LBNL does not include these sources, which accounted for around 35 percent of the F-gas emissions difference between WRI and LBNL studies in 2030 under the RS or similar scenarios.

Second, studies have different historic emission values for some gases. For example, between 2012 and 2030 under the RS or similar scenarios, WRI and LBNL project a very similar growth rate for HFC-134a (378 percent and 372 percent, respectively). However, the 2012 emissions in LBNL's study are only 27 percent of the BUR reported value, which was used by WRI. HFC-134a accounts for 23 percent of the difference between WRI and LBNL studies in 2030 under the RS or similar scenarios.

Last but not least, the studies use different methods and assumptions. For example, WRI and LBNL use similar historic emissions for HFC-125 from air conditioning and refrigerators and other F-gas emissions from metal and semiconductor manufacturing in 2012, but WRI projects much faster growth in these areas than LBNL. HFC-125 and other F-gas emissions from metal and semiconductor manufacturing account for 32 percent of the difference between WRI and LBNL studies in 2030 under the RS or similar scenarios.

DISCUSSION

Mitigating non-CO_2 GHG emissions has significant environmental and development benefits in addition to climate benefits. Because methane emissions increase tropospheric ozone, which is a major component of smog, mitigating methane will help improve air quality and reduce premature deaths from lung or cardiovascular diseases, especially among children and the elderly. By preventing tropospheric ozone formation, methane reduction will also benefit food production and ecosystem protection (CCAC n.d.). And because nitrous oxide emissions deplete stratospheric ozone, reducing nitrous oxide emissions will reduce skin cancers and eye diseases and protect food production (Leaf 1993).

Measures adopted to mitigate non-CO_2 GHGs also have significant development benefits. Coal mine methane recovery improves industrial safety by reducing the risk of explosions. Reducing methane emissions from landfills will also reduce odors, a major source of public complaints. Cai et al. (2018) conclude that methane reduction measures at landfill sites can greatly reduce the odors associated with the process as well as the size of the affected population in China. Captured methane, when utilized, is a clean fuel that emits fewer air pollutants and reduces energy costs. There are also cost-saving benefits from nitrous oxide mitigation. For example, Kanter et al. (2015) estimate that Chinese farmers can save as much as 20 percent in fertilizer costs over 20 years when the right implementation strategy is used to reduce nitrogen fertilizer application.

Table 3 | **Key Mitigation Measures to Support Higher Ambition**

EMISSION SOURCES	AMBITION LEVEL[A]	MITIGATION MEASURES	JUSTIFICATION FOR FEASIBILITY
HFCs	Modest	Freeze HFC production at 90% of the allowed baseline level from 2024 to 2029 and linearly phase down HFC production to meet the Kigali Amendment commitment.	Controlling production in anticipation of the upcoming phasedown will avoid overcapacity of stranded assets.
	High	In addition to measures with modest ambition level, replace 50% of HFC-134a and HFC-410a with HFO-1234yf and propane, respectively, in 2030 and increase the replacement rate over time.	Expert judgment based on current market conditions, as well as patents and pilots in China (Lin et al. 2018).
Methane from coal mining	Modest	Require the utilization or flaring of all coal mine methane emissions beyond 9% concentration.	The measure has low implementation cost (\$0.5–\$11/t CO_2e), especially when applied to relatively high-concentration coal mine methane (Yang et al. 2014).
	High	In addition to measures with modest ambition level, reduce coal consumption to less than 2,000 Mtce by 2030.	Feasible according to a series of original analyses conducted by the China Coal Cap Plan and Policy Research Project (2016), which has incorporated input from a wide range of researchers and stakeholders, including key industry associations.
Nitrous oxide from nitric and adipic acid production	Modest	Require nitrous oxide mitigation for all adipic acid and major nitric acid manufacturers by 2030.	The measures have low implementation costs even when excluding CDM support: \$0.12–\$1.35/t CO_2e for adipic acid and \$0.2–\$10/t CO_2e for nitric acid (secondary treatment). Adipic acid manufacturing is very concentrated. Nitric acid manufacturing is less concentrated but still has a manageable number of facilities. Therefore, regulation should be easier to implement (EPA 2013; Schneider and Cames 2014; Yang et al. 2014).
	High	Accelerate implementation measures with modest ambition level and expand the requirement to smaller nitric acid manufacturers.	
Nitrous oxide from agricultural soils	Modest	Promote best practices in the management of fertilizers; reduce nitrogen fertilizer application for rice, wheat, maize, and cash crops.	The measures have negative costs (Wang et al. 2014).
	High	Set the nitrogen fertilizer application reduction target starting from 2020. In 2050, the nitrogen fertilizer application is reduced to 50% of the 2015 level.	Expert judgement (Li 2018; Lin et al. 2018).

Table 3 | **Key Mitigation Measures to Support Higher Ambition (continued)**

EMISSION SOURCES	AMBITION LEVEL[A]	MITIGATION MEASURES	JUSTIFICATION FOR FEASIBILITY
Methane from enteric fermentation	Modest	Promote animal breeding,and the addition of probiotics and tea saponins, among other measures to improve the nutritional balance of animal feed.	The measures have negative costs (Wang et al. 2014).
	High	Improve the nutritional balance of livestock feed and improve feed digestibility to increase the meat and dairy production rate.	Expert judgment (Lin et al. 2018).
Methane from rice cultivation	Modest	Improve irrigation and fertilizer use.	These measures have negative costs and could be further implemented in China (Li 2018; Lin et al. 2018; Tian et al. 2018).
	High	In addition to measures with modest ambition level, pilot and promote the use of nitrification inhibitor, slow-release fertilizer, and biochar.	Literature review and expert judgement (Li 2018; Linquist et al. 2012; Xiao et al. 2018).
Methane emissions from wastewater treatment	Modest	Require methane recovery systems for all new and major existing anaerobic wastewater treatment plants (domestic and industrial).	The measure has acceptable implementation costs (\$7–\$9/t CO_2e), and there is significant potential based on the current status of wastewater treatment plants in China (Cai et al. 2015; Yang et al. 2014).
	High	Implement measures with modest ambition level with an accelerated schedule and expand the requirement to more facilities.	
Methane emissions from animal manure	Not assessed	Set and meet ambitious biogas development targets for rural biogas and animal farms in the 14th FYP and beyond.	NDRC and MOA (2017) estimate that China has a biogas production potential of around 122.7 billion cubic meters. The 13th FYP target, even if fully met by 2020, will account for less than 17% of the potential.
Methane emissions from solid waste	Not assessed	Set and meet ambitious waste recycling targets in the 14th FYP and beyond.	China is already making efforts to increase recycling in key cities during the 13th FYP (NDRC and MOHURD 2016). It should be feasible to set up a national recycling target at a later stage.
Sulfur hexafluoride emissions from power equipment	Not assessed	Promote practices of SF_6 recycling, substitution, leak detection and repair, and equipment refurbishment. Further measures to reduce electricity demand will also help mitigate emissions.	Relevant measures are sourced from Zhou et al. (2018) and EPA (2013). The EPA estimates that most measures cost less than \$2/t CO_2e.

Note: a. Measures aligned with the upper bound of emissions for the SPS are considered modest ambition level, and measures aligned with the lower bound of emissions for the SPS are considered high ambition level.
Source: WRI.

Early actions for HFCs would reduce costs to conform to Kigali Amendment obligations. According to the Kigali Amendment, China would need to curb HFC emissions and production starting in 2024. By anticipating this restriction ahead of time, China can limit the construction of new facilities and mitigate economic losses as a result of stranded assets.

Mitigation measures are readily available. This paper has identified mitigation measures to meet the assumptions needed to achieve the SPS. Table 3 summarizes these measures and corresponding justification for feasibility.

Emissions trading schemes could drive non-CO_2 GHG reduction. As most mitigation measures have low costs, emissions trading schemes (ETSs) could be used to reduce non-CO_2 GHG emissions. This is particularly true for nitrous oxide emissions from nitric and adipic acid production as well as F-gas emissions from aluminum, integrated circuit, flat panel display, and photovoltaic manufacturing, as these sources tend to be concentrated in a smaller number of industrial facilities and the associated emissions are generally easy to measure, report, and verify. Due to the high GWP values of non-CO_2 GHGs, companies should be motivated to reduce non-CO_2 GHG emissions if these gases are included in the ETS.

In its first phase, China's national ETS covers only the power sector and CO_2 emissions. By expanding the ETS coverage to above-mentioned industries and including non-CO_2 GHGs in subsequent phases, China can unlock significant mitigation potential.

RECOMMENDATIONS

Based on relevant findings, this paper recommends that China adopt ambitious and precise targets for non-CO_2 GHGs in its new or updated NDC in 2020, implement actions correspondingly, and identify further ways to reduce emissions by 2025. More ambitious NDCs will be critical to achieving the goals of the Paris Agreement. To be considered ambitious, the full implementation of the new or updated NDC should result in lower cumulative emissions than the fully implemented existing NDC (Fransen et al. 2017).

China does not have a quantitative top-line target for non-CO_2 GHGs in its current NDC. China supports the Kigali Amendment but has yet to ratify it. The target to achieve zero growth of industrial nitrous oxide emissions in 2020, while communicated in China's first BUR, was not a part of its first NDC in 2015. As these two policies account for more than 80 percent of emissions reduction between the RS and CPS, it is important that the new or updated NDC fully capture the emissions reduction from these policies.

Taking actions on non-CO_2 GHGs can demonstrate China's climate leadership and signal strong commitment to meeting the goals of the Paris Agreement. This paper demonstrates that it is feasible for China to reduce an additional 1.5–3.0 Gt cumulative CO_2e emissions from non-CO_2 GHGs by 2030. Because of the development and climate benefits, China should go beyond current policies and adopt one or more options to enhance its NDC as outlined below. These options are not mutually exclusive.

Option 1: Set an ambitious economy-wide GHG target. An ambitious GHG target should first of all take into account opportunities to enhance its CO_2 mitigation beyond what is specified in the current NDC. Additionally, the GHG target should reflect a commitment that non-CO_2 GHG emissions will stabilize starting in 2020 and that those emissions will begin to decline as early in the decade as possible.

Option 2: Set an ambitious economy-wide non-CO_2 GHG target. An ambitious non-CO_2 GHG target should stabilize emissions starting in 2020. Those emissions will begin to decline as early in the decade as possible.

Option 3: Set ambitious gas-specific reduction targets. Ambitious gas-specific reduction targets should cover a majority of non-CO_2 GHGs, including an 7–21 percent methane emissions reduction and a 7–11 percent nitrous oxide emissions reduction by 2030 compared with 2014, and commit to taking early actions to emit fewer HFCs cumulatively than the limit required under the Kigali Amendment.

Option 4: Commit to implementing ambitious source-specific actions. As an initial step, policymakers should implement all the measures and targets listed in Table 3.

Options 1, 2, and 3 have the advantage of clearly communicating the overall impact on GHG emissions, as adopting Option 4 alone may make it challenging to understand the aggregate impact of the NDC. Options 1 and 2 also give China more flexibility to meet relevant targets, since the country can make up less-than-ideal performance in one area with over performance in others. In contrast, Options 3 and 4 would provide more specificity and clarity to regulators, businesses, investors, and consumers.

Even if China fully adopts the above recommendations, the emissions reduction is probably not enough to be compatible with the 2˚C goal, let alone the 1.5˚C goal, of the Paris Agreement (Robiou du Pont and Meinshausen 2018). However, with technology progess and maturity over time, the scope of low cost and feasible mitigation options is likely to expand. More up-to-date data, emerging economic and social trends, and new research could also generate new policy insights to increase mitigation potential. For these reasons, in a couple of years, policymakers should reassess China's mitigation potential for non-CO_2 GHGs, with the intention of boosting the country's mitigation ambition by 2025.

APPENDIX A. METHODOLOGY AND KEY ASSUMPTIONS FOR THE PROJECTION OF CHINA'S NON-CO_2 GREENHOUSE GASES UNDER VARIOUS SCENARIOS

Basic Assumptions

Gross Domestic Product

This study applies the average of available GDP growth projections of those organizations with reputable economic research capacity. In terms of projections relating to 2018–20, the average derives from IEA (2017a, 2017b), IMF (2017), OECD (n.d.), and World Bank (2018). For those relating to 2021–40, the average has been drawn from IEA (2017a, 2017b) and OECD (n.d.). The average figures for 2041–50 are published by IEA (2017a) and OECD (n.d.). Since China's economy has undergone significant change in the past few years, only projections made after 2017 are included. Table A1 provides the assumed GDP growth rate.

Population

Because of a lack of alternative projections, this paper assumes that activity data related to certain emissions sources under some scenarios will move in proportion to population change after a certain date. These assumptions are based on the author's judgment that per capita demand will become stable as China's economy matures, so total activity data would then be driven mostly by population change. Table A2 details the relevant activity data and impacted scenarios and periods.

China's Population Project is sourced from UN DESA (2017). This paper interpolates to determine projected populations for years without UN DESA data. Table A3 provides the assumed population projection.

Emissions in 2012

Most emissions in 2012 are sourced from China's First BUR (GoC 2016), except for the following:

- For HFC-32, HFC-125, HFC-143a, and HFC-152a, the BUR does not include emissions from consumption. Since consumption accounts for the majority of these gas emissions, this paper draws emission estimates from Fang et al. (2016).

The BUR does not include data for PFC, SF_6 and NF3 emissions from semiconductor, flat panel display, and photovoltaic manufacturing. Emissions herein are calculated by applying 2012 emission estimates in EPA (2013).

Energy Sector

Methane and Nitrogen Dioxide Emissions from Fuel Combustion

Under all scenarios, this paper assumes that emissions are proportional to the total primary energy demand from fossil fuel, data for which were sourced from the 13th FYP for Energy Development (NDRC 2016a) and World Energy Outlook (WEO) 2017 (IEA 2017b) under the New Policies Scenario (NPS). Projections between 2041 and 2050 are extrapolated based on WEO NPS projections between 2030 and 2040. This paper uses the NPS rather than the CPS under the WEO because the NPS assumes policy targets that are aligned with China's NDC commitment in 2015, thus befitting the definition of the CPS for the purposes of this paper. Table A4 shows the assumed total fossil fuel demand under all scenarios.

Table A1 | **Assumed GDP Growth Rate**

	2018-20	2021-25	2026-30	2031-35	2036-40	2041-45	2046-50
Assumed GDP growth rate	6.45%	5.28%	4.96%	3.25%	3.03%	1.63%	1.53%

Sources: Average of projections from IEA (2017a, 2017b); IMF (2017); OECD (n.d.); and World Bank (2018).

Table A2 | **Emissions Sources, Scenarios, and Period where Activity Data Are Assumed to Move in Proportion to Population Change**

EMISSIONS SOURCES	IMPACTED SCENARIOS	IMPACTED PERIOD
Nitric and adipic acid production	RS	2031–50
HFC-143a, HFC-245fa, HFC-152a, HCFC-141b, HCFC-142b, HFC-134a (via light vehicle sales)	RS	2031–50
Metal production (aluminum)	RS, CPS, and SPS	2041–50
Integrated circuit manufacturing	RS, CPS, and SPS	2031–50
Flat panel display manufacturing	RS, CPS, and SPS	2031–50
Rice cultivation	RS, CPS, and SPS	2031–50
Enteric fermentation and animal manure management (via inventory of beef cattle, dairy cows, goats, sheep, and pigs)	RS, CPS, and SPS	2031–50
Agricultural soils (via nitrogen fertilizer application)	RS, CPS, and SPS	2031–50
Solid waste (via waste generation)	RS, CPS, and SPS	2031–50
Methane emissions from wastewater (via industrial wastewater)	RS, CPS, and SPS	2020–50
Methane emissions from wastewater (via domestic wastewater)	RS, CPS, and SPS	2030–50
Nitrous oxide emissions from wastewater	RS, CPS, and SPS	2013–50

Source: WRI.

Fugitive Emissions from Coal Mining

This paper first quantifies 2012 methane emissions before methane recovery and utilization by using BUR data (GoC 2016) and the 2012 coal mine methane utilization rate (Huang 2013). It then quantifies future methane emissions before abatement by assuming that they change in proportion to projected coal production. Finally, future fugitive emissions are quantified by subtracting projected utilized methane from emissions before recovery and utilization.

Coal production data between 2012 and 2040 derive from China Energy Year Book (NBS 2017), China 13th FYP for Coal Industry Development (NDRC and NEA 2016), Research Report on the 13th FYP Midterm Review and Outlook (China Coal Cap Plan and Policy Research Project 2018), and WEO NPS (IEA 2017b). Projections between 2041 and 2050 are extrapolated based on WEO NPS projections between 2030 and 2040. This paper uses the NPS instead of the CPS under WEO because the NPS assumes policy targets that are aligned with China's NDC commitment in 2015, thus befitting the definition of the CPS for the purposes of this paper.

Methane utilization rates for 2015 and 2020 are sourced from NEA (2017). Since China's coal mine standard for coal mine methane gas emissions is lower than 30 percent concentration (MEP and GAQSIQ 2008), and methane with a concentration level of more than 30 percent is considered easily utilized, this paper assumes recovered but not utilized coal mine methane were emitted.

RS: Assumes methane utilization stays at a 2015 level after 2015.

Table A3 | **Assumed Population**

	2017	2020	2030	2040	2050
Assumed population	1,409,517	1,416,762	1,441,182	1,402,820	1,364,457

Source: UN DESA (2017).

Table A4 | **Assumed Total Fossil Fuel Demand under All Scenarios**

	2012	2020	2030	2040	2050
Total fossil fuel demand (Mt CO_2e)	3,631	4,250	4,227	4,130	4,035

Sources: IEA (2017b); author's extrapolation.

Table A5 | **Assumed Coal Production under Various Scenarios**

	2012	2020	2030	2040	2050
RS, CP, SPS upper bound (Mt CO_2e)	2,675	2,614	2,536	2,365	2,205
SPS lower bound (Mt CO_2e)	2,675	2,614	1,978	1,419	907

Sources: IEA (2017b); China Coal Cap Plan and Policy Research Project (2016); author's extrapolation.

Table A6 | **Assumed Oil and Gas Production under All Scenarios**

	2012	2020	2030	2040	2050
Oil and gas production (Mt CO_2e)	442	552	494	539	599

Sources: IEA (2017b); author's extrapolation.

CPS: Assumes methane utilization stays at a 2020 level after 2020.

Upper bound of emissions for SPS: Yang et al. (2014) estimate the costs of mitigation from installing methane emission recovery, utilization, or flare systems in the range of \$0.5–\$11 per ton of CO_2e. Given the relative low cost, it is assumed that methane with relative high concentrations (higher than 9 percent) would be either utilized or combusted in flares.

Lower bound of emissions for SPS: Besides installing methane emission recovery, utilization, or flare systems, this paper assumes that China's coal consumption from 2020 to 2050 would reduce to the level projected by the Coal Control Scenario of the China Coal Cap Plan and Policy Research Project (2016) and that coal production and emissions would reduce proportionally. Table A5 shows the assumed coal production under various scenarios.

Fugitive Emissions from Oil and Gas Systems

Under all scenarios, it is assumed that emissions are proportional to oil and gas production, sourced from the 13th FYP for Natural Gas Development (NDRC 2016b), the 13th FYP for Petroleum Development (NDRC 2016c), and WEO NPS (IEA 2017b). Projections between 2041 and 2050 are extrapolated based on WEO NPS projections between 2030 and 2040. This paper uses the NPS instead of the CPS under WEO because the NPS assumes policy targets that are aligned with China's NDC commitment in 2015, thus befitting the definition of *scenario* for the purposes of this paper. Table A6 shows the assumed oil and gas production under all scenarios.

This paper uses the combined oil and gas production (in energy content) to estimate emissions, as the disaggregated emissions of oil and gas in 2012 are not available. This method does not account for the different emission factors between oil and gas production, not to mention the difference between shale gas and traditional gas. Therefore, the projection is less accurate. However, since the emissions from oil and gas are very small (only 1 percent in 2012), the impact of this simplification is extremely limited.

Industrial Processes

Nitric and Adipic Acid Production

RS: Emissions for 2020 are sourced from the reference scenario in Yang et al. (2014), which is based on assumptions that the production of adipic acid would reach 1.4 Mt in 2020 (emissions factor at 0.296 t N_2O/t adipic acid) and production of nitric acid would reach 17 Mt in 2020 (emissions factor at 0.0095 t N_2O/t nitric acid). Additionally, it is assumed that there are no future mitigation efforts. The 2030 projection is based on an estimated annual growth of 5 percent for adipic acid production (Schneider and Cames 2014). This assumption is close to the projected global adipic acid market growth rate of 4.7 percent until 2024 (GVR 2018). Production and associated emissions are assumed to alter in proportion to population change from 2031 to 2050.

CPS: Emissions are the same as the RS until 2020. Emissions after 2020 remain at the 2020 level per target communicated in the BUR (GoC 2016).

Upper bound of emissions for SPS: It is assumed that adipic acid production accounts for 75 percent of emissions from nitric and adipic acid, which is the same proportion in the 2020 projection by Yang et al. (2014). Technical mitigation costs for adipic acid are estimated between \$0.12 and \$1.35 (Schneider and Cames 2014). In 2010, 75 percent of the adipic acid production capacity in the world was equipped with mitigation systems, including a 100 percent installation rate in 7 out of 11 producing countries (EPA 2013). In addition, adipic acid production is highly concentrated and relatively easy to regulate. Therefore, it is assumed that China can reach a 100 percent installation rate for mitigation systems in adipic acid production by 2030. The mitigation effective rate is around 99 percent (Schneider and Cames 2014).

The mitigation costs for nitric acid production (secondary treatment) are estimated between \$0.2 and \$10, with a mitigation effective rate of 100 percent (Schneider and Cames 2014). Compared to adipic acid production, the production of nitric acid is more distributed (EPA 2013) and mitigation costs are higher. Therefore, it is assumed that China's technology adaptation rate for nitric acid production (secondary treatment) will reach 20 percent in 2030 and increase to 80 percent in 2050.

Lower bound of emissions for SPS: Based on the same above-mentioned literature, it is assumed that with more proactive policies in place, China will be able to achieve a 100 percent installation rate for mitigation systems in adipic acid production by 2030 and a technology adaptation rate for nitric acid production (secondary treatment) of 40 percent and 100 percent in 2030 and 2050, respectively.

HFC-23

RS: Emissions are drawn from the business-as-usual scenario of Fang et al. (2016). It is assumed that HCFC-22 production for the phaseout of ODS use will be based on the Montreal Protocol, although domestic feedstock production will continue to grow in proportion to GDP. Export feedstock production is extrapolated based on GDP growth of the entire world at the exclusion of China. It is assumed that Clean Development Mechanism (CDM) projects will continue to run under government support in the absence of a decontamination mandate for HFC-23 emissions.

CPS and SPS: It is assumed that China will ratify the Kigali Amendment by 2020 (Zhao 2017). HFC-23 emissions should reach zero in 2020 per the amendment's Article 2J(6) (UN Environment Ozone Secretariat 2018).

Other HFCs

This paper first quantifies the demand for HFCs, which represent the would-be consumption for HFCs in lieu of other constraints. Based on the demand, this study applies consumption constraints (or lack thereof) under various scenarios to quantify HFC consumption. Emissions are quantified based on annual consumption, HFCs inventory in equipment, and the HFC emission factor. Formula and emissions factors are sourced from Fang et al. (2016).

In all scenarios, it is assumed that emission factors will remain the same and there will be no HFC recovery. This paper only includes emissions from HFC consumption since those relating to production are small.

Estimate demand

Following the method used by Fang et al. (2016), this paper breaks HFC demand into two parts. The first accounts for the natural growth of demand for HFCs that existed prior to 2015.

The primary uses of HFC-32 and HFC-125 include room air conditioners (ACs) and refrigerators. It is assumed that their demand will grow in proportion to room AC sales in China. This paper uses the average apparent consumption between 2012 and 2014 (Zhejiang Research Institute of Chemical Industry 2016) and makes adjustments to account for exports. Adjustments are necessary given that apparent consumption includes HFC-32 and HFC-125, which are used in manufacturing exported room ACs, and emissions associated with exported equipments should not be included in China's GHG national inventory. This study applies the export and domestic AC sales ratio between 2012 and 2014 from the China Industrial Information Net (2018) to calculate HFC-32 and HFC-125 domestic demand average between 2012 and 2014.

The primary uses of HFC-143a, HFC-245fa, and HFC-152a are mobile refrigeration and foaming. For these HFCs, it is assumed that the demand will grow in proportion to GDP before 2030 and in proportion to post-2030 population change, since HFC demand is likely to closely correlate to economic activity until certain stages of development. Once the economy is mature, per capita demand should become stable and demand would then be driven mostly by population change. This assumption is the same as

Table A7 | **China Light Vehicles and Room Air Conditioner Sales, Projection (Three-Year Average)**

	2012	2020	2030	2040	2050
Light vehicles (millions)	15.5	31.5	35.7	34.7	33.85
Room AC (millions)	56	79	100	111	118

Sources: Kuhnert et al. (2018); IEA (2018); author's calculation.

Fang et al. (2016). HFC-134a is primarily used in mobile ACs. It is assumed that its demand will alter in proportion to annual light vehicles sales.

Baseline demand for HFC-134a, HFC-143a, HFC-245fa, and HFC-152a are calculated using the apparent average annual consumption rate between 2012 and 2014 (Zhejiang Research Institute of Chemical Industry 2016). Since China does not export a significant share of equipment that uses these compounds, no adjustments for exports were made.

The light vehicles sales projection from 2017 and 2030 is sourced from Kuhnert et al. (2018). This paper assumes that light vehicles sales will change in proportion to the population during 2031 and 2050, since China's light vehicles sales may peak before 2030. Using China's room AC inventory projection provided by IEA (2018), this paper calculates annual room AC sales by assuming a 12-year life cycle. Since annual sales figures for room AC and light vehicles fluctuate significantly from year to year, the three-year average figure is applied. Table A7 shows the historic and projected light vehicle and room air conditioner sales.

The second part of HFC demand accounts for an increase due to HCFC replacement.

Per the Montreal Protocol, amended in 1997, HCFC consumption and production in China is subject to quota restrictions since 2015. The quota would decrease over time until a complete phaseout in 2040. It is assumed that part of the phaseout of HCFCs will be replaced by HFCs, thus increasing HFC demand.

This paper first uses the HCFC baseline consumption rate prior to 2015 and the projected room AC and GDP growth for future years in order to calculate HCFC demand without quota restriction. Subsequently it uses the HFC baseline demand, HCFC quota, and replacement factors to quantify the HFC demand that is driven by the HCFC phaseout.

The average consumption of HCFC-22, HCFC-141b, and HCFC-142b between 2012 and 2014 is sourced from the Secretariat of the Multilateral Fund for the Implementation of the Montreal Protocol (2016). HCFC-22 is primarily used as a refrigerant in AC and refrigerators, and part of the pre-2015 consumption is used to manufacture appliances that are eventually exported. HFCs used to replace this part of HCFCs should not be included in China's GHG national inventory. This paper uses the export and domestic AC sales ratio between 2012 and 2014 from China Industrial Information Net (2018) to calculate HCFC-22 domestic consumption between 2012 and 2014. No export adjustment is made for other HCFCs, since export of relevant equipment is not significant.

It is assumed that HCFC-22 domestic demand without quota restriction will grow in proportion to domestic room AC sales. For HCFC-141b and HCFC-142b, it is assumed that their demand will grow in proportion to GDP before 2030 and in proportion to population change post-2030. The same assumptions were used in Fang et al. (2016). HCFC quotas are sourced from UN Environment Ozone Secretariat (2018). The quota for HCFC-22 is adjusted to exclude quotas expected to be used for exported AC. The replacement factor between HFCs and HCFCs is drawn from Fang et al. (2016).

Estimate consumption

RS: Without the Kigali Amendment to the Montreal Protocol, there is no regulation on HFCs in addition to the HFC-23 control target mentioned in China's NDC. The demand is the same as consumption.

CPS: HFC consumption is the same as its demand until 2023. It is assumed that China will ratify the Kigali Amendment to the Montreal Protocol and conform to its requirements.

According to the Kigali Amendment, the average HFC consumption between 2020 and 2022, plus 65 percent of the HCFC baseline consumption, would become the baseline for HFCs. The permitted HFC consumption in the Kigali Amendment includes HFCs in domestic and exported equipments. This paper excludes the HCFC baseline consumption used for exported equipment and the HFC-32 and HFC-125 in exported equipment from 2020 to 2022 to establish an HFC baseline for domestic consumption. HFC domestic consumption would freeze from 2024 to 2029 at the baseline level and phase down over time, based on a stipulated timetable in the Kigali Amendment.

Upper bound of emissions for SPS: HFC consumption is the same as its demand until 2023. Use the following assumption to quantify consumption after 2024: Domestic

HFC consumption from 2024 to 2029 is assumed to remain at 90 percent of the domestic HFC consumption baseline. Beginning in 2030, it is assumed that HFC consumption will reduce equally each year (instead of the step phasedown indicated in the Kigali Amendment) to meet the target consumption limit and time stipulated by the Kigali Amendment. This assumption is cost-effective because production installations usually depreciate over 10 years. Controlling and reducing HFC consumption and production five years ahead of schedule would mitigate an economic loss as a result of stranded assets.

Lower bound of emissions for SPS: HFC consumption is the same as its demand until 2019. Use the following assumptions to quantify consumption after 2020: HFO-1234yf and propane would replace 50 percent of HFC-134a and HFC-410a (consisting of 50 percent HFC-32 and 50 percent HFC-125), respectively, by 2030, and the replacement rate would increase to 100 percent by 2035. These assumptions are similar to those of Lin et al. (2018), who analyzed the application and patent status of HFO-1234yf around the world, including China, as well as its production in Jiangsu Province. To develop the alternative scenario, Lin et al. (2018) also considered the use of propane and the pilot effort of the Midea Group in China. Consumption of other HFCs is the same as in the upper bound of emissions for the SPS.

Metal Production (Aluminum)

Under all scenarios, it is assumed that emissions associated with aluminum are proportional to primary aluminum production. Production data for 2020 are derived from the Nonferrous Metals Industry Development Plan (2016–20) (MIIT 2016); 2021–40 production is assumed to be equal to primary aluminum demand (Abubakar 2015). Emissions for 2041–50 are assumed to be proportional to population change.

Integrated Circuit Manufacturing or Semiconductor Manufacturing

Under all scenarios, this paper uses emissions that are estimated by the EPA (2012), since the baseline assumes an activity data change in proportion to mainland China's integrated circuit (IC) production. The emission factor would reduce by 30 percent between 2010 and 2020, according to the World Semiconductor Council target (WSC 2016). It is assumed that there will be no further emissions reduction factor after 2020. Production data for 2010–18 are sourced from Qianzhan Industry Research Institute (2018a) and Zhongshang Industry Institute (2018). It is assumed that China's IC production between 2019 and 2020 will maintain the same compound annual growth rate between 2015 and 2018. It is assumed that mainland China's production between 2020 and 2026 will rise at the same rate as the projected growth rate for Asia Pacific semiconductors (Inkwood Research 2017). It is assumed that production will change in proportion to GDP growth between 2027 and 2030 and in proportion to population changes after 2030.

Flat Panel Display Manufacturing

Under all scenarios, use the 2010 emissions estimate by the EPA (2012); emissions are assumed to be in proportion to production area. It is assumed that 2010–11

Table A8 | **Assumed Mitigation Measures, Costs, and Potential under the Upper Bound of Emissions for the Strengthened Policies Scenario**

MITIGATION MEASURES	MAXIMIZED MITIGATION POTENTIAL BY 2020 (MT CO_2E)	ESTIMATED COST ($/T CO_2E)
Animal breeding	4.4	-395
Adding probiotics to the diet	5.53	-8.6
Adding tea saponins to the diet	1.09	-1,089

Source: Wang et al. (2014).

production will be proportional to a production capacity change in the same period (Qianzhan Industry Research Institute 2018b). Area production data for 2011–17 are derived from Qianzhan Industry Research Institute (2018c), and the 2018–24 projection is assumed to be proportional to global demand growth (Hsieh 2018). Production between 2025 and 2030 is assumed to be proportional to GDP growth. After 2030, it is assumed that production will change in proportion to population change.

Photovoltaic Manufacturing

Under all scenarios, this paper applies 2010 emission estimates based on EPA (2012) and assumes that they are in proportion to solar photovoltaic (PV) cell production in China. Data for 2010–17 are sourced from MIIT (2018). Between 2017 and 2020, it is assumed that production in mainland China will be proportional to the projected growth rate of global solar PV (ESCN 2017; GVR 2017). It is assumed that solar PV cells will continue to grow at 10 percent per year between 2021 and 2030, resulting in a 7 percent per year growth rate between 2031 and 2040, and will lower to a 5 percent per year growth between 2041 and 2050.

Power Equipment

Electrical equipment is the primary sector for SF_6 consumption and the main source of future SF_6 emissions, since leakage during production is negligible. SF_6 has been phased out in the production of semiconductors and magnesium in China (Zhou et al. 2018).

Zhou et al. (2018) have estimated SF_6 emissions to 2050, and they incorporate considerations on power demand, power mix, SF_6 initial filling, life cycle of equipment, and various emission factors for manufacturing, installation, operation, and maintenance, as well as the residual ration and recovery ratio (Zhou et al. 2018). Their study, however, assumes a higher power capacity value. More important, their study of SF_6 emissions in 2012 is almost three times higher than those reported by the BUR.

Under all scenarios, this paper makes the following adjustments. First, to improve consistency, this study adjusts the assumption for power capacity to the level projected by the NPS in WEO (IEA 2017b). This is possible since Zhou et al. (2018) conducted sensitivity analyses on the impact of power capacity of 2050 projected emissions. Second, assuming that the BUR's reported emissions are more comprehensive and accurate, this paper applies its 2012 emissions as a baseline, as well as the growth rate from adjusted emissions, to arrive at projections for future years.

Agricultural Sector

Methane Emissions from Rice Cultivation

For the RS and CPS, it is assumed that emissions will change in proportion to estimated harvested rice area in China, based on data drawn from the *OECD-FAO Agricultural Outlook 1990–2028* (OECD and FAO 2017). The estimated harvested rice area from 2028 to 2030 was extrapolated based on projections between 2022 and 2027. Because of a lack of alternative sources of projection, this paper assumes that harvested areas from 2031 to 2050 will change in proportion to population change. This assumption is based on the understanding that per capita demand for rice will stabilize once China attains fairly high levels of per capita food consumption, beyond which the scope for further quantitative increases is limited.

Upper bound of emissions for SPS: Using the DeNitrification-DeComposition model, the Decision Support System for Agro-technology Transfer model and the Agro-ecological Zone model, and based on field test results from nine major rice regions in China, Tian et al. (2018) estimate that China will be able to mitigate 25 percent of methane emissions from rice cultivation with negative costs by combining midseason drainage and balanced fertilization according to crop requirements and soil testing. A climate change expert from the Chinese Academy of Agricultural Sciences agrees that given the way rice is farmed in China, there is potential to achieve negative or low-cost mitigation through improved irrigation. Based on discussions with experts, Lin et al. (2018) assume that China will be able to reduce methane emissions by 30 percent compared to the baselines for 2015 and 2050. Since rice cultivation is not concentrated only in China, it is a challenge to promote new techniques and technologies. Thus, this paper assumes conservatively that by using negative or low-cost mitigation measures, China will able to achieve a 12.5 percent and 25 percent reduction of methane emissions by 2030 and 2050, respectively.

Lower bound of emissions for SPS: According to a climate change expert from the Chinese Academy of Agricultural Sciences, besides irrigation and better fertilization usage, the application of a nitrification inhibitor and a slow-release fertilizer or biochar would further reduce emissions (Li 2018). Linquist et al. (2012) reviewed relevant experiments and studies and concluded that certain nitrification inhibitors and slow-release fertilizers can reduce methane emissions by 15 percent from the cultivation of rice. In addition, China's field experiment indicates that appropriately using biochar and water-saving irrigation, would reduce methane emissions by 30 percent (Xiao et al. 2018). Based on this information, it is assumed that in addition to improved irrigation practices and reduced fertilizer application, using a nitrification inhibitor and slow-release fertilizer or biochar would reduce emissions by 30 percent and 50 percent in 2030 and 2050, respectively, compared to CPS emissions.

Enteric Fermentation

For beef cattle, dairy cows, goats, sheep, and pigs, this paper uses 2012 China Stat Year Book data for animal inventory as a baseline and assumes activity data change in proportion to the animal inventory change projected by OECD and FAO (2017) between 2012 and 2027. This paper extrapolates the OECD-FAO projection for 2028–30. For 2030–50, it is assumed that the change will be proportional to population change over the same period. This assumption is based on the understanding that per capita demand for meat will stabilize once China attains fairly high levels of per capita food consumption, beyond which the scope for further quantitative increases is limited.

For horses, donkeys, mules, and camels, this paper uses the same method of projection as Lin et al. (2018), which applies a linear regression based on historical data. It assumes that the animal inventory remains the same over a certain period of time.

Because of the lack of data relating to how animals are raised, this paper calculates a simplified emission factor for each animal by averaging various emission factors for the animal in the *Guidelines for Provincial GHG Inventory in China* (NDRC 2011).

Using this method, the emissions calculated for 2012 are lower than those reported by the BUR. Assuming that the difference results from emission factors and the BUR data are more robust, this adjustment factor (1.1978) is developed by dividing the reported BUR emissions by those calculated. The adjustment factor is then multiplied by the calculated value for future years to achieve the final emission projections.

Upper bound of emissions for SPS: Wang et al. (2014) develop a mitigation cost curve for China's livestock industry based on relevant meta-analyses and studies. Since the country's livestock industry is not concentrated only in China and is harder to regulate, it is assumed that only mitigation measures with a negative cost would be deployed (see Table A8). It is assumed that 70 percent and 100 percent of the mitigation potential of these measures will be realized by 2030 and 2050, respectively.

Table A9 | **Assumed Mitigation Measures, Costs, and Potential under the Upper Bound of Emissions for the Strengthened Policies Scenario**

MITIGATION MEASURES	MAXIMIZED MITIGATION POTENTIAL BY 2020 (MT CO_2E)	ESTIMATED COST ($/T CO_2E)
Fertilizer best management practices—right rate	30.65	-67
Fertilizer best management practices (wheat and maize)—right time and right placement	11.38	-475
Fertilizer best management practices (cash crops)—right products, right time, and right placement	21.86	-290

Source: Wang et al. (2014).

Lower bound of emissions for SPS: Based on expert discussions, Lin et al. (2018) assume that by improving the nutritional balance of livestock feed and feed digestibility, emissions can be reduced by 17 percent and 30 percent in 2020 and 2050, respectively. This paper assumes the same mitigation reduction rates, albeit with mitigation commencing post-2020.

Field Burning of Agricultural Residues

This is an insignificant source of emissions in China. For simplicity, it is assumed that emissions will remain constant at the 2012 level under all scenarios.

Animal Manure Management

For all scenarios, the same methodology applies, as enteric fermentation is used to determine activities data and emission factors.

RS: It is assumed that there will be no additional rural biogas development after 2015.

CPS and SPS: This paper incorporates the impact of new biogas production and utilization post-2015. Because there is no quantified policy target, it is assumed that rural biogas will remain at the 2020 level post-2020. According to the 13th FYP for National Rural Biogas Development, China should achieve an additional 17.62 Mt CO_2e each year in 2020 compared to 2015 (NDRC and MOA 2017). The estimate includes methane reduction from animal manure and CO_2 emissions from a reduced use of fossil fuel energy due to energy substitution. It is assumed that coal is replaced as a result. Based on emission factors sourced from the *Guidelines for Provincial GHG Inventory in China* (NDRC 2011) and the energy substitution target in the 13th FYP for National Rural Biogas Development (NDRC and MOA 2017), it is calculated that animal manure methane emissions will reduce by 9 Mt CO_2e.

Agricultural Soils

RS and CPS: It is assumed that emissions are proportional to the application of nitrogen fertilizer. Data for 2012–17 are sourced from the National Bureau of Statistics (NBS n.d.). Based on the assessment of the International Fertilizer Association that China's fertilizer use will continue to contract (IFA 2018), it is assumed that nitrogen fertilizer application will remain at its 2017 level until 2020. Because of the zero-growth target in the NDC (NDRC 2015) and the nitrous oxide zero-growth target in the BUR (GoC 2016), it is assumed that emissions will remain at the 2020 level between 2020 and 2030. It is also assumed that nitrogen fertilizer application will change in proportion to the population from 2031 to 2050. This assumption is based on the understanding that per capita demand for crops will stabilize once China attains fairly high levels of per capita food consumption, beyond which the scope for further quantitative increases is limited.

Upper bound of emissions for SPS: Wang et al. (2014) develop a mitigation cost curve for China's crop farming industry based on relevant meta-analyses and studies. Since crop farming is not concentrated solely in China and is harder to regulate, it is assumed that only mitigation measures with a negative cost will be deployed (see Table A9). It is assumed that 70 percent and 100 percent of these measures' mitigation potential will be realized by 2030 and 2050, respectively.

Lower bound of emissions for SPS: Based on discussions with experts from the China Academy of Science, Lin et al. (2018) note that China has been using more nitrogen fertilizer than needed; it is assumed that nitrogen fertilizer application will first increase by 20 percent from 2010 to 2015, and then decrease 50 percent by 2050. A similar assumption is adopted that China's nitrogen fertilization application will begin to decrease in 2020 until it reaches 50 percent of its 2015 level in 2050.

Waste Sector

Methane Emissions from Solid Waste

Solid waste includes industrial waste and MSW. A majority of China's industrial solid waste derives from mining, quarrying, and other categories (MEP 2017). Relevant emissions should be very low (IPCC 2006). Therefore, this paper does not take into account emissions from industrial solid waste. MSW includes solid waste from cities and counties. Since there is little research on county solid waste projections, it is assumed that solid waste at the county level will change in proportion to changes at the city level.

Under all scenarios, this paper projects emissions from solid waste by using data relating to rates in MSW collection weight, harmless treatment, and treatment by applying three methods (landfill, incineration, and other), landfill gas recovery, and reported emissions for 2012 (GoC 2016).

An equation developed by Ma and Gao (2018) is used to project MSW collection weight before 2030: MSW collection weight = 0.5041+0.3124*ln (GDP).

Post-2030, it is assumed municipal solid waste will change in proportion to the population. This is because per capita municipal solid waste generation tends to stabilize after the economy has developed to a certain stage. For example, per capita municipal solid waste generation changed insignificantly between 1990 and 2015 (EPA n.d.).

In the past, the harmless treatment rate was sourced from the National City Construction Yearbook (MOHURD 2013, 2016). Based on past trends, it is assumed that the treatment rate will reach 100 percent in 2030. MSW treatment weight can be calculated based on the MSW collection weight and harmless treatment rate. Landfill treatment weight is calculated based on the MSW treatment weight and landfill treatment rate. It is assumed that parameters such as the methane conversion factor, the composition of MSW, the oxidation rate, and the half-life value will remain constant. Therefore, methane emissions from MSW before considering landfill gas recovery are proportional to landfill treatment weight.

According to the United Nations Framework Convention on Climate Change (UNFCCC), there were 56 registered landfill gas CDM projects in China by the end of 2012, with an estimated annual reduction of 7.15 Mt CO_2e. By the end of 2015, there were 58 registered landfill gas CDM projects, with an estimated annual reduction of 7.34 Mt CO_2e (UNFCCC n.d.a). Based on a review of select CDM project documents, it is assumed that 15 percent of the reduction results from fossil fuel replacement, while 85 percent comes from reduced methane emissions. It is further assumed that CDM projects roughly equal landfill recovery in China.

RS: It is assumed the landfill rate (MOHURD 2016) and methane reduction from landfill recovery (UNFCCC n.d.a) will remain at the 2015 level.

CPS and SPS: It is assumed that the landfill and incineration rate will reach the target level indicated in the 13th FYP for National Municipal and County Domestic Waste Harmless Treatment Facility Construction (NDRC and MOHURD 2016) in 2020, and that it will remain at the same level after 2020. It also is assumed that methane reduction from landfill recovery (UNFCCC n.d.a) will remain at the 2015 level.

Table A10 | **Methane Emission Factors for Municipal Wastewater Treatment Plants in China**

WASTEWATER TREATMENT	TREATMENT PROCESS	EMISSION FACTOR (KG CH_4/KG COD)	2012 NATIONAL WEIGHTED AVERAGE EMISSION FACTOR (KG CH_4/KG COD)
Domestic wastewater	Anaerobic + methane recovery	0.0030	0.0078
	Anaerobic	0.0440	
	Primarily aerobic	0.0040	
Industrial wastewater	Anaerobic + methane recovery	0.0008	0.0354
	Anaerobic	0.1400	
	Primarily aerobic	0.0040	

Source: Cai et al. (2015).

Methane Emissions from Wastewater

RS and CPS: Du et al. (2018) use an artificial neural network to estimate methane emissions from wastewater in 2020 based on GDP, population growth, and location factors. This paper sources 2020 emissions from the study. For industrial wastewater emissions to rivers, lakes, and oceans, it is assumed that the compound annual change rate from 2021 to 2050 will be the same from 2015 to 2020. For industrial wastewater from treatment plants, it is assumed emissions after 2020 will alter in proportion to the population. As Du et al. (2018) note, relevant emissions will become stable during 2018 and 2020. For domestic wastewater, it is assumed that emissions will change in proportion to GDP between 2021 and 2030 and will further alter in proportion to population between 2031 and 2050.

Upper bound of emissions for SPS: Yang et al. (2014) review CDM projects for wastewater treatment and estimate that the cost of mitigation, using methane recovery, and/or a flaring system will be around $7–$9 per ton of CO_2e. Cai et al. (2015), a review of the data from municipal wastewater treatment plants and field experiments, identified emission factors for China's municipal treatment plant (see Table A10). The authors note that, in China, the aerobic process is the primary treatment approach for domestic wastewater, while the anaerobic process is the primary approach for industrial wastewater treatment.

Although treatment plants that use anaerobic and methane recovery processes have the lowest emission factor, it is not economical to convert existing aerobic wastewater treatment plants into anaerobic ones. Therefore, it is assumed that the emission factor for the primarily aerobic treatment process is the lowest achievable emission factor for China. This means there is a 49 percent and an 89 percent mitigation potential when compared to the national weighted average in 2012 for domestic and industrial wastewater, respectively.

Based on the rationale and information mentioned above, it is assumed that by installing methane recovery systems in addition to existing anaerobic treatment plants, emissions from domestic wastewater treatment can be reduced by 20 percent and 30 percent by 2030 and 2050, respectively, while emissions from industrial wastewater treatment can be reduced by 36 percent and 53 percent by 2030 and 2050, respectively.

Lower bound of emissions for SPS: It is assumed that by installing methane recovery systems in addition to existing anaerobic treatment plants, emissions from domestic wastewater treatment can be reduced by 25 percent and 44 percent by 2030 and 2050, respectively, while emissions from industrial wastewater treatment can be reduced by 46 percent and 80 percent by 2030 and 2050, respectively.

Nitrous Oxide Emissions from Wastewater

For all scenarios, this paper uses 2012 BUR data (GoC 2016) as a baseline and assumes emissions changes in proportion to population changes between 2013 and 2050.

Nitrous Oxide Emissions from Waste Incineration and Solid Waste Landfill

For all scenarios, this paper uses 2012 BUR data (GoC 2016) as a baseline and assumes emissions changes in proportion to MSW landfill treatment weight and incineration treatment weight. The methodology and assumptions to project MSW collection weight are the same as the ones used to quantify methane emissions from solid waste.

RS: It is assumed that the landfill rate and incineration rate will remain at the 2015 level (MOHURD 2016).

CPS and SPS: It is assumed that municipal solid waste landfill and incineration rates will meet the target set in the 13th FYP for National Municipal and County Domestic Waste Harmless Treatment Facility Construction (NDRC and MOHURD 2016) and remain so after 2020.

APPENDIX B. PROJECTION SPREADSHEET FOR CHINA'S NON-CO_2 GREENHOUSE GAS EMISSIONS

The spreadsheet can be downloaded at https://bit.ly/2FQLZ3A.

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ENDNOTES

1. Emissions data for 2014 are not used in the analysis because they were not available at the time the analysis was conducted.
2. While the GHG Protocol (n.d.) recommends using the latest GWP values, this paper uses SAR values to be consistent with the custom of Chinese policymakers and experts.
3. HFC-23 emissions in China result from the production of HCFC-22. Article 2(J)(6) of the Montreal Protocol reads, "Each Party manufacturing Annex C, Group I, or Annex F substances shall ensure that for the twelve-month period commencing on 1 January 2020, and in each twelve month period thereafter, its emissions of Annex F, Group II, substances generated in each production facility that manufactures Annex C, Group I, or Annex F substances are destroyed to the extent practicable using technology approved by the Parties in the same twelve-month period." HCFC-22 is in Annex C Group I, and HFC-23 is in Annex F Group II.

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ABOUT THE AUTHOR

Ranping Song is a Senior Associate and the Developing Country Climate Action Manager at WRI's Global Climate Program. He develops, coordinates, and implements strategy and research projects to facilitate developing countries' efforts to design and implement multisector policies and plans to achieve targets for GHG emissions reductions.

Contact: rsong@wri.org

ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.