



ROADMAP FOR U.S.-CHINA METHANE COLLABORATION: METHANE EMISSIONS, MITIGATION POTENTIAL, AND POLICIES

November 2022

Background and Acknowledgements

From January to June 2022, researchers from a group of 20 U.S., Chinese, and international research institutions convened over two workshops to discuss opportunities for advancing methane-related research in the United States and China. The contributions of all workshop participants are gratefully acknowledged. In parallel to the workshop, and informed by those discussions, a core research team conducted additional analysis and produced a report based on the resulting research and policy guidance from a larger research team. The workshops and report were facilitated by the Center for Global Sustainability at the University of Maryland with support from Energy Foundation China.

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November 2022

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Stands For
ACR	American Carbon Registry
AFOLU	Agriculture, Forestry and Other Land Use
AIM/CGE	Asia-Pacific Integrated Model/Computable General Equilibrium
AMM	Abandoned Mine Methane
AR6	IPCC's Sixth Assessment Report
B.C.	British Columbia
BIC	Business in Calgary
BIL	Bipartisan Infrastructure Law
BLM	Bureau of Land Management
CAFOs	Concentrated Animal Feeding Operations
CAIXA	Carbon Partnership Facility built cooperation with Caixa Econômica Federal
CAR	Climate Action Reserve
CBM	Coalbed Methane
CCAC	Climate and Clean Air Coalition
CCAPP	China Carbon Neutrality and Clean Air Synergy Pathway Annual Report Working Group
CCE	Circular Carbon Economy
CCER	China Certified Emissions Reduction
CDM	Clean Development Mechanism
CE	Circular Economy
CEC	China Electricity Council
CEDS	Community Emissions Data System
CEPA	Canadian Environmental Protection Act, 1999
CERC	U.S. China Clean Energy Research Center
CERLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CESY	Chinese Energy Statistical Yearbook
CH ₄	Methane
China NCCC	National Communication on Climate Change
CMATSP	Coal Mining Abatement Technology Support Package
CMIP6	Coupled Model Intercomparison Project 6
CMM	Coal Mine Methane

Acronym/ Abbreviation	Stands For
CMOP	Coalbed Methane Outreach Program
CNOOC	China National Offshore Oil Corporation
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CO ₂ e	Carbon Dioxide Equivalent
COFFEE	Computable Framework for Energy and the Environment
COP	California Compliance Offset Program
COP26	Glasgow Climate Change Conference
CRF	Common Reporting Format
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DOE	Department of Energy
DOI	Department of Interior
DOL	United States Department of Labor
EDF	Environmental Defense Fund
EDGAR	Emissions Database for Global Atmospheric Research
EIA	U.S. Energy Information Administration
EPA	Environmental Protection Agency
ERF	Emissions Reduction Fund
ETS	Emissions Trading Scheme
EU	European Union
FAO	Food and Agriculture Organization of the United Nation
FAOSTAT	Food and Agriculture Organization of the United Nations
FERC	Federal Energy Regulatory Commission
FYP	Five-Year Plan
GAINS	Greenhouse Gas-Air Pollution Interactions and Synergies
GAO	United States Government Accountability Office
GCAM	Global Change Analysis Model
GCCS	Gas Collection and Control System
GEF	Global Environment Facility
GFED	Global Fire Emissions Database
GFEI	Global Fuel Exploitation Inventory
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Reporting
GLOBIOM	Global Biosphere Management Model
GMB	Global Methane Budget
GMI	Global Methane Initiative

Acronym/ Abbreviation	Stands For
GWP	Global Warming Potential
HEHE	A Healthy Environment and a Healthy Economy
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
IMEO	International Methane Emission Observatory
IPAC	Integrated Energy and Environment Policy Assessment model for China
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
LBNL	Lawrence Berkeley National Laboratory
LDAR	Leakage Detection and Repair
LHF	Low Hanging Fruit
LMOP	Landfill Methane Outreach Program
LNG	Liquefied Natural Gas
LULC	Land Use Land Cover
MAC	Marginal Abatement Cost
MARA	Ministry of Agriculture and Rural Affairs
MEE	Ministry of Ecology and Environment
MEM	Ministry of Emergency Management of the People's Republic of China
MESSAGEix	Model for Energy Supply Systems and their General Environmental Impact
MHURD	Ministry of Housing and Urban-Rural Development
MOF	Ministry of Finance
MoHURD	Ministry of Housing and Urban-Rural Development
MRV	Reporting and Verification
MSW	Municipal Solid Waste
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Statistics
NDC	Nationally Determined Contribution
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NESHAP	National Emission Standards for Hazardous Air Pollutants
NGER Act	National Greenhouse and Energy Reporting Act 2007
NGFS	Network for Greening the Financial System
NGOs	Non-Governmental Organizations
NIMBY	"Not in My Backyard"
NMHC	Non-methane Hydrocarbons
NMOCs	Non-methane Organic Compounds

Acronym/ Abbreviation	Stands For
NO ₂	Nitrogen Dioxide
NPDES	National Pollutant Discharge Elimination System
NSPS	New Source Performance Standards
NZAGRC	New Zealand Agriculture Greenhouse Gas Research Center
O ₃	Ozone
OGCI	Oil and Gas Climate Initiative
OGEMR	Oil and Gas Emissions Management Regulations
PCF	Pan-Canadian Framework on Clean Growth and Climate Change
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIPES	Protecting Our Infrastructure of Pipelines and Enhancing Safety
PM	Particulate Matter
POLES	Prospective Outlook on Long-term Energy Systems
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act of 1976
REAP	Rural Energy for America Program
REMIND- MAGPIE	REgional Model of Investment and Development-Model of Agricultural Production and its Impacts on the Environment
RGGI	Regional Greenhouse Gas Initiative
RMB	Renminbi
RPS	Renewable Portfolio Standard
RRS	Resource Recycling Systems
RTO	Regenerative Thermal Oxidation
SACMS	State Administration of Coal Mine Safety
SARA	The Superfund Amendments and Reauthorization Act
SMM	Surface Mine Methane
SO ₂	Sulfur Dioxide
SOE	State Owned Enterprise
U.S. GHGI	U.S. Greenhouse Gas Inventory
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	UN Framework Convention on Climate Change
USD	U.S. Dollar
USDA	U.S. Department of Agriculture
VAM	Ventilation Air Methane
VCS	Verified Carbon Standard

Acronym/ Abbreviation	Stands For
VOC	Volatile Organic Compound
WHO	World Health Organization
WITCH	World Induced Technical Change Hybrid
WWTPs	Wastewater Treatment Plants

Unit	Stands For
Gg	Gigagrams
kt	Kilotonne
mcf	Thousand Cubic Feet Per Day
mt	Metric Ton
Mt	Megaton
Mtce	Mega Tonnes of Coal Equivalent
ppb	Parts per billion
t	Tonne
Tg	Teragrams

01 | INTRODUCTION

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Methane currently contributes to 20% of human-caused climate forcing (Forster et al., 2021). Rapid and sustained methane reduction is critical to keeping the world on a path to 1.5°C. Anthropogenic methane emissions can be reduced by as much as 45% by 2030, which would avert nearly 0.3°C of global warming by 2045 and would critically also reduce the level of peak warming (CCAC & UNEP, 2021b).

China and the U.S. are the first and third largest methane emitters, respectively, and collectively account for roughly one-quarter of total global methane emissions (GMI, 2022b). Both countries have made significant progress in developing policies to address methane mitigation since the 2021 United Nations Climate Change Conference (COP26). For example, by August 2022, 14 congressional bills and 10 policies that directly address methane mitigation have been adopted and/or proposed by the U.S. and China, respectively. Joint efforts of the U.S. and China to reduce methane emissions can accelerate

methane mitigation in both countries and also are key to limiting near-term warming, which would lead to improved local air quality and economic and health benefits.

This report provides new, in-depth analysis of opportunities and challenges for methane mitigation in the U.S. and China, as well as opportunities for improving methane mitigation outcomes through collaborative activities and research. It provides a comprehensive overview of current methane emissions, policy frameworks, and mitigation opportunities in both countries. It also identifies low-hanging fruit for methane mitigation and sheds light on opportunities for collaboration between the U.S. and China in terms of inventory development, policies and standards, and technology deployment. Moreover, building on new, multi-model analysis and the survey of recent literature, it provides a quantitative basis for methane mitigation potential in China and the U.S. under carbon neutrality or net-zero pathways.

02 | CURRENT STATUS OF METHANE GOVERNANCE AND POLICIES IN THE U.S. AND CHINA

@ Image by Alparslankaya from PxHere



Although its urgency has been in the spotlight since the 26th United Nations Climate Change Conference (COP26) in Glasgow in 2021, methane mitigation is not an entirely new challenge for either the U.S. or China. While important gaps remain, governance structures and policy frameworks can catalyze stronger commitments to tackle the methane issue. This chapter compares the current situations of both countries by

identifying the relevant government authorities and their corresponding responsibilities at the federal/central government level and by presenting an extensive review of existing methane policies. The goal is to not only answer the question of where we are, but also to help understand the drivers of methane mitigation prior to Glasgow and the gaps that need to be filled to create new incentives and capacities.

2.1 METHANE GOVERNANCE STRUCTURES IN THE U.S. AND CHINA

Methane (CH₄) emissions reduction is a complex issue that requires multi-sector efforts. While CO₂ emissions are predominantly from fossil fuel combustion (nearly 70% of global CO₂ emissions come from the energy sector), methane emissions involve three major sectors: energy, agriculture, and waste, each of which has its own field of expertise, regulatory complexity, and challenges. In addition, each of the sub-sectors also belongs to different administrative divisions. This is not to understate the complexity of CO₂ emissions reduction, where the sectoral focus is generally connected to energy use, such as building, transport, and industry. Rather, it is to argue that methane mitigation is a multi-centric challenge and calls for more collaborative, yet dispersed, governance efforts and both scientific and technical knowledge from these sectors.

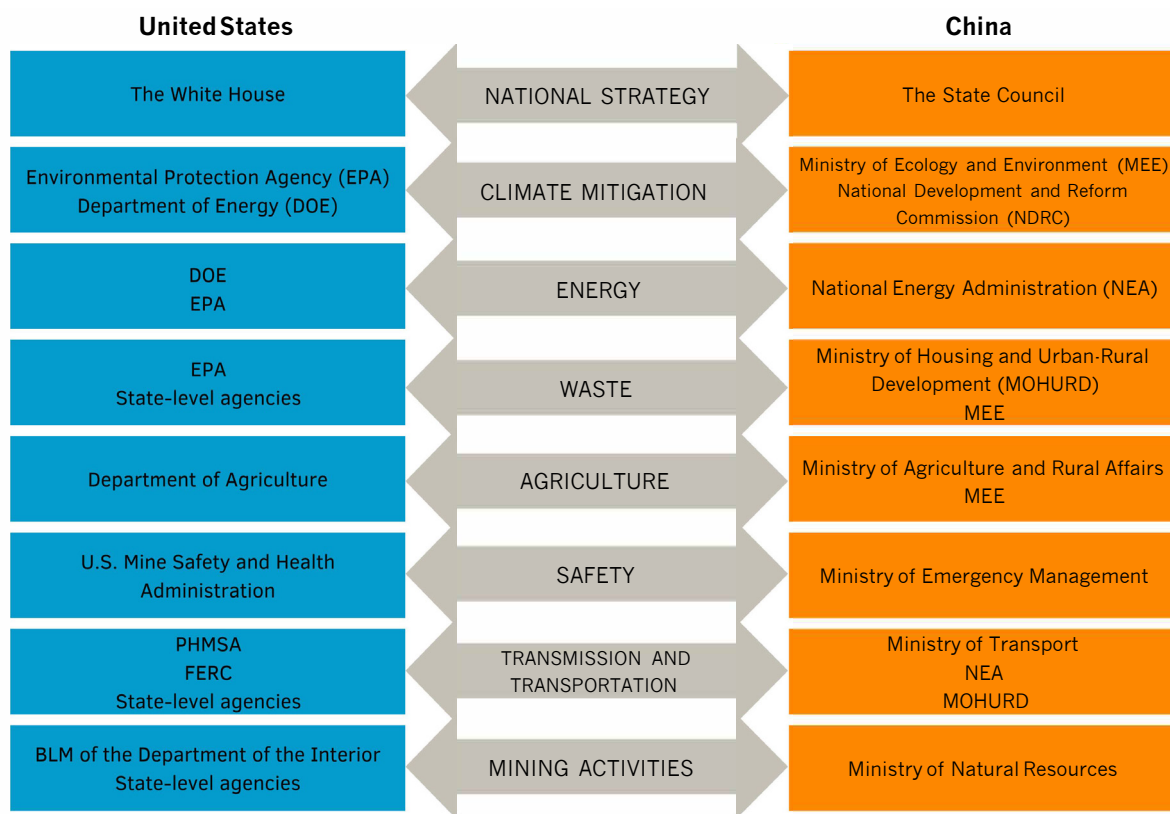
The key administrative elements associated with methane mitigation include: (1) developing overarching national strategy; (2) recognizing methane emissions as a climate change challenge; (3) reducing and recovering methane emissions

from energy, agricultural, and waste activities; (4) preventing methane emissions from pipeline transmission and transportation; (5) regulating methane as an explosive gas for safety reasons; (6) minimizing methane emissions from the extraction and mining operations for coal, oil, and gas (e.g., venting and leakage); and (7) encouraging mineral resource conservation and utilization. Figure 2.1 shows the major departments and ministries at the federal/central level that are responsible for methane mitigation in the U.S. and China.

It is important to note that, in spite of the listed government authorities, the governance structure for methane mitigation in the United States is more complicated, due to its decentralized federal system and land rights policies. The complexity has a larger impact on the energy sector, at both the federal and state levels, with respect to leasing regulations associated with land property rights for mining, (e.g., federal, tribal, state and private land), state regulations for coal mine and oil and gas exploitation activities, and interstate gas transmission rules.

FIGURE 2.1: EXISTING GOVERNANCE STRUCTURE FOR METHANE MITIGATION IN THE U.S. AND CHINA.

PHMSA stands for the Department of Transportation’s Pipeline and Hazardous Materials Safety Administration. FERC stands for the Federal Energy Regulatory Commission. BLM stands for the Bureau of Land Management.



The Environmental Protection Agency (EPA) of the U.S. and the Ministry of Ecology and Environment (MEE) of China are the agencies that supervise methane mitigation in each country. China’s National Development and Reform Commission (NDRC) is a macroeconomic management agency in China which has broad administrative and planning control over socio-economic development, including leading on the achievement of dual-carbon objectives. It serves as the overarching planning entity for many of China’s climate actions. It also supervises

resource conservation and utilization, such as promoting a circular economy for material reuse and recycling, which is key to methane emissions reduction in the waste sector. It is worth noting that municipal and rural solid waste is primarily managed by the Ministry of Housing and Urban-Rural Development (MOHURD) in China, subject to regulations from MEE, while in the U.S. state and local governments are responsible for landfills and wastewater treatment, subject to regulations from the EPA and other state and local oversight.

2.2 FEDERAL/CENTRAL POLICY FRAMEWORKS IN THE U.S. AND CHINA

Methane emissions reduction is not exclusive to the climate change agenda, but methane's multiple physical properties make it unique for mitigation policy. In contrast to carbon dioxide (CO₂), for example, which, under most conditions, is an inert gas, methane (CH₄) is combustible and explosive when mixed with air at 5%-14% by volume. Methane thus is a greenhouse gas, an explosive hazard, an energy/industrial resource, and impacts atmospheric chemistry. That means that due to safety concerns and economic benefits, the incentives to reduce CH₄ emissions are comparatively stronger than those for reducing CO₂ emissions, even in the absence of carbon markets, as the benefits are more easily monetized with sufficiently high volumes of capture and utilization. For example, because coal mine methane (CMM) and coalbed methane (CBM) have been considered "unconventional" sources of natural gas, they have enjoyed government support for decades in the U.S. and China. Therefore, many policies have already been made to address methane emissions, directly or indirectly, in both countries. These existing policies also lay a foundation for future actions and help to identify the gaps that need to be addressed. One important principle for future policy making is to reinforce the existing drivers of methane mitigation and to create new incentives for further emissions reduction.

This section provides a holistic and systematic review and mapping of existing methane-related policies at the federal and central levels in the U.S. and China, with the goal of identifying commonalities and differences. The analysis includes policies that are directly targeted in methane mitigation and those that were originally designed for sectoral targets, such as coal mining safety, industrial development, and

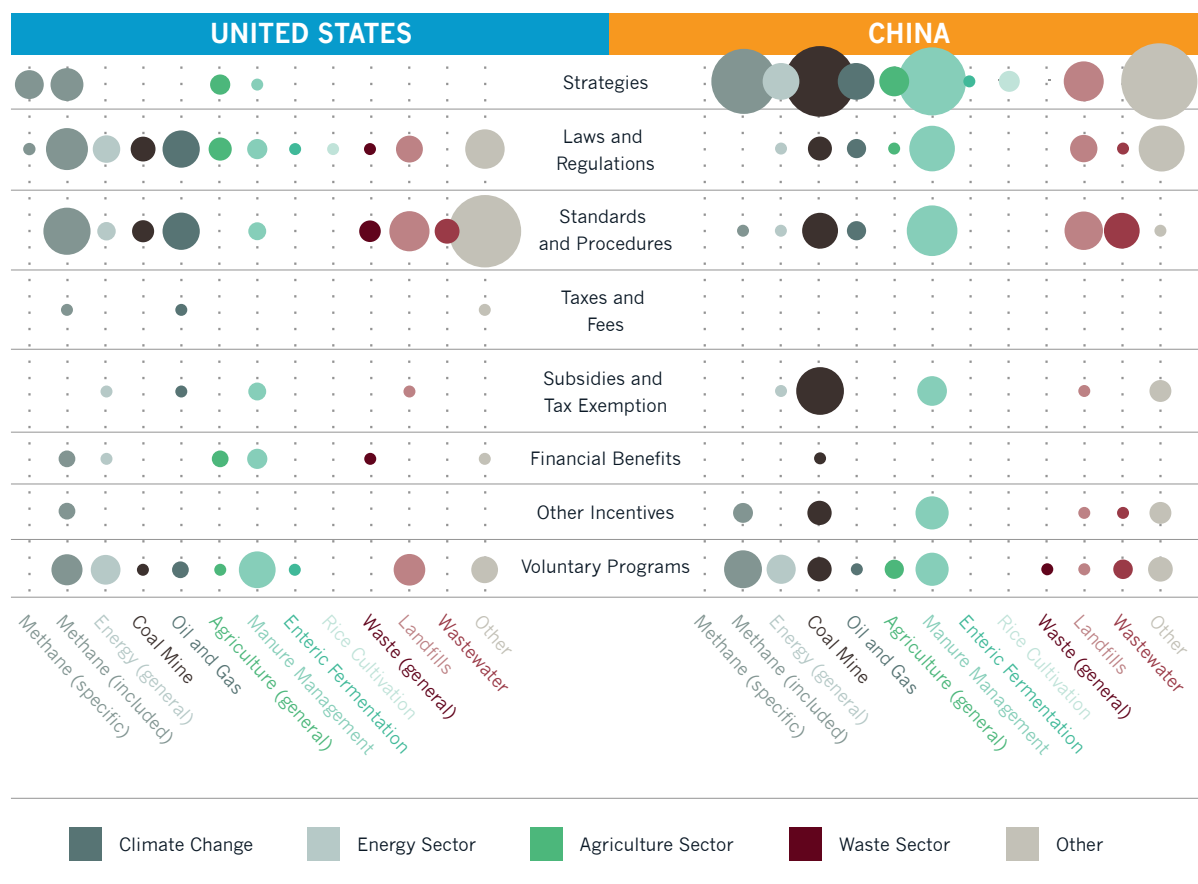
resource conservation, but that have methane emissions control as a co-benefit. To present a comprehensive picture, a total of over 4,000 policy documents with the keyword "methane" and its synonyms were reviewed from policy databases in both countries. Around 500 most relevant policy documents were selected for further analysis – approximately 250 for each country – and categorized according to both sectoral and policy dimensions (Figure 2.2). The goal is to understand how methane emissions have been addressed, both in climate change and other sectoral contexts, and what types of policy instruments are used in these sectors, including strategic planning (e.g., action plans or the Five-Year Plans); regulatory policies (e.g., laws, regulations and rules); incentive-based policies (e.g., carbon markets, tax credits, exemptions, and subsidies); and voluntary policies (e.g., pilots and government-sponsored programs). The following section: (1) elaborates on the commonalities and differences between the U.S. and China by sector and with respect to the policy agenda, sectoral focus and areas that need future attention, as well as by preferred policy instruments; (2) identifies the existing drivers of methane mitigation; and (3) identifies gaps in the current policy frameworks of both countries.

The analysis in this chapter focuses on providing a better understanding of what methane policies exist in each country and what types of policies have historically been utilized most. It is important to note that the type of policies does not in itself necessarily indicate the overall level of policy-driven action, the level of effort or difficulty inherent in achieving the existing policies, or the projected emissions reductions from existing or potential new policies.



FIGURE 2.2: A COMPARISON OF THE U.S. AND CHINA IN TERMS OF METHANE-RELATED POLICIES BY SECTOR AND POLICY TYPE.

See the list of key policies in the Summary for Policymakers.



The Development of Methane Mitigation Policies in the U.S.

In the United States, methane and other greenhouse gases are defined as air pollutants that endanger public health and welfare. As a component of U.S. climate change strategy, methane mitigation was addressed in the 1993 Climate Change Action Plan signed by President Clinton and the 2013 Climate Action Plan signed by President Obama. Methane mitigation has become a specific focus of climate change mitigation since the Climate Action Plan: Strategy to Reduce Methane Emissions was released in 2014 by the White House. In 2015, the Obama Administration set the first U.S. methane emissions target: to cut methane

emissions from the oil and gas sector by 40%-45% from its 2012 level by 2025 (EPA, 2016). The Biden Administration released the U.S. Methane Emissions Reduction Action Plan in 2021, which detailed the national strategies for methane mitigation (U.S. Congress, 2022). Most recently, the Inflation Reduction Act of 2022 (IRA) was passed as a historic climate deal which aims to reduce greenhouse gas emissions by 40% from the 2005 levels by 2030 and is by far the strongest legislation of methane emissions in the United States. In addition, the United States co-led and signed the Global Methane Pledge at COP26, which commits signatories (currently over 120 countries) to a collective goal of 30% reductions in methane emissions by 2030.

Methane mitigation was officially incorporated in the national climate policy agenda in 1992 through the Voluntary Greenhouse Gas Reporting Program required by the Energy Policy Act and implemented by the Department of Energy (DOE). This established the U.S. greenhouse gas reporting scheme, which includes detailed inventories of methane emissions. In 2009, greenhouse gas reporting (GHGRP) became an EPA mandate. This requires large sources and suppliers in the United States to report greenhouse gas emissions annually. Under the GHGRP, methane emissions from underground coal mines, industrial wastewater, municipal solid waste, and industrial waste landfill sectors, as well as the petroleum and natural gas systems, must be monitored and reported (EPA, 2010a, 2010b). Even though methane emissions have not yet been regulated in U.S. coal-fired and natural gas power

utilities (EPA, 2015a, 2015b), methane reductions are a co-benefit highlighted by the CO₂ emissions regulations as well as by the Clean Power Plan, finalized in 2015 and targeted at the power sector.

Notably, in the U.S. there are two compliance and three voluntary GHG emissions trading programs at the regional level. Four of these allow methane emissions reductions and offsets from most sectors, including coal mines (CMM, AMM, SMM and VAM)¹, oil and gas, landfills, livestock and rice cultivation. The four GHG emissions trading programs are the California Compliance Offset Program (COP), the Climate Action Reserve (CAR), Verra's Verified Carbon Standard (VCS), and the American Carbon Registry (ACR) (Table 2.1). The Regional Greenhouse Gas Initiative (RGGI) does not yet cover methane emissions.

TABLE 2.1: COMPARISON OF U.S. GHG EMISSIONS TRADING PROGRAMS FOR METHANE MITIGATION PROJECTS.

Information collected from EPA reports (EPA, 2021a) and the websites of these programs.

	COP	CAR	VCS	ACR
Type	Compliance	Voluntary	Voluntary	Voluntary
Eligible Project Location	U.S.	U.S.	Global	North America
Methane Sources	CMM, AMM, SMM, VAM, Manure management	CMM, VAM, Rice cultivation, Landfills, Wastewater, Manure management, Enteric fermentation	CMM, AMM, SMM, VAM, Oil & Gas, Manure management, Enteric fermentation, Landfills, Wastewater, Rice cultivation	CMM, AMM, SMM, VAM, Landfills, Wastewater, Manure management (inactive), Enteric fermentation (inactive), Rice cultivation (inactive)

¹ Abandoned mine methane (AMM), surface mine methane (SMM), ventilation air methane (VAM)



TABLE 2.2: PROGRESS OF METHANE LEGISLATION IN THE U.S. SINCE THE GLASGOW CLIMATE CHANGE CONFERENCE (COP26).

Policies collected by July 27, 2022.

Policies	Introduced Date	Sector	Current Status ²
H.R. 2471 - Consolidated Appropriations Act, 2022	April 2021	Livestock	Became Law
Infrastructure Investment and Jobs Act (Bipartisan Infrastructure Law of 2021)	June 2021	Oil & Gas	Became Law
H. R. 4521 - United States Innovation and Competition Act of 2021	July 2021	Climate change	Resolving Differences
Inflation Reduction Act of 2022	September 2021	Climate change	Became Law
H. R. 6168 - Future Generations Protection Act	December 2021	Climate change	Introduced
H. R. 6351 - Climate Solutions Act of 2021	December 2021	Climate change	Introduced
S. 3400 - Marginal Well Protection Act	December 2021	Oil & Gas	Introduced
S. 3714 - American Energy Independence Act of 2022	February 2022	Oil & Gas	Introduced
S. 3699 - Department of Energy Science for the Future Act of 2022	February 2022	Livestock	Introduced
S. 3822 - Energy Regulations Certainty Act	March 2022	Oil & Gas	Introduced
H. R. 7094 - Energy Freedom Act	March 2022	Oil & Gas	Introduced
H. R. 7131 - Great Lakes Authority Act of 2022	March 2022	Energy	Introduced
H. RES. 1148 - Recognizing the benefits of natural gas to the United States economy and environment, recognizing natural gas as an affordable and "green" energy.	May 2022	Oil & Gas	Introduced
S. 4355 - Clean Competition Act	June 2022	Climate change	Introduced

Methane-related legislative progress has been made in the U.S. since COP26. From the end of 2021 to date, 14 congressional bills have been introduced or made major progress regarding methane mitigation in various sectors (Table 2.2). Most significantly, the IRA provides economic incentives for methane mitigation actions, including monitoring and reporting mechanisms in the oil and gas sector. It also regulates methane gas waste from oil and gas production processes by imposing charges, known as the methane fee (See Box 2.1 for more details).

² Updated on September 27, 2022.

BOX 2.1 THE INFLATION REDUCTION ACT (IRA) ON METHANE MITIGATION

The Inflation Reduction Act (IRA) facilitates \$369 billion of investment in climate change mitigation and clean energy transition. Specifically, it addresses methane emissions by deploying a set of policy tools, including funding methane mitigation actions, providing tax credits for market actors, and charging methane fees. It has direct impacts on the oil and gas, agriculture, and waste sectors with respect to methane emissions reduction. Methane mitigation outcomes can be achieved through key measures, including:

1. Strengthening Methane Monitoring and Reporting.

- ▶ The IRA aims to improve the capacity to monitor methane emissions by appropriating funding of \$20 million to EPA from 2022 to 2031 as a part of the Greenhouse Gas Reduction Fund. The activities and grants covered by this funding include: (1) research and development program for prevention and control of air pollution; (2) authorized activities in establishing research and development programs; (3) air pollutant monitoring, analysis, modeling, and inventory research; and (4) grants for support of air pollution planning and control programs.
- ▶ The IRA also aims to strengthen greenhouse gas corporate reporting by appropriating \$5 million to EPA through 2031 to support: (1) enhanced standardization and transparency of corporate climate action commitments and plans to reduce greenhouse gas; and (2) enhanced transparency for meeting these commitments and implementing those plans.

2. Regulating the Oil and Gas Sector. The IRA puts a great emphasis on this sector through both economic incentives and penalties by developing the Methane Emissions and Waste Reduction Program for Petroleum and Natural Gas Systems through EPA.

The program includes:

- ▶ **Incentives for Methane Mitigation and Monitoring.** \$850 million is appropriated to EPA through 2028 to support methane mitigation activities, including for: (1) providing financial and technical assistance to owners and operators of applicable facilities to prepare and submit GHG reports; (2) methane emissions monitoring; (3) providing financial and technical assistance to reduce methane and other GHG emissions and

mitigate legacy air pollution from the oil and gas sector; as well as (4) funding for climate resiliency of communities, industrial equipment and processes that reduce methane, innovation in reducing methane emissions, permanently shutting in and plugging wells on non-Federal land, and mitigating health effects of methane emissions.

- ▶ **Incentives for Methane Mitigation from Conventional Wells.** Funding of \$700 million is appropriated to EPA through 2028 specifically for methane mitigation activities at the marginal conventional wells – i.e., wells that have low production rates and/or high production costs from its location.
- ▶ **Waste Emissions Charge.** This is also known as the **methane fee**, where a charge is imposed on methane emissions that exceed applicable waste emissions thresholds listed in the Act from facilities that report more than 25,000 Mt of carbon dioxide equivalent (CO₂e) of GHGs emitted per year. The charge is applicable to facilities for onshore and offshore oil and gas production, onshore natural gas transmission, processing, gathering and boosting, underground and liquified natural gas storage, and liquified natural gas import and export equipment. The charges will increase on a yearly basis: \$900/ton for 2024; \$1,200 for 2025; \$1,500 for 2026 and each year after. A number of exemptions for the waste emissions charges are available under multiple conditions. Nevertheless, in aggregate this fee represents a major new U.S. policy and it is expected with high confidence that it should make a large impact on overall methane emissions.

In addition, the IRA also imposes royalties on all methane extracted from federal land and on the Outer Continental Shelf, including gas that is consumed or lost by venting, flaring, or negligent releases during upstream operations, with a few exceptions. The legislation also may increase both onshore and offshore royalty rates from 12.5% to 16.67%, and up to 18.75% in some cases.

3. Supporting Agricultural and Rural Methane Mitigation Practices. The IRA provides strong incentives to boost methane mitigation efforts in the agriculture sector. Approximately \$40 billion – roughly

10% of the funds approved for climate change and clean energy investment in the IRA— will go to the agriculture sector.

▶ **Additional Agricultural Conservation Investments**

- Environmental Quality Incentives Program. This program receives \$8.45 billion through 2031. The funding prioritizes proposals that utilize diet and feed management to reduce enteric fermentation methane emissions. It also supports agricultural conservation practices, including GHG reduction and capture/sequestration associated with agricultural production, and prioritizes projects and activities that mitigate or address climate change through the management of agricultural production, including reducing or avoiding methane emissions among other GHGs.
 - The Conservation Stewardship Program. This program receives \$3.25 billion to address climate change in agricultural activities.
 - The Agricultural Conservation Easement Program. This program receives \$1.4 billion for climate actions in the sector.
 - The Regional Conservation Partnership Program. This program receives \$6.75 billion to support reducing, capturing and sequestering GHGs associated with agricultural production and other climate actions in this sector, including leveraging supply chain sustainability commitments and utilizing models that pay for methane mitigation in the sector.
- ▶ **Conservation Technical Assistance.** IRA provides \$1 billion to support conservation technical assistance and \$300 million to carry out a carbon sequestration and GHG emissions quantification program, which collects field-based data to assess GHG mitigation outcomes associated with agricultural activities
- ▶ **Additional Funding for Electric Loans for Renewable Energy.** This provision aims to support renewable electrical power development in rural areas. The IRA provides \$1 billion through 2031 for the cost of loans that are forgiven for related projects. This action can contribute to methane

mitigation by providing incentives to biogas production and utilization in manure management.

- ▶ **Rural Energy for America Program (REAP).** REAP is a major existing program for rural energy development, including biogas recovery, a common technological approach for manure management. The IRA enhances REAP by providing over \$1 billion in grant funds through 2031. In addition, underutilized renewable energy technologies in rural areas are supported by the program with additional funding of \$177 million through 2031.
- ▶ **Biofuel Infrastructure and Agriculture Product Market.** \$500 million is appropriated through 2031 to increase the sale and use of agricultural commodity-based fuels through infrastructure improvements for blending, storing, supplying and distributing biofuel. This contributes to methane mitigation in rural areas by improving biogas infrastructure.
- ▶ **U.S. Department of Agriculture (USDA) Assistance for Rural Electric Cooperatives.** This provision also contributes to biogas utilization in rural areas by supporting electric cooperatives for robust and zero-emission rural electric systems. \$9.7 billion is provided through 2031.

4. **Benefitting Biogas/Landfill Gas Production and Utilization. Biogas production and utilization has been supported through diverse rural development programs and other policies to increase biogas, or landfill gas.** The IRA provides additional incentives, particularly in expanding tax credits for biogas operations that begin construction before 2025. The incentives will have positive impacts on both manure management and the waste sector.
5. **Improving Energy Infrastructure. The IRA supports new investments in energy infrastructure, enhancing the effectiveness of methane mitigation in energy-related activities, such as methane recovery and utilization in the coal mine and oil and gas sectors.** The Energy Infrastructure Reinvestment Financing proposes \$5 billion through 2026 to support the redevelopment of energy infrastructure that can avoid, reduce, utilize, or sequester GHG emissions, including methane. Energy infrastructures in the IRA include those for the generation and transmission of electric energy

and the production, processing, and delivery of fossil fuels, fuels derived from petroleum, or petrochemical feedstocks.

6. Reducing Methane Emissions as Climate Pollutants. Several provisions targeting GHG pollution will contribute to methane mitigation.

- ▶ **Greenhouse Gas Air Pollution Plans and Implementation Grants.** The IRA appropriates two sets of grants – the Greenhouse Gas Air Pollution Planning Grants and the Greenhouse Gas Air Pollution Implementation Grants – to support eligible entities in developing and then implementing plans to reduce greenhouse gas air pollution. \$250 million and \$4.75 billion are provided for the two grants through 2031 and 2026, respectively.
- ▶ **Greenhouse Gas Reduction Fund.** The fund is appropriated to state and local governments to provide financial and technical assistance for climate actions in disadvantaged communities on a competitive basis. The fund provides \$7 billion through 2024 to enable low-income and disadvantaged communities to deploy or benefit from zero-emission technologies and carry out GHG emissions reduction activities. The fund also provides around \$12 billion through 2024 for general assistance for GHG mitigation activities. In addition, \$8 billion is provided for financial and technical assistance in low-income and disadvantaged communities.



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Coal Mine Sector

Concern over methane emissions first emerged as a consideration in U.S. energy policy prior to its appearance in the climate agenda. Coal mine safety was the primary initial focus of methane emissions control. The federal government started to investigate coal mine safety in 1941, after the promulgation of the Act of Coal Mines, Inspections and Investigations. The Federal Coal Mine Health and Safety Act was first enacted in 1969 and amended in 1977 (known as the Mine Act). It is the legislation that currently governs coal mine safety in the U.S. The Act regulated coal mine methane emissions by monitoring drainage and ventilation to keep the emissions well below the lower explosive limit. However, the act does not require actions to cut methane emissions. No further laws or regulations have since been enacted at the federal level to mandate methane emissions in the coal mine sector.

In addition to coal mine safety concerns, the resource view of CMM also contributed to methane emissions reduction in the U.S. It is worth mentioning that the development of coalbed methane (CBM) is differentiated from CMM recovery in U.S. policy. CBM has been considered as an unconventional natural gas industry, independent from coal mining. It refers to methane in coal seams that will never be mined. CMM, however, refers to the byproduct of coal mining activities. The production of CBM in the U.S. does not necessarily contribute to methane emissions reductions. However, in China, CBM and CMM are generally considered to be the same even though CBM development belongs to the oil and gas industry. This is because the development of CBM has been largely accompanied by coal mine activities since coal plays a significant role in China's energy system.

This does not mean that the CBM industry is irrelevant to CMM recovery in the U.S. In response to the energy crisis of the late 1970s, the Powerplant and Industrial Fuel Use Act of 1978 prohibited the use of natural gas to fuel power plants. Nevertheless, unmarketable "high-cost gas," including methane from coal seams, was excluded from this act, which laid a foundation

for the development of CBM and CMM. The Windfall Profit Act of 1980 further encouraged unconventional gas development, including CBM and CMM, to cope with the energy crisis. The Section 29 Production Tax Credits of the Act provided strong incentives for CMM recovery in the U.S. The Energy Policy Act of 1992 also encouraged the production of waste methane from coal mines as an alternative fuel. In 1993, the EPA launched the Coalbed Methane Outreach Program (CMOP) to work with the coal mining industry to reduce coal mine methane (CMM) emissions through recovery and use projects. By 2017, there were 13 active underground mines and 20 abandoned mine methane (AMM) projects supervising 51 abandoned coal mines operating methane recovery and use (EPA, 2019a).

Notably, at the state government level many U.S. states have considered CMM as an important alternative energy source to help meet their Renewable Portfolio Standards (RPSs), which direct electricity providers to generate minimum shares of their power from eligible energy sources such as wind and solar. Some of the top coal-producing states, such as Pennsylvania, Ohio, Utah, Indiana, and Colorado, have included CMM in their renewable energy strategies.

Oil and Gas Sector

The oil and gas sector has been an important focus of U.S. emissions policy for several decades. There have been three primary sets of policies targeting methane emissions from this sector: (1) distribution and pipeline transportation safety; (2) coping with climate change; and (3) resource conservation and recovery. However, some of the key regulations for methane mitigation have faced a series of administrative and legal challenges that have impeded full implementation of some of those regulations (GAO, 2022).

For the first target, the Department of Transportation issued "Leakage Surveys on Distribution Lines Located Outside Business Districts" in 1993, which required distribution lines to use methane leak detectors for mandated leakage surveys. In 2016, the Protecting Our

Infrastructure of Pipelines and Enhancing Safety (PIPES) Act was promulgated, then amended in 2020. Aiming to advance the safe transportation of energy and other hazardous materials, the Act directs the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) to take regulatory actions related to pipeline safety, including methane emissions mitigation, by updating the leak detection and repair regulatory requirements. More recently since November 2021, PHMSA has been directed by the Bipartisan Infrastructure Law (BIL), which aims to rebuild infrastructure in the U.S., including natural gas pipelines, to minimize methane emissions from gas leak through multiple rulemakings. Specifically, PHMSA is implementing the Natural Gas Distribution Infrastructure Safety and Modernization Grant Program, which is established under the BIL. The program provides \$200 million annually for five years to improve the safety of high-risk, leak-prone natural gas distribution infrastructure in both urban and rural areas (PHMSA, 2022). The second target – coping with climate change – has been a major driver of methane mitigation in the sector. The EPA launched its Natural Gas STAR program in 1993. The program provided a framework for the U.S. oil and gas industry to implement methane-reducing technologies and track the voluntary emissions reduction activities of industrial participants. In addition, the New Source Performance Standards (NSPS) of the oil and gas sector issued in 2012 by the EPA originally regulated air pollutants, primarily volatile organic compounds (VOCs) emissions, from new facilities. While originally only targeting conventional air pollutants, these standards also result in methane emission reductions. The 2016 amendments of the Oil and Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources first set standards for GHGs, specifically methane emissions. The rule requires a 95% reduction of all emissions, including methane, from new or substantially upgraded wet seal centrifugal compressors and pneumatic pumps. It also requires owners/operators to capture excess emissions and route them to a process or flare and adds methane standards for reciprocating compressors. The EPA rule covers crude oil and gas production, natural gas transmission, and

storage. However, the EPA regulation only has effects on facilities constructed, modified, or reconstructed after September 18, 2015. Facilities in existence prior to that time are not regulated by this rule. Due to administrative challenges, the EPA rescinded the 2016 methane standards and eliminated all oil and gas NSPS requirements for sources in the transportation and storage processes in the 2020 policy rule. The 2016 standards and requirements for methane were reinstated in 2021 as the Congress passed and the President signed a resolution of disapproval under the Congressional Review Act for the 2020 Policy Rule (GAO, 2022).

In 2021, the EPA proposed new standards to further address methane emissions from new sources and, for the first time, address existing sources. The standards require the use of zero-emission technologies and regular monitoring for leaks, and methane emissions from small wells to be addressed (Watson & LaMair, 2021). This brief summary highlights the complex regulatory landscape in the United States.

The IRA covers both new and existing sources, as well as natural gas gathering, transmission and storage. In addition, the IRA of 2022 aims to strengthen methane mitigation efforts in this sector by amending the Clean Air Act to provide economic assistance for methane monitoring and mitigation activities of the marginal wells, and charge fees for excessive methane emissions (see Box 2.1 for more details).

The third target - encouraging resource conservation and recovery - was supported by Waste Prevention, Production Subject to Royalties, and Resource Conservation – a regulation issued by the Bureau of Land Management (BLM) in 2016. It was rooted in the Mineral Leasing Act of 1920, which required the BLM to ensure that oil and gas operators “use all reasonable precautions to prevent waste of oil or gas.” The goal of the BLM regulations is to reduce natural gas leakage in production activities and prevent reductions in royalty revenue. It replaced the 1979 Notice to Lessees and Operators of Onshore Federal and Indian Oil and Gas Leases,



Royalty or Compensation for Oil and Gas Lost, and updated the regulations to reduce natural gas waste from venting, flaring, and leaks during oil and gas production activities on federal and tribal lands, for both new and existing facilities. This rule further strengthened methane mitigation by recognizing methane emissions as a waste of valuable resources. It required operators to reduce flaring by capturing the emissions for utilization in production activities. It also required operators to carry out Leakage Detection and Repair (LDAR) at their well sites and for associated equipment. In addition, it specified when produced gas lost through venting, flaring, or leaks was subject to royalties and when oil and gas production may be used royalty-free on-site. In particular, a

loss of gas was subject to royalties when it was considered “avoidable,” and royalty-free when it was unavoidable. However, similar to the EPA rule, the 2016 BLM rule was mostly vacated due to legal challenges, resulting in the BLM reverting to the 1979 standards (GAO, 2022). Nevertheless, the IRA mandates royalties for all extracted methane from the oil and gas upstream operations and increases royalty rates from 12.5% to 16.67% and up to 18.75%.

The loss of gas and methane emissions and regulations on VOC emissions from well sites have also been regulated by many states, including Wyoming, California, Colorado, North Dakota, Texas, and Pennsylvania (Table 2.3).

TABLE 2.3: EXAMPLES OF STATE REGULATORY REQUIREMENTS TO REDUCE METHANE EMISSIONS.

Source: modified from GAO report (GAO, 2022).

	Regulate methane or volatile organic compounds (VOCs)	State regulation of existing sources	State leak detection and repair (LDAR) program	Requirement for equipment
California	Methane and VOCs	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Colorado	Methane and VOCs	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
North Dakota	Methane and VOCs	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Pennsylvania	Methane and VOCs	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Texas	VOCs	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Wyoming	Methane and VOCs	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Waste Sector

The U.S. started to regulate methane emissions in the waste sector not long after the energy sector initiated such regulations. The Resource Conservation and Recovery Act of 1976 (RCRA), an amendment of the Solid Waste Disposal Act of 1965, emphasized solid waste as a potential source of gas that could be converted into energy. In 1979, the EPA promulgated the Criteria for Classification of Solid Waste Disposal Facilities

and Practices, in which methane was first identified as the principal source of explosions associated with solid waste disposal and indicated that it needed to be controlled below the lower explosive limits. Methane was recognized as a GHG emission contributing to global climate change in the waste sector for the first time in the Standards for the Use or Disposal of Sewage Sludge in 1993. A major regulation for landfill wastewater management, the policy mandated

the collection and treatment of leachate to control methane gas and required facility owners to monitor methane gas for three years after the closing of the last active sewage sludge. It specified that, for safety concerns, the volume of methane gas for sludge treatment should not exceed 25% of the lower explosive limit. Methane recovery was also encouraged in this policy.

Under the Clean Air Act, methane emissions were further clarified as GHG emissions in the Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills in 1996 issued by EPA (known as the New Source Performance Standards -NSPS). It mandated landfill gas collection and limited non-methane organic compounds (NMOCs) emissions from landfills of a certain size in the United States. Even though this and the most recent updated NSPS for municipal solid waste in 2016 did not set up a specific target for landfill methane emissions, it has been a primary concern in these policies and has been regulated indirectly through NMOCs. For existing sites, EPA issued the 2003 National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills (known as the MSW landfills National Emission Standards for Hazardous Air Pollutants [NESHAP]), which was updated in 2016 and finalized in 2020. This policy regulates hazardous air pollutant emissions from MSW landfills that are major or regional sources and have been in operation since 1987. It requires the owner or operator of a landfill to control the gas by installing a collection and control system (GCCS), flare and combustion devices or recovery treatment systems. For new sites, the Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills issued in 2016 and its amendments emphasized the significance of this regulation on methane emissions reduction. The most recent rule limits NMOCs emissions from the new facilities to no more than 34Mg/year (lowered from 50Mg/year). In addition, the EPA launched the Landfill Methane Outreach Program (LMOP), which is a voluntary program that works closely with industry stakeholders and policy makers in the waste sector to reduce/avoid methane emissions from

landfills. The program encourages the recovery and utilization of biogas generated from landfills. In addition, the IRA of 2022 will have a direct impact on landfill gas recovery and utilization as it expands tax credits for biogas operations.

Agriculture Sector

Methane emissions from the agriculture sector in the U.S. have generally attracted less attention than other sectors. There has been no federal mandate for methane emissions regulation in the agriculture sector. Among the three subsectors of agriculture methane emissions – manure management, enteric fermentation, and rice cultivation – manure management has more methane-relevant policies than the others due to pollution and energy recovery concerns. First, the U.S. regulates manure discharge through the National Pollutant Discharge Elimination System (NPDES) Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs) issued in 2003. This rule has ensured that appropriate actions are taken to effectively manage manure from large CAFOs, with the aim of protecting the nation's water quality. It also emphasizes methane emissions reduction as a co-benefit.

Second, biogas recovery is an important means of utilizing methane emissions from livestock manure. The U.S. supports biogas production with various laws and policies. The Energy Policy Act, the Agriculture Act of 2014, and the 2018 Farm Bill encourage biofuel investment and production in farms and rural areas. Multiple biobased energy programs, including the Rural Energy for America Program (REAP) and AgSTAR, have been established. Economic incentives for biogas in the U.S. include tax credits (e.g., the Renewable Fuels Production Tax Credit, the Alternative Fuel Excise Tax Credit, the Renewable Electricity Production Tax Credit) and guaranteed loans.

However, climate change has been an increasing concern in the agriculture sector. One of the most important commitments of agriculture methane mitigation was the agreement by the U.S. Department of Agriculture (USDA) and U.S.



dairy producers in 2009 to reduce greenhouse gas emissions by 25% by the year 2020. Yet the emissions reduction target was not achieved as the dairy cattle emissions increased from 2010 to 2020 (EPA, 2022b). In addition, the USDA announced its climate change adaptation plan in 2014, which addressed the agency's action on methane mitigation. Even though enteric fermentation and rice cultivation emissions have not been addressed specifically in the existing policy framework, they were mentioned in the Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program issued by the EPA in 2010 as part of the life-cycle assessment for renewable fuels. Currently, the USDA is establishing an Interagency Biogas Opportunities Task Force to facilitate the collection and use of methane for on-farm renewable energy applications. It has also initiated an incentive-based "climate-smart" agriculture program that will reward farmers and ranchers for reducing methane emissions. A Climate-Smart Partnership Initiative will be launched to explore the establishment of new markets for agricultural commodities based on the application of a climate-friendly supply chain.

More recently, the IRA of 2022 provides strong economic incentives for climate actions in the agriculture sector. Approximately \$40 billion – around 10% of the total IRA funds – will support this sector to cope with climate challenges (see Box 2.1 for more details). Even though those provisions for agricultural GHG emissions reduction do not include methane emissions, funds are also available for methane mitigation in the sector. In particular, reducing emissions from enteric fermentation by feed management is supported by the Environmental Quality Incentives Program. Rural renewable energy, including biogas, is strongly supported by funding through several programs in the IRA.

The Development of Methane Mitigation Policies in China

As a climate challenge, methane emissions reductions did not attract significant attention from the Chinese government until recently. Methane is not currently included as a mandate in China's 2030 carbon peak. Methane mitigation is also not mandatory in China's updated 2030 Nationally Determined Contribution (NDC) despite that the NDC briefly touches upon some of the methane mitigation efforts, such as reducing methane emissions from the energy sector, developing coalbed methane, as well as strengthening manure management and biogas development. However, methane was not completely missing from China's climate policy discourse. China's 2060 carbon neutrality target covers non-CO₂ greenhouse gases, including methane. Methane recovery was listed as a key area in the Administrative Provisions of Clean Development Mechanism (CDM) Projects in 2005, the first time that methane mitigation was mentioned in a climate policy document (NDRC et al., 2005). The CDM projects played an indispensable role in methane mitigation actions in China. Nearly 300 methane projects on coal mine methane (CMM), manure, oil and gas, and wastewater were supported by CDM in China³.

China's National Climate Program, released in 2007, expressed ambition in methane mitigation in various sectors, including coal mine, manure management and enteric fermentation, rice cultivation, and municipal solid waste. The general aim of methane mitigation was brought up in numerous national climate plans, such as the 12th and the 13th Five-Year Plans for GHG Emissions Control, and the National Plan for Tackling Climate Change (2014-2020) (NDRC, 2014; The State Council, 2011, 2016). It was also mentioned in the Central Government's Notice on Promoting Ecological Civilization, issued in 2015, which has been one of China's most important policy documents on sustainable development.

³ 285 methane-related projects are included in the CDM database.

While no specific commitment or detailed plan has yet been made to reduce methane emissions, China has raised its ambition to tackle methane emissions since 2021. Methane mitigation was mentioned for the first time in the 14th Five-Year Plan (FYP) for National Economic and Social Development (2021-2025). This indicates that the issue has risen in the national policy agenda. Methane emissions are also addressed in the key national action plans and strategies for climate change, including the Action Plan for Reaching Carbon Emissions Peak before 2030 and the Central Government's Opinion on Implementing the Carbon Peak Emissions and Carbon Neutrality Targets, issued in 2021 (The State Council, 2021a, 2021b). However, direct methane targets and mandates are not yet included in these national action plans. With respect to carbon markets,

the China Certified Emission Reduction (CCER) initiated in 2012 has served as a major emissions trading platform for methane emissions. CCER refers to emissions reduction activities conducted by companies on a voluntary basis, and are those certified by the Chinese government. Methane-related CCER covered various sectors such as landfill gas, liquefied natural gas (LNG), and biogas projects. Approval of CCER was suspended in 2017; however, according to the "Administration of National Carbon Emission Trading" (2020) (MEE, 2020), CCER was still considered a key method for methane mitigation, increasing the expectation that it will soon be reinstated.

Since the U.S.-China Joint Glasgow Declaration, ten policies which address methane mitigation actions have been issued (Table 2.4).

TABLE 2.4: PROGRESS OF METHANE POLICY-MAKING IN CHINA SINCE THE GLASGOW CLIMATE CHANGE CONFERENCE (COP26).

All the policies were collected by July 27, 2022.

Policies	Date of Issue	Sector
Opinions on Implementing Accelerating Rural Energy Transformation and Development to Promote Rural Revitalization (2021)	Dec. 2021	Agriculture
The 14 th Five-Year Plan on Soil, Underground Water and Rural Ecological and Environmental Protection	Dec. 2021	Agriculture
Guideline on Promoting Ecological Farms	Jan. 2022	Agriculture
The Action Plan for Agricultural and Rural Pollution Control (2021-2025)	Jan. 2022	Agriculture
Notice of the Ministry of Housing and Urban-Rural Development on Organizing the Application for 2022 Science and Technology Plan Projects	Jan. 2022	Landfills
Opinions on Improving the System, Mechanism and Policy Measures for the Green and Low-Carbon Transformation of Energy	Jan. 2022	Climate
Notice of the State Council on Printing and Distributing the "14 th Five-Year Plan" to Promote the Modernization of Agriculture and Rural Areas	Nov. 2021	Agriculture
The 14 th Five-Year Plan on Modern Energy System Planning	Mar. 2022	Energy
Implementation Plan for Improving Synergistic Effect of Pollution Reduction and Carbon Reduction	June 2022	Waste
Implementation Plan on Emissions Reduction and Carbon Sequestration for Agriculture and Rural Areas	June 2022	Agriculture



Coal Mine Sector

Similar to the U.S., concern for methane emissions first emerged as a safety issue in China's coal mine sector. As the world's largest coal producer, China has long faced significant challenges related to CMM. CMM-related explosions in China once caused large numbers of coal mine worker fatalities every year. The first major regulation in coal mine safety with respect to CMM control, the Safety Code for Coal Mines issued in 1952, has been amended over the decades (Fuel Industry Press, 1952; MEM, 2022). Based on this regulation, the Norms on CMM Drainage was issued in 1997. In 2005, the central government established the Leadership Group of Inter-Ministerial Coordination for CMM Prevention and Treatment, which resolved to address the severe challenge in China's coal mine sector. In the following years, several major regulations, procedures and standards were issued for monitoring, extracting and draining CMM. In general, there are two key quantitative requirements related to methane emissions: (1) the Safety Code for Coal Mines stipulates that the safe concentration of methane in main return airways or one-wing return airways should not exceed 0.75%; and (2) the CBM/CMM Emissions Standards (2008) forbids methane venting with a volume concentration over 30% (Ministry of Environmental Protection, 2008). It also requires operators to follow the principle of "CMM drainage first and coal mining second". These regulations have constituted a milestone for the direct control of CMM emissions in China. In addition, the latest safety code requires that for new coal mines, CMM must be drained prior to beginning mining operations (State Administration of Work Safety & State Coal Mine Safety Supervision Bureau, 2016).

Recovering and utilizing CMM/CBM as an energy resource have been strongly emphasized as a key approach to tackling methane emissions in China. Even though a specific emissions reduction target has not been set for this sector, it has been mentioned as a way to limit methane/non-CO₂ emissions in several other climate-related policy documents, beginning with the Administrative

Provision of CDM Projects released in 2005 and most recently in the Action Plan for Carbon Emissions Peak before 2030 that was published in 2021. However, the drive to facilitate CMM/CBM utilization ran far ahead of methane being explicitly incorporated into China's climate agenda (Yang, 2009). In the early 1990s, the U.S. EPA provided technological outreach and financial support for a coal mine methane recovery and utilization program in China. The United Nations Development Program (UNDP) and Global Environment Facility (GEF) financed China's first coal-bed methane surface pre-drainage and underground directional drilling demonstration project in China (Yang, 2009). The assistance of the international community accelerated China's policy-making on CMM/CBM capture and utilization.

Coal mine safety and energy security were the primary driving forces behind CMM/CBM development. In 1994, the Implementation Provision of the Mineral Resource Law confirmed CMM/CBM as an independent energy industry (Chang & Zhang, 2017; The State Council, 1994). Since then, the industry has been supported by numerous policies to achieve commercialization. The key industrial policies include: (1) various sectoral FYPs since 2001; (2) the Opinions on Accelerating CBM Drainage issued by the State Council in 2006, in which the central government decided to support CMM/CBM recovery and utilization with subsidies and tax exemptions (The State Council, 2006); and (3) Industrial Policy for CBM issued in 2013. The subsidy provided to CMM/CBM utilization as household gas and chemical raw material was 0.2 RMB/m³, based on the 2007 policy from the Ministry of Finance, and was increased to 0.3 RMB/m³ from 2016 to 2019 when the subsidy was adjusted to be in accordance with the excess amount of annual production (MOF, 2016, 2019; NEA, 2007). It was decided that the subsidy for CMM/CBM power generation would be the same as the Feed-in-Tariff of biomass power – 0.25 RMB/kw since 2007 (NDRC, 2007). Most recently, the 14th Five-Year Plan on Modern Energy System Planning issued in March 2022 emphasizes that the development of CBM, among other unconventional natural gas

sources, is critical to energy security in China and therefore needs to be further encouraged. The policy also sets a target that CMM utilization should reach 6 billion m³ (NDRC & NEA, 2022).

Many local governments, such as Shanxi Province and Guizhou Province, also provide subsidies to CMM/CBM utilization. In addition to the subsidies, developers are exempt from the prospecting and licensing fees on CBM development, and no royalties are levied (MOF & State Taxation Administration, 2007). Coal mine companies equipped with coal mine drainage and recovery systems are allowed to use production safety funds to develop CMM drainage and utilization. (More detailed information on China's CMM/CBM government incentives can be found in (Yang, 2009)). China has also set quantitative targets for CMM/CBM recovery and utilization. The most recent targets of utilization rates for CMM and CBM were 50% and 90%, respectively, by 2020, as set in the 13th FYP (NEA, 2016b). In addition, recovery and utilization of the low-concentration CMM has been urged in a 2020 policy on the environmental impact assessment of coal mine development (MEE et al., 2020). The policy requires CMM with a concentration level of 8% and above to be utilized without adversely affecting safety. It also encourages the utilization options for CMM with a concentration level of 2%-8%, as well as VAM to be further explored. However, the target for CMM utilization was not met, despite the fact that it had already been lowered from the 60% threshold set in the 12th FYP. In 2018, the Ministry of Natural Resources issued a policy that set the lower limits for the utilization of multiple mine resources (Ministry of Natural Resources, 2018), including CBM. The lower limit of the CBM recovery rate was set to 86%, and the recovery factors were 37% for low permeability gas reservoirs and 30% for ultra-low permeability gas reservoirs.

Oil and Gas Sector

Compared to the extensive body of CMM/CBM policies, the Chinese government has seldom addressed methane emissions reduction explicitly in policy documents for the oil and gas sector.

The central government has not yet established direct methane emissions reduction targets for this sector. Nonetheless, the goal is often implied in relevant policies as a way to prevent the waste of natural gas and encourage energy conservation. For example, the Natural Gas Utilization Policy (NDRC, 2012b), issued in 2012, aimed at “improving the utilization efficiency and conservation”. The key national policies relevant to methane mitigation in this sector include: the 12th FYP for Natural Gas Development, which emphasized the promotion of methane gas recovery and natural gas-saving technologies, and policies that guide the oil and gas industry to recover and utilize vented methane. In addition, the Shale Gas Development Plan (2016-2020) (NEA, 2016a) also specifically states that methane emissions need to be recovered or treated during production activities.

In recent years, pollution control has become a new driving force in indirectly regulating methane emissions in the oil and gas sector. Two important policies indicate a growing awareness of this issue by Chinese policymakers: (1) the Notice of Advancing the Environmental Impact of the Oil and Gas Industry (2019) (MEE, 2019); and (2) Air Pollutants Discharge Standards for Onshore Oil and Gas Mining Activities (2020) (MEE & State Administration for Market Regulation, 2020). The first emphasizes the detection of methane leakage. The latter sets quantitative targets for air pollution abatement, including non-methane hydrocarbons (NMHC). It also requires oil and gas producers to remove methane emissions by venting or flaring if it cannot be recovered. Producers must report to the local environmental authority if they are unable to employ either method. This policy is a milestone, because it is the first time the Chinese government has expressed more detailed and explicit requirements on methane emissions reduction in this crucial sector.

Despite the lack of overarching methane mitigation targets from the central government, major oil and gas industry actors in China have nonetheless made recent commitments to reduce methane emissions from their business activities.



The three largest oil and gas producers in China — PetroChina, Sinopec, and China National Offshore Oil Corporation (CNOOC) – are central state-owned enterprises that dominate China’s oil and gas industry. Together they account for nearly 100% of China’s natural gas production and over 90% of the crude oil production. They established the China Oil and Gas Methane Alliance in 2021, in which the members must agree to limit methane emissions intensity within 0.25% (PetroChina News, 2021). To date, ten companies have joined the Alliance. PetroChina has also committed to reducing methane emissions intensity by 62.3% by 2025 from its 2017 level. Sinopec has set a target of reducing intensity by 50% by 2025 (EDF, 2021). Although there are yet no official commitments from the government, the voluntary efforts made by these giant state-owned industry actors can be taken as an indicator of national ambition and will be essential to methane emissions reduction in China’s oil and gas sector.

Waste Sector

While methane emissions from the waste sector have not attracted significant attention, it has been considered a part of China’s climate strategies since the early 2000s. In 2005, the Ministry of Housing and Urban-Rural Development released a policy document that required provincial governments to submit information on landfill gas recovery/utilization and the deployment of municipal solid waste (MSW) incinerators within their jurisdictions to support methane emissions reduction and China’s climate commitment under the Kyoto Protocol. The National Climate Change Program, released in 2007, and the National Plan for Tackling Climate Change (2014-2020) also stated the willingness to reduce landfill methane emissions by landfill gas recovery and utilization as well as by constructing municipal solid waste incinerators. The 11th FYP for Environmental Protection (2006-2010) also stated the ambition to limit methane emissions from MSW.

However, few policies have been established to directly regulate methane as a GHG. Instead, most methane-related policies in the waste sector have been driven by concerns about

safety, environmental pollution and resource conservation, especially with respect to landfills and wastewater management. In particular, methane was first addressed in wastewater treatment policies. For example, in 1986 the State Council issued the Provisions for Water Pollution Prevention and Treatment, in which biogas recovery/utilization from sludges was encouraged for resource conservation purposes. The Technological Guidelines for Sludge Treatment and Pollution Prevention of Municipal Wastewater Plants (MEE, 2009) issued in 2009 further addressed biogas recovery/utilization for sludge treatment. Methane recovery was further emphasized in Guidelines for Overall Management of Urban and Rural Sewage in County (City) Regions (Trial Version) (MHURD, 2014).

The first municipal landfill regulation was issued in 1997 - the Standard for Pollution Control on the Landfill Site for Domestic Waste (Agency of Environmental Protection, 1997), which limited the landfill methane concentration volume and required treatment for methane emissions, including utilization and flaring. Most of the standards and procedures for landfill construction and operation regulate methane emissions out of safety concerns (Ministry of Construction, 2004; MOHURD, 2003, 2009; MOHURD et al., 2010). However, methane/biogas recovery and utilization have also been encouraged by various landfill policies, including the FYPs for the Planning and Construction of Facilities of Municipal Solid Waste Treatment and Neutralization (The State Council, 2012). In addition, waste management in the rural areas still remains a prominent challenge with respect to both pollution concerns and methane mitigation. No direct policies have yet been made to address methane emissions from rural landfills and wastewater directly. Nevertheless, the Action Plan for Agricultural and Rural Pollution Control (2021-2025) sets a target for the rural wastewater treatment rate to reach 40%, which provides opportunities for methane mitigation in the waste sector in rural areas (MEE et al., 2022).

It is worth noting that while the massive deployment of MSW incinerators in China over the last decade has made large contributions to

methane emissions reduction in this sector, the motivation for this policy change was the tension created by surging amounts of MSW in the context of insufficient land availability, rather than direct methane mitigation. During the 13th FYP (2016-2020), the number of MSW incinerators in China grew by 110% (China Environment Chamber of Commerce, 2021).

Agriculture Sector

For the agriculture sector, methane mitigation was first addressed in the 2007 National Climate Program, which included the reduction of methane emissions from livestock manure and enteric fermentation, and rice cultivation. However, methane emissions and climate change mitigation in this sector drew little attention from national policymakers until 2022, when three key agricultural policies were issued. The first was the so-called “No. 1 central document”, launched on a yearly basis and generally considered the most important central government policy on agriculture and rural development. The 2022 document was the first to address the agriculture sector’s actions to cope with climate change. The policy encourages research and development of agricultural technologies to reduce carbon emissions and to increase the carbon sink, as well as value-creation for carbon sink products. The second policy was the Guidelines for Promoting Eco-Farms, in which methane emissions reduction from rice cultivation, enteric fermentation, and manure management were listed as key sectors to be supported by low-carbon compensation policies. In addition, the Department of Agriculture and Rural Affairs and the NDRC most issued the Implementation Plan on Emissions Reduction and Carbon Sequestration for Agriculture and Rural Areas (MARA & NDRC, 2022) in June 2022. This policy covers methane emissions reduction in the agriculture sector, including livestock manure management, enteric fermentation, and rice cultivation, and indicates China’s growing ambitions to tackle the problem. However, methane mitigation in this sector is generally understated in the current policy framework. In particular, specific policies for enteric fermentation and rice cultivation methane

emissions have been largely missing from the existing policy discourse.

More attention has been paid to manure management in the sustainability-related policies of the agriculture sector. As a major pollution source in rural areas, manure discharge is also regulated in China by the 2003 Discharge Standard of Pollutants for Livestock and Poultry Breeding (MEE, 2001), in which manure pollution treatment is mandated and manure utilization is strongly encouraged. The 14th Five-Year Plan on Manure Utilization and Crop-Livestock Integration issued in October 2021 detailed seven regional plans for manure management including anaerobic digester deployment to cope with water pollution and energy supply challenges. The rate of manure utilization has become a mandatory target in the 14th FYP for the Modernization of Agriculture and Rural Areas (The State Council, 2022). The target has been set to above 80% by 2025 (MEE et al., 2022; The State Council, 2022). As an important means of manure utilization, biogas has played a significant role in manure management in rural China and has contributed to China’s agricultural methane mitigation for decades (Mancl, 2020).

China has a long history of producing biogas in rural areas. China has long had a large agrarian economy, and, even today, is home to one of the world’s largest rural populations. As a clean energy and a key tool for rural development and environmental governance, biogas development remains central to numerous rural development policies and has received substantial support from the central government for nearly 40 years (The State Council, 1984). In 2021-2022, facilitating biogas development in rural areas has already been mentioned in eight policies, such as Opinions on Implementing Accelerating Rural energy Transformation and Development to Promote Rural Revitalization (NEA, 2021). The co-benefits of reducing manure pollution and providing low-cost clean energy to rural households have been emphasized by numerous policies. The central government was already determined to promote biogas development in rural areas in 1984, as indicated in the Report on Advancing Biogas



Development issued by the State Council. Biogas has been considered a pathway for promoting eco-friendly agriculture since 1985 (The State Council, 1985). The massive development of biogas started in 2001. Several subsidies were provided by the Chinese government for both anaerobic digesters deployment and biogas power generation (Qiu et al., 2013). Biogas power has enjoyed subsidies as

a renewable energy source (NDRC, 2006b) since 2006. The feed-in-tariff of biomass power has been 0.75 RMB/kw since 2010 (NDRC, 2010). Biogas companies also enjoy other preferential policies, such as tax exemptions. In addition, rural clean energy supply through manure management has been highlighted again in the 14th Five-Year Plan on Modern Energy System Planning in 2022.

2.3 KEY FINDINGS AND POLICY GAPS

Policies that have methane reduction co-benefits - particularly those that address operational safety, pollution abatement and energy security - have been the primary contributors to existing mitigation actions in both countries. Actions to limit methane emissions were taken long before the issue entered the two countries' climate change agenda, due in large part to methane's characteristics as an explosive gas and an energy source (in addition to its role as a greenhouse gas). This also indicates the importance of synergies and co-benefits for methane mitigation.

- (1) Both the U.S. and China issued safety regulations regarding methane emissions for coal mining, oil and gas production and transmission, as well as for landfills and wastewater treatment to prevent on-site explosions. Although safety regulations have minimal effects on methane emissions reduction since they often focus solely on controlling the concentration volume of methane rather than containing overall emissions, these regulations contribute to the monitoring and detection of methane emissions, which are fundamental for inventory data collection.
- (2) Both the U.S. and China have pollution abatement policies that also contribute to methane mitigation. Pollution abatement policies with a co-benefit of methane emissions reduction are found in the landfill sector in the U.S. In China, the recent air pollution regulations for the oil and gas sector

aim to strengthen methane leakage detection, methane emissions recovery, and venting and flaring, if it cannot be recovered. In addition, both countries have mandated livestock manure pollution treatment, which indirectly addresses the effects of methane mitigation. Although these policies may not directly address methane mitigation, the requirements for air pollutant containment and treatment can help with capturing methane emissions for flaring or recovery.

- (3) Methane recovery and utilization play an important role in the development of methane policies in both countries, but particularly in China. Both countries have both encouraged or mandated methane recovery and utilization in the landfill, coal mine, oil and gas, and manure management sectors. In China, conserving or utilizing methane as an energy resource has been a major driver of methane emissions reduction for decades. It has been strongly encouraged across most subsectors (except for enteric fermentation and rice cultivation). In particular, recovering/utilizing CMM/CBM, as well as biogas, from manure and landfills has been proactively supported by both the central and local governments, which have provided various subsidies for nearly 20 years. Compared to methane flaring, utilizing methane emissions as an energy source makes a greater contribution to climate change mitigation because it has substitution effects for more carbon intensive energy, such as coal.

Both countries could better quantify their methane mitigation targets and enact more climate policies that directly support those targets. So far, the U.S. has more climate-related policies for methane mitigation than China. For example, the U.S. has supported quantified methane targets through the Global Methane Pledge's collective goal of 30% reductions by 2030. It has already mandated GHG reporting from underground coal mines, industrial wastewater, industrial waste landfills, and oil and gas systems. It also has four regional carbon emissions trading schemes that cover major methane emissions sources, including AMM, enteric fermentation, and rice cultivation. The federal government also requires direct methane emissions reduction and leak detection and repair for the oil and gas facilities that are subject to these regulations (e.g., new facilities, facilities located on federal and Native American lands). The regulations cover crude oil and gas production, gas transmission, and storage. These elements are not yet available in China's methane policy frameworks.

However, quantified methane emissions reduction targets are far from enough for both countries. Both countries do not have economy-wide methane emissions reduction targets. Few sectoral emissions reduction targets exist except for the oil and gas sector in which the U.S. has some level of quantified methane emissions reduction mandates (e.g., 95% reduction of methane emissions from wet seal centrifugal compressors and pneumatic pumps) and China has quantified targets for methane emissions intensity committed by major oil and gas companies (all of which are state-owned enterprises and account for over 90% of oil and gas production in China). Moreover, in the U.S., even though the recently passed IRA is ambitious and proactive on methane mitigation, few direct emissions reduction targets have been developed. Also, the IRA is less specific about methane mitigation in the agriculture sector despite its significant financial support for agricultural climate actions. These issues, therefore, require further attention from the federal government. In China, although several key policies on climate change express the ambition to deal with methane

emissions, only a few include explicit targets and detailed approaches. Except for quantified technical standards regarding safety and pollution, many of the quantitative targets in China are industry-related, such as the development targets of CMM/CBM and biogas.

Both countries have not focused on all sectors, which calls for necessary sectoral policies to close the gaps. The U.S. and China have paid close attention to oil and gas and coal mine sectors, respectively. Both have paid the least attention to enteric fermentation, rice cultivation, and AMM emissions.

Specifically, the sectors that attract a high level of attention from the U.S. federal government are: (1) the oil and gas sector, in which a certain level of direct methane emissions reduction requirements, economic incentives and methane fees are applied; and (2) the landfill sector in which NMOCs are controlled by a specific target and act as a surrogate for methane emissions. Given their methane emissions levels, not enough attention has been paid by the federal government to the following sectors: (1) the enteric fermentation sector, for which few specific regulations have been developed at the federal level, except for broad funding opportunities for GHG emissions reduction in the agriculture sector ensured by the IRA of 2022; (2) the coal mine sector, in which no federal regulations, except for the safety rules, have been enacted to control CMM and AMM emissions. However, voluntary programs and state-level policies have covered CMM/AMM governance (Denysenko et al., 2019); and (3) rice cultivation, in which few regulatory activities are found in the existing policy framework.

The sectors that attract a high level of attention from the Chinese central government are: (1) the coal mine sector, in which the recovery and development of CMM/CBM are strongly supported by various industrial policies; and (2) the manure management sector, in which manure utilization is mandatory, and biogas recovery, in particular, has been extensively promoted. The sectors to which the Chinese government has paid the least attention are: (1) the enteric fermentation and



rice cultivation sectors, in which no direct policies exist to address methane emissions; and (2) AMM emissions, which have not been specifically addressed in the current policy framework.

Commonly utilized policy types in the U.S. and those in China are distinct, which creates opportunities for sharing experiences and policy learning.

To achieve methane reduction goals, the U.S. has primarily utilized regulatory policy instruments and diversified economic incentives, while China has preferred planning instruments – particularly industrial policies to encourage methane utilization and subsidies/tax exemptions for methane mitigation. Policy instruments are the techniques used by the government to achieve policy goals. This study adopts a typology of four major policy instrument types: planning instruments (e.g., Five-Year Plans, action plans); regulatory instruments (e.g., laws and rules); economic instruments (e.g., subsidies, tax exemptions, and carbon markets); and voluntary instruments (e.g., pilots, programs). A more granular classification is shown in Figure 2.2.

(1) The U.S. has used larger numbers of regulatory instruments for methane-related policy targets, which limit methane emissions by mandatory requirements and legal compliance. Violation of these regulations may lead to penalties. China has used more planning instruments such as Five-Year Plans (FYPs), industrial policies, action plans, and guidance, which do not necessarily require legal compliance. However, this does not mean that those strategic planning policies are

less important; rather, this usually indicates that the issue has gained high political attention and will be strongly supported by the central government, particularly if the issue is specifically addressed in key strategic policies, such as the FYPs. The regulatory versus planning preferences on methane policies also indicate that the two countries have adopted different perspectives toward methane emissions, i.e., the U.S. tends to consider methane emissions more as a climate pollutant that requires regulations for abatement, whereas China takes methane emissions as valuable resources and infant industries that need to be supported and promoted.

(2) Both the U.S. and China have provided economic incentives for methane recovery. For example, biogas recovery from manure and landfills is encouraged by energy policies in both countries. However, China tends to adopt subsidies and tax exemptions as key economic instruments while the U.S. is more inclined to provide federal grants, tax credits, and preferential loans, as highlighted by the IRA. In addition, regional U.S. carbon markets cover methane emissions from all sub-sectors, including AMM and rice cultivation. In China, methane emissions trading has not yet been implemented in the national Emissions Trading Scheme (ETS) launched in 2021. However, the China Certified Emissions Reduction (CCER) that was suspended in 2017 is likely to be restarted soon.

FIGURE 2.3: SUMMARY OF KEY FINDINGS.

This figure summarizes the key policy areas of the U.S. and China related to methane mitigation. The * in the climate change category indicates that the U.S. has partially committed to methane emissions reduction targets subject to climate change. The * in the oil and gas category indicates that China only has mitigation targets across major oil and gas companies.

SECTOR	SAFETY REGULATIONS	POLLUTION REGULATIONS	GHG-ORIENTATED REGULATIONS	DIRECT EMISSION REDUCTION TARGETS	METHANE RECOVERY INCENTIVES AT THE NATIONAL LEVEL	MANDATORY GHG EMISSIONS REPORTING	CARBON MARKETS
Climate change	●	●	●	○*	●	●	●
Coal mines (CMM)	● ●	●	○	○	●	●	●
Coal mines (AMM)	○	○	○	○	○	○	●
Oil & Gas	● ●	● ●	●	● ●*	●	●	●
Transmission, Leakage, and Storage	● ●	● ●	○	○	●	●	●
New Sources	● ●	● ●	●	●	●	●	●
Existing Sources	● ●	● ●	○	○	●	●	●
Landfills	● ●	● ●	●	○	● ●	●	●
New Sources	● ●	● ●	○	○	● ●	●	●
Existing Sources	● ●	● ●	○	○	● ●	●	●
Wastewater	● ●	● ●	○	○	●	●	●
Manure Management	●	● ●	○	○	● ●	○	●
Enteric Fermentation	●	●	○	○	●	○	●
Rice Cultivation	●	●	○	○	●	○	●

● U.S.
 ● CHINA
 ● N/A
 ○ NONE

03 | UNCERTAINTIES IN HISTORICAL METHANE EMISSIONS

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To enact meaningful, ambitious and effective policy actions and targets, historical data that reflects real-world methane emissions is needed. However, estimating anthropogenic methane emissions is challenging due to the complexity of methane emission processes. Methane emissions are largely from either fugitive (coal mines and oil and gas operations) or biological (flooded rice, livestock, and landfills) sources where emission rates depend on site-specific conditions and operational procedures, which leads to high levels of uncertainty. There are two approaches commonly used for estimating methane emissions: 1) bottom-up calculations, which use emission factors or process models to estimate emissions from historical activity levels and 2) top-down calculations, which use atmospheric measurements, generally combined with atmospheric model calculations, to estimate emissions from a given region. Top-down estimates use some combination of observations from surface stations, aircraft, and satellites and have the advantage of representing real-world conditions, but cannot always differentiate between natural and anthropogenic sources. Bottom-up inventory methods provide much more detail on the sectoral sources of emissions.

Based on comprehensive literature review and data collection, we compare methane (CH₄) emissions across 9 bottom-up and 12 top-down inventories to characterize anthropogenic methane emissions in the U.S. and China across several subsectors, including energy (coal, oil, and gas), agriculture (rice cultivation, enteric fermentation, and manure management), and waste (wastewater and landfill). We also compare the spatial distribution of methane emissions in 4 inventories that provide gridded data. This helps us understand hotspots for methane emissions, identify potential regions for early actions or pilot projects, and to understand some of the differences in inventory estimates, as the location of emissions is critical for reducing uncertainty in methane emission estimates.

Comparing historical emissions across inventories helps us: (1) understand the characteristics and dynamics of methane emissions in the U.S. and China; (2) assess sources of discrepancies among inventories; (3) shed light on further improvements in estimating CH₄ emissions and developing national GHG inventories; and (4) highlight potential areas of collaboration between the two countries.

3.1 CURRENT STATUS OF METHANE EMISSIONS

China and the U.S. are the first and third leading emitters of methane by country, respectively. Collectively, both countries account for approximately 25% of global methane emissions (GMI, 2022b). Methane emissions in the U.S. and China differ in magnitude, sectoral makeup, and trends over time. In 2014, the latest year that nationally reported data is available for both countries, China and the U.S. reported 55 TgCH₄ and 28 TgCH₄ total methane emissions, respectively (Figure 3.1) (China NCCC, 2018; EPA, 2022a). As reported by other inventories, China's total methane emissions reached the highest value to date since 1990. After 2015, total emissions declined through 2016, but then continued to increase afterwards. Total methane emissions in

the U.S. showed an overall decreasing trend since 2014, with a continuous decline from 2014-2016, a small increase from 2016-2018, and a return to a decreasing trend after 2018.

According to nationally reported data, methane emissions in both countries are primarily attributed to the energy, agriculture, and waste sectors (Figure 3.1). The energy sector accounts for about 40% of the total methane emissions in both the U.S. and China (China NCCC, 2018; EPA, 2022a). The overwhelming majority of methane emissions from the energy sector in China are attributed to coal production, which comprises only about 10% of emissions in the U.S., while oil and gas production accounts for nearly a



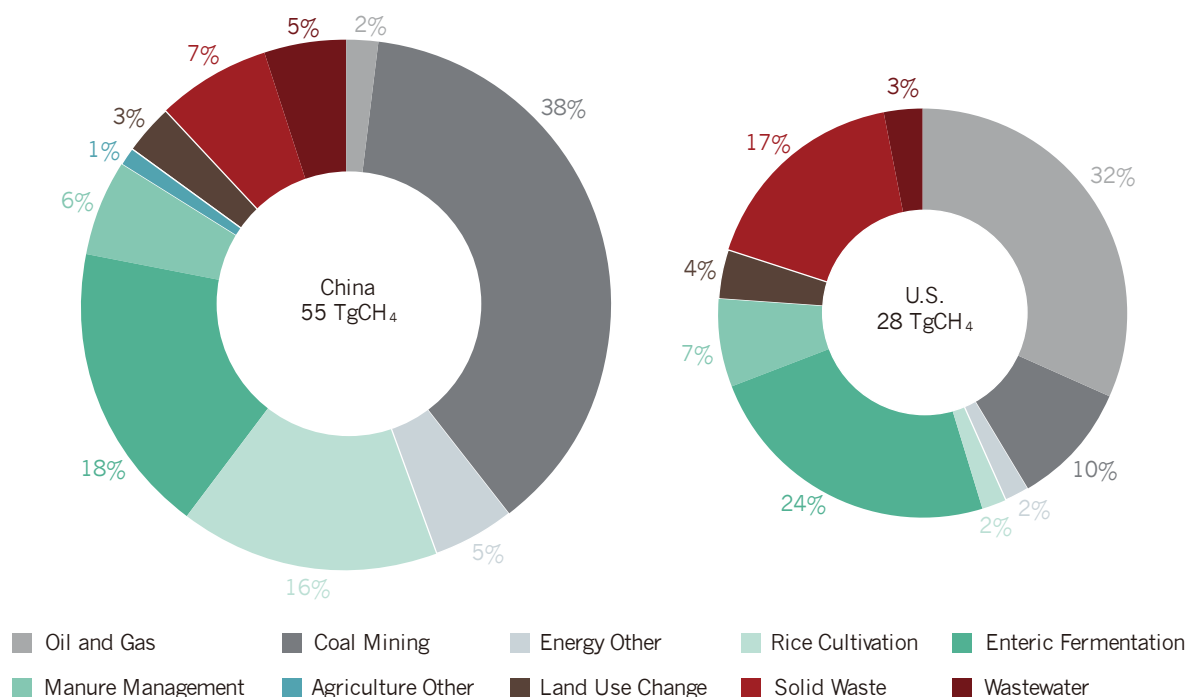
third of total methane emissions in the U.S., and a minimal amount of China emissions. The agriculture sector emits more than a third of total national methane emissions in both the U.S. and China. Methane emissions from the agriculture sector in China are mostly from livestock and rice cultivation. In both countries emissions from livestock are attributed primarily to enteric fermentation, with a smaller amount from manure management. Slightly more than one tenth of total Chinese and one fifth of total U.S. methane emissions are attributed to the waste sector, with over half of waste emissions attributed to

solid waste and the remainder to wastewater management in both countries. The solid waste sector includes both managed and unmanaged solid waste disposal sites, including landfills.

However, not all methane emissions inventories align with nationally reported historical data in either country. This report evaluates other inventory estimates to understand sources of uncertainty and different methodologies for estimating emissions to inform policy priority areas and target-setting.

FIGURE 3.1: CHINA AND U.S. METHANE EMISSIONS BY SOURCE IN 2014.

This figure is based on countries' national inventories. China developed official GHG inventories for years 1994, 2005, 2010, 2012, and 2014; the U.S., as an Annex I country, submits its national GHG inventory on an annual basis. Here we compare methane emissions in 2014, the latest year that official GHG inventory data is available for both countries. Shares in this figure may not sum to 100% due to rounding. Other energy is total energy emissions minus coal and oil/gas fugitive emissions.



3.2 TOTAL METHANE EMISSIONS IN THE U.S. AND CHINA

This report utilized a wide range of both top-down and bottom-up inventories to measure methane emissions from selected sectors in the U.S. and China. Bottom-up inventories include the Community Emissions Data System (CEDs), the Emissions Database for Global Atmospheric Research (EDGAR) v6.0; the Environmental Protection Agency's (EPA) Global Non-CO₂ Projections & Mitigation Potential Reports; the Food and Agriculture Organization's Statistical Database (FAOSTAT); the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model v4; Global Fuel Exploitation Inventory (GFEL) v2; Initial/ Second/ Third National Communication on Climate Change of the People's Republic of China, the People's Republic of China First/ Second Biennial Update Report on Climate Change (China NCCC) and the Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. GHGI). EPA and U.S. GHGI data collected varied slightly because they were from different years. EPA data was collected from a global 2019 report, and the U.S. GHGI data includes the latest update from April 2022. Most bottom-up inventories provided data at the national level, with some exceptions. The Global Methane Budget (GMB) provided both bottom-up and top-down inventories with reported averages over an 8-year period. To compare our bottom-up estimates, we collected top-down data estimates from published literature (Chen et al., 2022b; Deng et al., 2022; Lu et al., 2021a; Miller et al., 2019; Qu et al., 2021; Sheng et al., 2021; Stavert et al., 2022; Wang et al., 2021; Worden et al., 2022; Zhang et al., 2021b).

Sources of activity data and emission factors differed across bottom-up inventories, with the most referenced sources of activity data for the energy sector including the IEA (International Energy Agency) World Energy Balances, IEA World Energy Outlook, EIA (Energy Information Administration) International Energy Outlook, and the BP Statistical Review of World Energy. FAO was the most referenced source of activity data for the agriculture sector. Waste activity data

often referenced the IEA World Energy Outlook and FAO. U.S. and China emissions and activity level data was reported to the UN Framework Convention on Climate Change (UNFCCC) through the Common Reporting Format (CRF) tables and were also utilized in several inventories. Emission factors also varied by inventory. Intergovernmental Panel on Climate Change (IPCC) default emission factors were most commonly used; however, several inventories utilized sector-specific emission factors. Additional sector-specific emission factors or activity data adjustments will be discussed in later sections. For more information on inventories used in this research, please refer to the technical appendix (S1).

The anthropogenic methane emissions estimates in 2014 range from 52.9-66.9 TgCH₄ in China and 25.6-27.7 TgCH₄ for the U.S. Discrepancies are observed between top-down data and bottom-up inventories, especially in later years with additional top-down data sources, such as in 2017, where the range is 40.0-70.7 and 22.0-42.9 for China and the U.S., respectively.

For China, inventories with time-series data show rather consistent trends in the long-term, with total methane emissions in China increasing between 1990 and 2020, largely due to increased methane emissions from the energy and waste sectors. Specifically, during 2000-2010, emission ranges increased from 34.6-47.3 TgCH₄ to 49.6-62.0 TgCH₄, an increase of 31-43%. The rate of increase in China's methane emissions has slowed since 2010, compared to the previous decade (Liu et al., 2021). Between 2012-2015, all the inventories except CEDs, EPA & Sheng et al. 2021 show emissions peaking, then starting to decline, while after 2016, EPA, CEDs & Sheng et al. 2021 showed a slightly increasing trend (Figure 3.2).

In the U.S., according to the nationally reported data, total methane emissions decreased by ~4.8 TgCH₄ from 1990 to 2020. Bottom-up inventories show significant agreement in overall trend, as

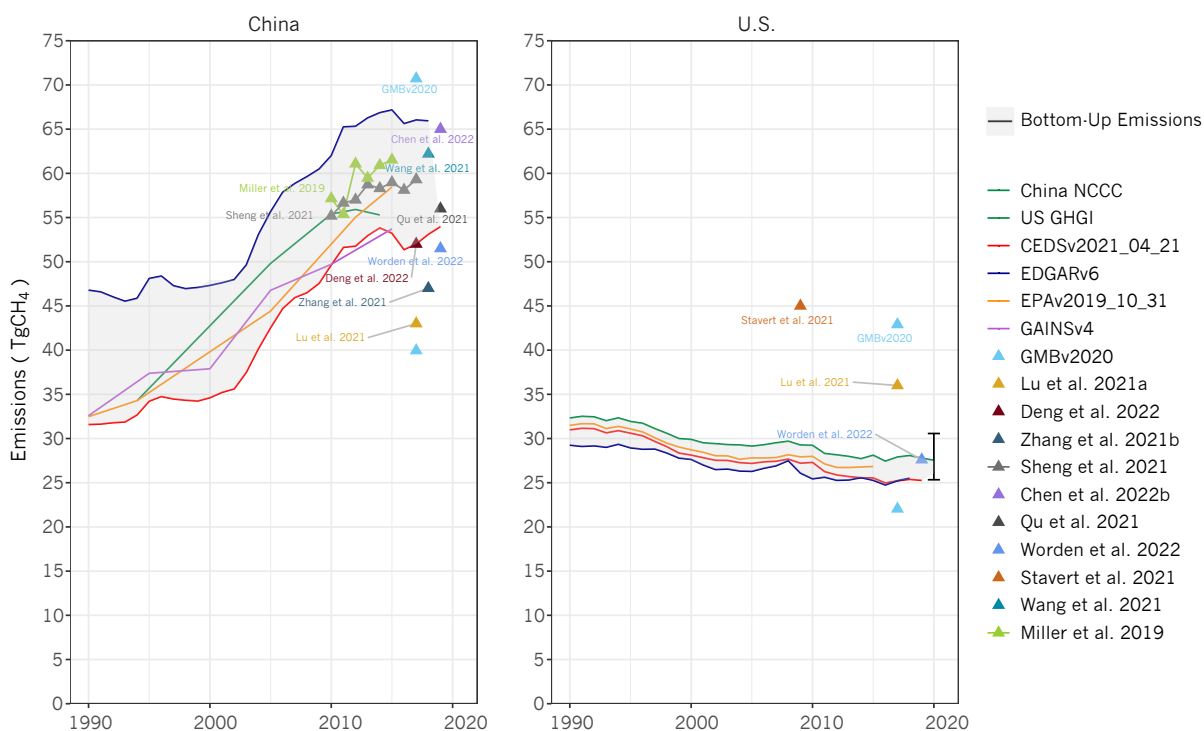


emissions decline from 1994-2005 increase slightly between 2005-2008, then decrease through 2016, before increasing slightly through

the latest available data. Emissions peak prior to 2000 and have been slowly declining since (Figure 3.2).

FIGURE 3.2: NATIONAL TOTAL METHANE EMISSIONS IN THE U.S. AND CHINA.

GAINS estimates are only included for China because data is not available for the U.S. The error bar for the U.S. is the EPA uncertainty range for methane (-8 - +11%) (EPA, 2022b). Many inventories only reported an average of emissions over several years. To represent this data, we included a single data point for the latest year included in the average. Since the GMB data is a collection of several inventories, we included only the highest and lowest reported values, to represent the range across collected inventories. The shaded area represents the emission interval estimated from all bottom-up inventories. Triangle data points represent top-down data. Bottom-up inventories include: CEDS; EDGAR; U.S. EPA; GAINS; the China NCCC and the U.S. GHGI. Sources: (Chen et al., 2022b; Deng et al., 2022; Lu et al., 2021a; Miller et al., 2019; Qu et al., 2021; Sheng et al., 2021; Stavert et al., 2022; Wang et al., 2021; Worden et al., 2022; Zhang et al., 2021b)

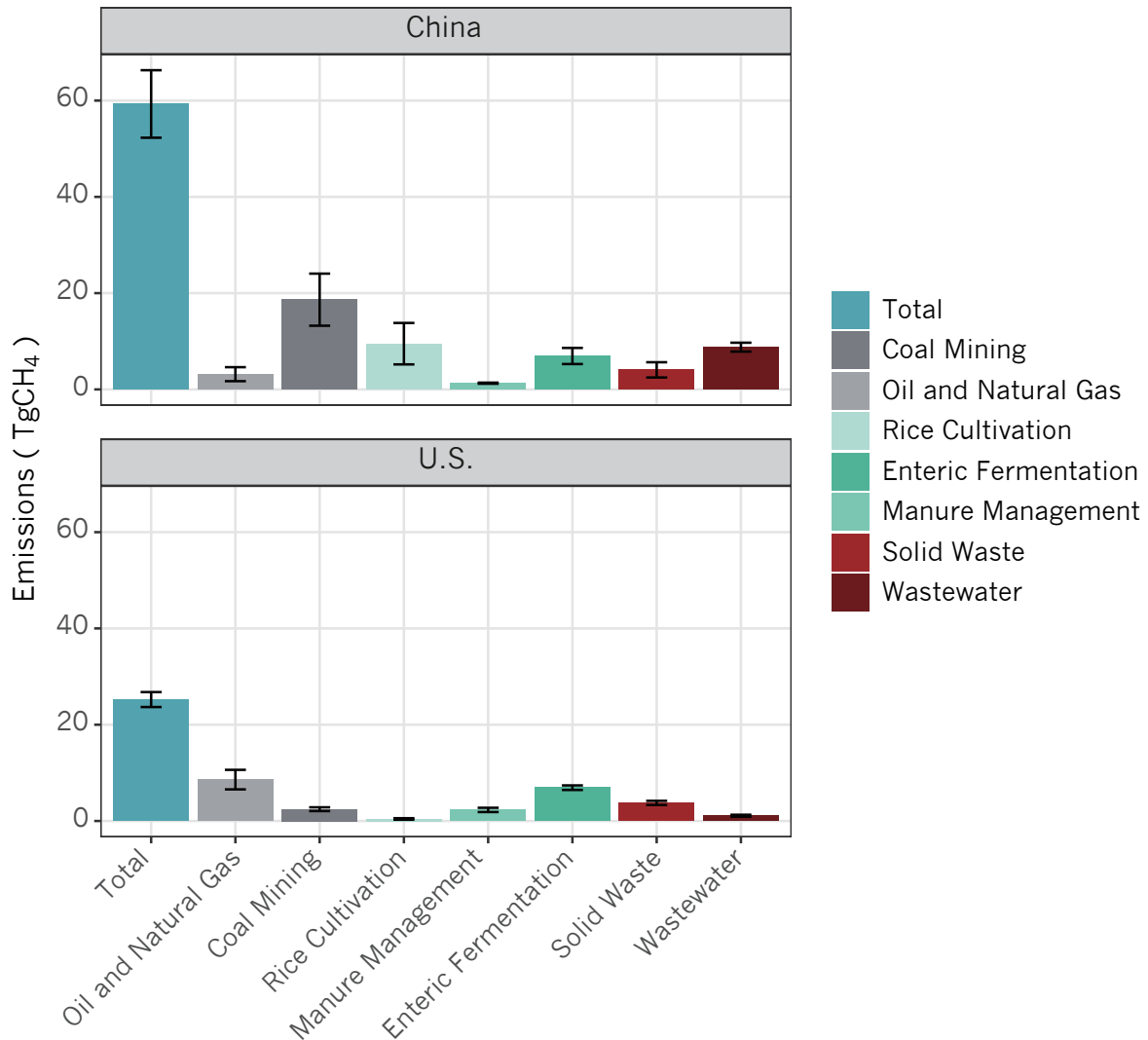


To better understand how bottom-up and top-down inventory estimates differ, we calculated one standard deviation above and below the median estimate across inventories in 2017, the year with the most data available (Figure 3.3). Uncertainty varies across sectors and across countries, with relatively higher uncertainty in oil and gas and total emission estimates in the U.S., due in part to the wide variation in top-down estimates for U.S. oil and gas emissions. Uncertainty in rice

cultivation, enteric fermentation, coal mining, and wastewater across collected inventories are significantly higher in China in 2017. Given the variation across inventories for methane emissions in both the U.S. and China, further understanding inventory methodological approaches for key methane emission sources in both countries is critical for understanding historical emissions data.

FIGURE 3.3: INVENTORY ESTIMATES AND UNCERTAINTY ACROSS SECTORS IN 2017.

Bars represent the median estimate across all inventories included in Figure 2 with data reported in 2017, as it was the year with the most data available. The error bars are +/- one standard deviation from the median for each sector.



3.3 METHANE EMISSIONS FROM ENERGY ACTIVITIES

Both the U.S. and China rely heavily on fossil fuels for energy production. China is the world’s largest producer of coal, and the U.S. is the largest producer of natural gas and oil (EIA, 2019). Given

the high share of methane emissions stemming from energy production, improving historical estimates is critical for mitigation.

Uncertainty in Coal Mine Methane Emissions

China and the U.S. were the first and fifth largest coal producers in 2020 (IEA, 2021b), making coal mine methane a key area of mitigation for both countries.

There is agreement across inventories in terms of magnitude of emissions and overall long-term trend in the U.S., with a range in 2014 from 2.5-2.8 TgCH₄ and some variation in the rate of emissions decline after 2015 (Figure 3.4). In the U.S., all inventories show declining emissions over time, which may be driven by a combination of declining coal production, which peaked in 2007 or 2008 (Mendelevitch et al., 2019), and increasing utilization of methane released by mining operations for energy, as about 48% of underground mining methane emissions were recovered in 2020 compared to only 28% in 2005 (EPA, 2022b).

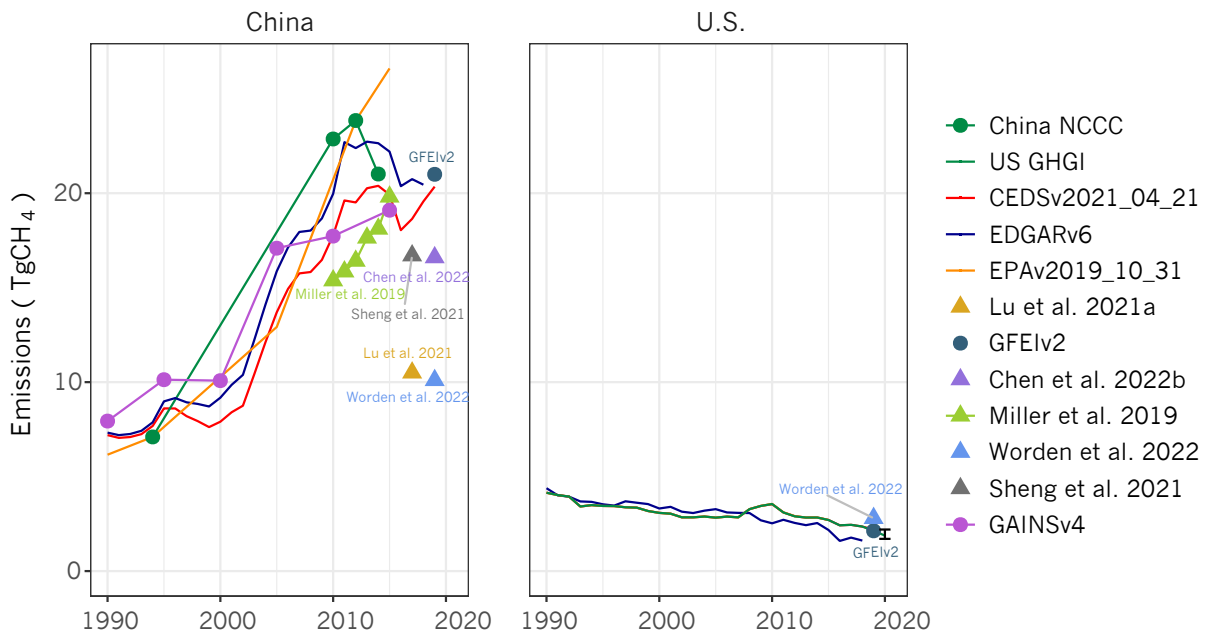
Coal emissions have been increasing in China since 2000, but slowed since about 2010, with most models showing constant or declining emissions from 2012-2015 (Figure 3.4). Reduction in emissions after 2012-2015 is likely related to a reduction in coal production, which peaked in 2013, then declined through 2016 (NBS, 2021). However, some inventories, such as CEDS and Sheng et al. (2021), show increasing emissions post-2015. Some research suggests that methane emissions have not declined as much as production, and that abandoned mine methane emissions are negating some of the potential emissions reduction gains from decreasing production (Sheng et al., 2021). Additionally, coal production started to increase again after 2017 and recent analysis shows increasing coal production in 2022, with current production 11% higher than in 2021 (Xu, 2022).

Most of the inventory estimates are fairly well-aligned in both countries, with the exception of several top-down estimates from recent studies, which estimate lower emissions from coal mining in China. In China, the discrepancy between top-down and bottom-up inventories may be from differences in geospatial information (Sheng et al., 2021), as well as the high uncertainty in the accuracy, precision, and variability of estimates among bottom-up inventories (Cheewaphongphan et al., 2019). Bottom-up inventories emission factors may not reflect recent coal production trends (Chen et al., 2022b), as current emission factors may not account for shifting production in China to northwestern China, which has low methane content coal reserves, the closure of less efficient mines through coal de-capacity policy in the past decade, or the ratio of underground and surface mining (Gao et al., 2021). Additionally, China's coal bed gas utilization ratio has increased from 2010 to 2019 by about 25%, which may not be reflected in emission factors (Lu et al., 2021b).

Large discrepancies across bottom-up estimates may result from region-specific activity data and differences in emission factors. Previous research has found that the emission factor used by EDGAR and EPA is higher than other inventories for coal mines, leading to higher emissions estimates (Gao et al., 2020; Lin et al., 2021). Emission factors vary based on the geology, depth of mine, and characteristics of coal in a region (Gao et al., 2020; Zhu et al., 2017), and provincial-level emission factors may be needed to evaluate CMM adequately. Research suggests that differences in emission factors for underground mining may be a more significant driver of uncertainty across inventories than activity data, along with different inventory assumptions about the share of surface and underground mining (Gao et al., 2020).

FIGURE 3.4: METHANE EMISSIONS FROM COAL MINES.

GAINS estimates are only included for China because data is not available for the U.S. The error bar for the U.S. is the EPA developed uncertainty range for coal mine methane emissions (-9 - +17%) (EPA, 2022b). Many inventories only reported an average of emissions over several years. To represent this data, we included a single data point for the latest year included in the average. Triangle data points represent top-down data and dotted data points represent reported years from bottom-up inventories that don't report data annually. Several estimates for the U.S. overlap, so not all inventories are displayed in the figure.



BOX 3.1: CHINA COAL MINE SPECIFIC INVENTORY ASSUMPTIONS

All bottom-up inventories made some adjustments to their standard methodology for coal emissions to account for regional differences in China. EDGAR used findings from the research on coal quality to adopt a different emission factor, while the GAINS inventory calibrated emissions to estimates from recent country-level analyses (Peng et al., 2016). The EPA estimate used granular emission factor assumptions for

different stages of coal production, including VAM, mining, and post-mining processes. GFEI uses regional production information and nationally reported emissions data for scaling emissions. Sheng et al., 2021, uses data from the Chinese State Administration of Coal Mine Safety (SACMS) on reported methane emissions from 10,093 operating mines. See [technical appendix \(S1\)](#) for more information.

BOX 3.2: ABANDONED MINE METHANE

AMM will be an increasingly important source of emissions, especially for China. The number of coal mines closed increases every year, and coal mines may continuously emit methane for more than eight years after closure (Kholod et al., 2020). Previous research suggests that global AMM emissions may have been underestimated by potentially as much as 50% in 2010 (Kholod et al., 2020), and the current magnitude of AMM emissions in China are still highly uncertain (Gao et al., 2021; Peng et al., 2016; Zhang et al., 2014).

For the U.S., annual methane AMM emissions declined from 0.29 to 0.23 TgCH₄ from 1990 to 2020, and generally comprised ~7% to around 12% per year of total coal methane emissions. The fluctuations over time are mainly due to the number of mines closed in a given year and the scale of emissions from those mines while they are active (EPA, 2022b). AMM emissions peaked in 1996 (0.40 TgCH₄) due to the closure of a large number of gassy mines (mines with emissions > 100 mcf/d) between 1994 and 1996 (EPA, 2004). Despite this fluctuation, emissions from AMM have generally declined since 1996 to 0.23 TgCH₄ in 2020. This decline may possibly be due to increased methane recovery and utilization, as 31% of the methane emissions from abandoned mines were recovered in 2020, compared to none in 1990 (EPA, 2022b).

As a Non-Annex I country, China is not required to report AMM emissions in reporting to UNFCCC. Most bottom-up inventories of methane coal emissions have not calculated AMM emissions in China (Hoesly et al., 2018; Liu et al.,

2021; Olivier & Peters, 2020; Sheng et al., 2021), and some bottom-up inventories have included estimates of AMM emissions in China but did not report AMM as separate from total coal mine emissions (China NCCC, 2018; Kholod et al., 2020; Schwietzke et al., 2014). Several studies have developed estimates for AMM, including a 2015 U.S. study that found AMM emissions to correspond to approximately 13% of active coal mine methane emissions (EPA, 2017). Based on this research, GAINS assumes AMM emissions are equivalent to 10% of active hard coal mine emissions for Non-Annex I countries (Höglund-Isaksson et al., 2020). Other estimates for AMM may be as high as 17% of coal mine emissions (Kholod et al., 2020).

Regional studies have found that AMM emissions in China increased rapidly from 1998-2005 (Chen et al., 2022a), when more than half of China's small coal mines had been closed under the Chinese government's shutdown policy, beginning in 1998 (Bai et al., 2012; Lu et al., 2020). During 2006-2015, AMM emissions generally showed a decreasing trend, which is consistent with the time period between China's 11th and 12th FYP period, when a number of policies were enacted to reduce production from depleted coal mines (NDRC, 2006a, 2012a). From 2015 to 2017, AMM emissions estimates increased from 1.6-3.9 TgCH₄ to 2.0-4.9 TgCH₄, then decreased to 2.1-4.7 TgCH₄ in 2019 (Chen et al., 2022a; Gao et al., 2021). These estimates range from 7-18% in 2015, 11-26% in 2017, and 13-28% in 2019 of median coal mine emissions from the inventories we collected, suggesting emissions may exceed the 10% or 13% estimates used in prior research.

Uncertainty in Oil and Gas Methane Emissions

In 2021, the U.S. was the world's leading producer of both oil and gas and China was ranked fifth in oil production and fourth in gas production globally (EIA, 2022a). Although the magnitude of emissions varies across countries, both have high levels of uncertainty in inventory estimates.

In the U.S., most global inventories show a high-level of consistency, with a range in 2014 from 7.7-8.8 TgCH₄ (Figure 3.5). However, the only

top-down inventories with oil and gas data (Lu et al., 2021a; Worden et al., 2022) exceed the U.S. uncertainty range, estimating about 40-63% and 17-40% more emissions in 2017 and 2019 separately than bottom-up estimates. Bottom-up inventories use primarily IEA activity data (EDGAR, GAINS) and IPCC default emission factors (EDGAR) and/or U.S.-specific activity data, emission factors or nationally reported emissions data (EPA, U.S. GHGI, GAINS, CEDS, GFEI). Most inventories include production and distribution of oil and gas in the U.S. Other research has identified a large discrepancy between bottom-up and top-

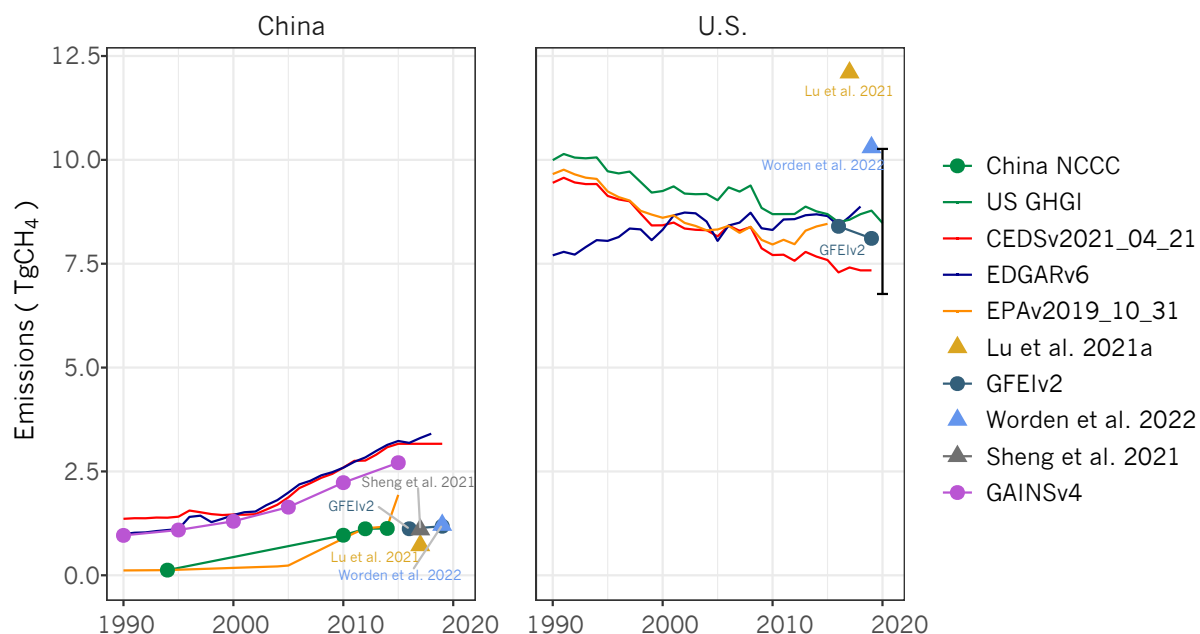
down oil and gas methane emissions in the U.S., as U.S. bottom-up inventories may not capture emission leaks or other malfunction events that release methane (Rutherford et al., 2021). One study estimated that leaks from the oil and gas supply chain in the U.S. were 60% higher in 2015 than the U.S. GHGI estimate and speculated that the use of component-level, rather than facility-level, emission factors could contribute to underestimating abnormal facility events in the national inventory (Alvarez et al., 2018). Other research supports this finding, and that typical operations are insufficient to explain observed emissions at the facility level. In the Barnett Shale region in Texas, one third of total emissions could be from unintended events that are not captured in component-level inventories (Zavala-Araiza et al., 2017). Another study found that methane emission leaks in the Permian Basin in Texas were about twice as high as nationally reported estimates (Zhang et al., 2020), and previous top-down inversions find 2010-2015 oil and gas emissions reported by U.S. GHGI to be lower than their estimate by a factor of two (Maasackers et al., 2021). Also, methane oil and gas emissions vary spatially and temporally (Lavoie et al., 2017), and aggregated emission factors may not be representative of local emissions that occur over short time periods (Vaughn et al., 2018). Variation in flaring efficiency estimates and in the granularity of emission factors and activity data assumptions for onshore, offshore production, transmission and distribution, and heavy production also may contribute to inventory differences. More continuous monitoring of emissions sites to better identify the sources of unintended emissions is needed (Zavala-Araiza et al., 2017). A recent observational study in the U.S. found that oil and gas flaring systems are

not as efficient as often assumed, and that the combination of inefficient flaring and unlit flares results in higher methane emissions than many current estimates (Plant et al. 2022).

In China, oil and gas methane emissions have been historically low, but are increasing. Some inventories show an increase from 2015 through the latest data, suggesting potentially continued growth in this sector (Figure 3.5). Though the scale is small, estimates from inventories vary, with the range in 2014 from 1.2-3.4 TgCH₄. Better understanding the differences between nationally reported data and other global inventories will be critical for understanding not only the magnitude of oil and gas emissions in China, but also the trendline, as nationally reported 2014 data shows constant emissions from 2012 to 2014, while other inventories demonstrate increasing emissions through 2014 and most recent data (GFEI, EDGAR and GAINS), driven at least in part by increasing production volumes. Total petroleum production and crude oil production has been increasing in China since 2005, though it peaked in 2015 (NBS, 2021, 2022a, 2022b, 2022c; EIA, 2022b). Nationally reported gas production has been increasing in China, making oil and gas an increasingly important source of emissions in the future (NBS, 2021, 2022a, 2022b, 2022c; EIA, 2022b). One study that evaluated oil and gas estimates in China found that variation across emission factors was a major driver of variation in inventory estimates, more than activity data or scoping differences (Gao et al., 2022). The emission factor for oil production used in China's official inventory is lower than the IPCC default, which GAINS, EDGAR and CEDS use (Gao et al., 2022).

FIGURE 3.5: METHANE EMISSIONS FROM OIL AND GAS.

GAINS estimates are only included for China because data is not available for the U.S. The error bar for the U.S. is the EPA developed uncertainty range for oil and gas methane emissions (-20 - +21%) (EPA, 2022b). Many inventories only reported an average of emissions over several years. To represent this data, we included a single data point for the latest year included in the average. Triangle data points represent top-down data and dotted data points represent reported years from bottom-up inventories that don't report data annually.



3.4 METHANE EMISSIONS FROM AGRICULTURAL ACTIVITIES

The agriculture sector is a significant source of methane emissions in both the U.S. and China, making up over one third of total emissions in 2014 (China NCCC, U.S. GHGI). As the world's leading producer of rice and meat products, mitigating agricultural emissions is essential to reduce methane emissions in China (FAOSTAT, 2021b; Xin et al., 2020). China produced 77,142,724 metric tons of meat and 213,610,729 metric tons of rice in 2020 (FAO, 2021; FAOSTAT, 2021a). Although China is the world's leading producer of meat, the U.S. is the world's leading producer of beef; the U.S. produced 12,357,232 metric tons of beef in 2020, compared to 6,048,629 metric tons of beef produced in China in 2020 (FAOSTAT, 2021a). As the world's leading

producer of beef, reducing livestock agricultural emissions is also important in the U.S. (Gleason & White, 2019), especially as global meat consumption is expected to increase 14% by 2030 (FAOSTAT, 2021b).

Uncertainty in Rice Cultivation Emissions

Methane emissions from rice cultivation in the U.S. are minimal at less than 2.5% of total emissions, or 1 TgCH₄, ranging across inventories from 0.32 to 0.62 TgCH₄ in 2014 (Figure 3.6). Emissions between 1990 and 2020 have significantly fluctuated year-to-year but have generally trended

downward over time and all inventory estimates are within the bounds of the EPA developed uncertainty range.

Methane emissions from rice cultivation are a significant source of emissions in China, but inventory estimates vary significantly, as estimates range from 5.4 to 14.2 TgCH₄ in 2014 (Figure 3.6). Most inventories report emissions remaining relatively stable between 1990 and 2020 but have slightly different trends across inventories. FAO and sources that rely on FAO data, such as CEDS and EDGAR, estimate emissions declined from 1990-2003 before increasing again slightly, with emissions peaking in 1990. EPA and the China NCCC show a positive trend in methane emissions from rice cultivation between 1990 and 2020, with emissions peaking in the latest available data year. The range between estimates in 2019 is even higher than 2014, between 5.3-30 TgCH₄.

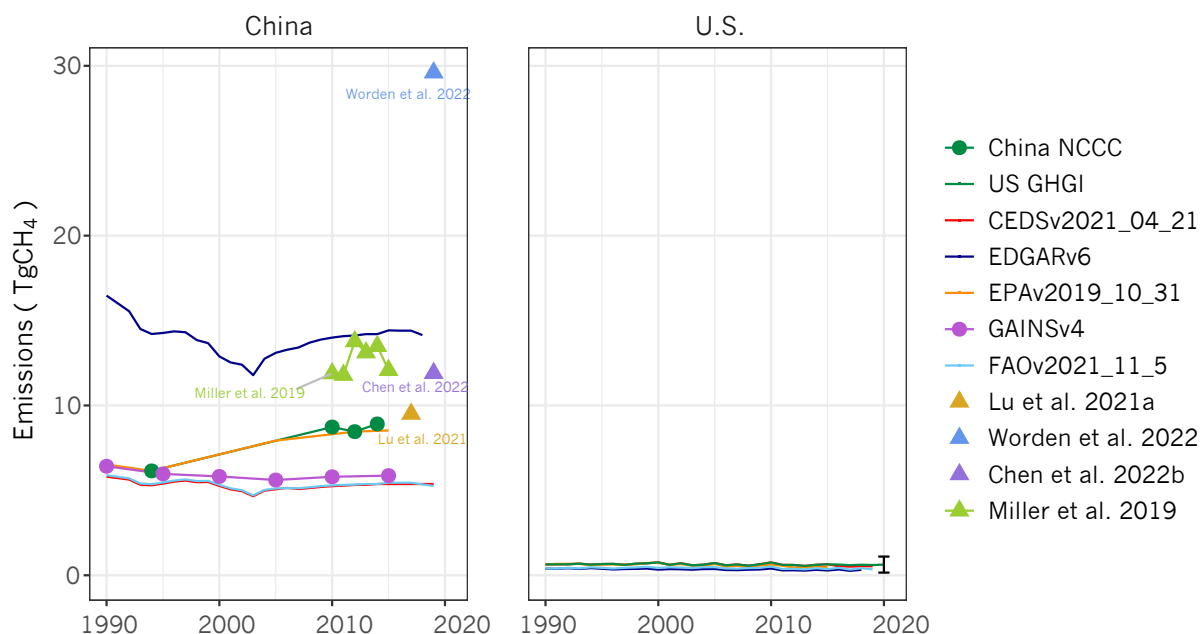
The range of estimates in rice cultivation can be attributed, in part, to variations in the proportions of flooding in rice cultivation ecosystems and emission factors (Cheewaphongphan et al., 2019). Higher rates for parameters in bottom-up estimates were used in EDGAR, such as assuming a higher proportion of continuous floods relative to other bottom-up inventories (Cheewaphongphan et al., 2019). Rice cultivation emissions depend on regional conditions, management practices (fertilizer inputs, straw application, irrigation), and system type (i.e., irrigation or rain-fed), which

is not reported at the national level (Peng et al., 2016). Top-down inventory estimates can vary in part because coal mines, rice cultivation and livestock production areas often overlap within the spatial resolution used for developing top-down inventories estimates, especially in China, and emissions in these regions may be attributed to different sectors in various studies (Worden et al., 2022). Freshwater aquaculture in China is typically co-located with or converted from rice paddies, or flooded areas used for rice production (Sheng et al., 2021). The top-down inventory with the highest emissions from rice cultivation, Worden et al., 2022, might be higher than other estimates due to differences in data sources and/or sectoral attribution of areas across inventories. Worden et al., 2022, uses EDGARv4.3 gridded data as its prior estimate, which has a higher emission factor for rice cultivation than other bottom-up estimates. Other top-down estimates included in Figure 3.6 use nationally reported emissions data as the prior estimate, except for Miller et al., 2019, which also uses EDGAR, but v4.3.2. Miller et al., 2019 and Worden et al., 2022 have similar total emissions estimates, but vary in the sectoral breakdown, as Miller et al., 2019 reports higher coal emissions, and Worden et al., 2022 reports higher emissions from rice cultivation. The co-location of coal mines, aquaculture, and rice paddies, often within the same areas in China, can potentially lead to the same areas being attributed to different sectors across analyses.



FIGURE 3.6: METHANE EMISSIONS FROM RICE CULTIVATION.

GAINS estimates are only included for China because data is not available for the U.S. The error bar for the U.S. is the EPA developed uncertainty range for rice cultivation methane emissions (-75 - +75%) (EPA, 2022b). Many inventories only reported an average of emissions over several years. To represent this data, we included a single data point for the latest year included in the average. Triangle data points represent top-down data and dotted data points represent reported years from bottom-up inventories that don't report data annually.



Uncertainty in Livestock Emissions

Methane emissions from manure management in the U.S. and China are fairly similar, with estimates ranging from 1.4-2.5 TgCH₄ and 1.3-3.3 TgCH₄ in 2014, respectively (Figure 3.7). Enteric fermentation emissions have historically been higher in China than in the U.S., with inventories ranging from 6.8 to 10.8 TgCH₄ and 5.7 to 6.6 TgCH₄ in 2014, respectively (Figure 3.8). In recent years, some inventories estimate that China's enteric fermentation emissions are similar to the U.S., with both countries estimating around 7 TgCH₄.

Inventory estimates for livestock emissions are within the U.S. uncertainty range, with one outlier, FAO, estimating lower methane emissions.

Otherwise, there is fairly consistent agreement across inventories that manure management emissions have been increasing since 1990, and that enteric fermentation emissions have remained overall relatively stable, with some variation over time. Bottom-up models may underestimate emissions from livestock in the U.S. due to the increased intensity within concentrated animal feeding operations (CAFOs). While the high concentration of livestock in CAFOs also increases the potential for emissions efficiency improvements, the increased intensity of air and water pollution and the greater consumption of freshwater supplies can result in local environmental degradation (Hayek & Miller, 2021).

FIGURE 3.7: METHANE EMISSIONS FROM MANURE MANAGEMENT.

The error bar for the U.S. is the EPA developed uncertainty range for manure management methane emissions (-18 - +20%) (EPA, 2022b). Dotted data points represent reported years from bottom-up inventories that don't report data annually.

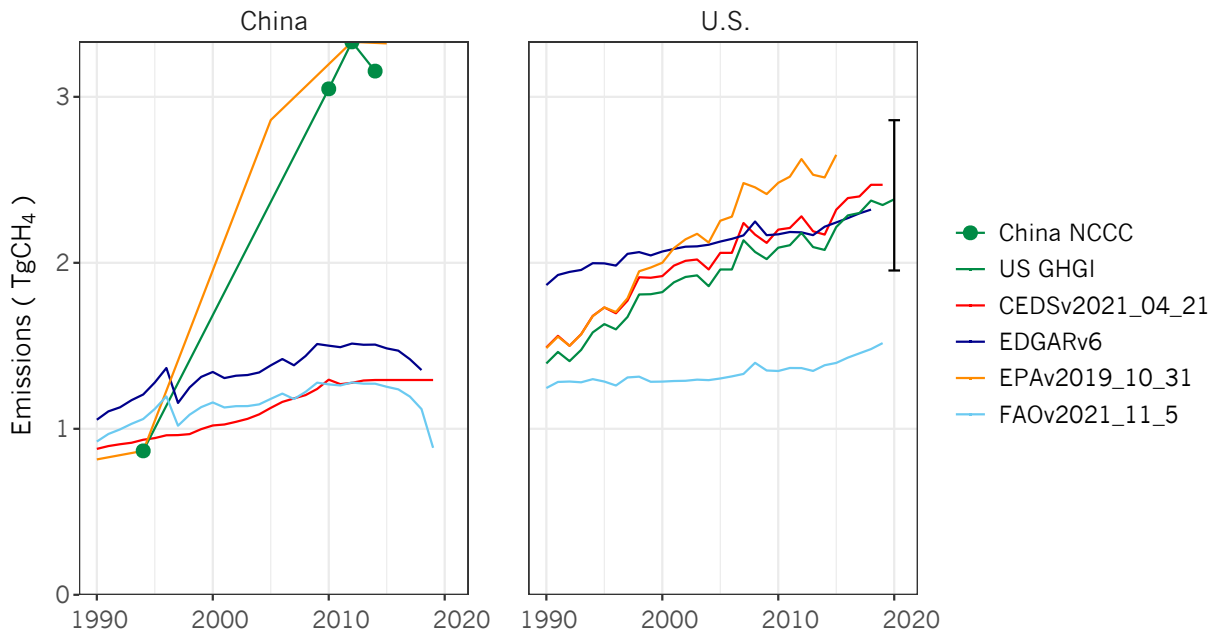
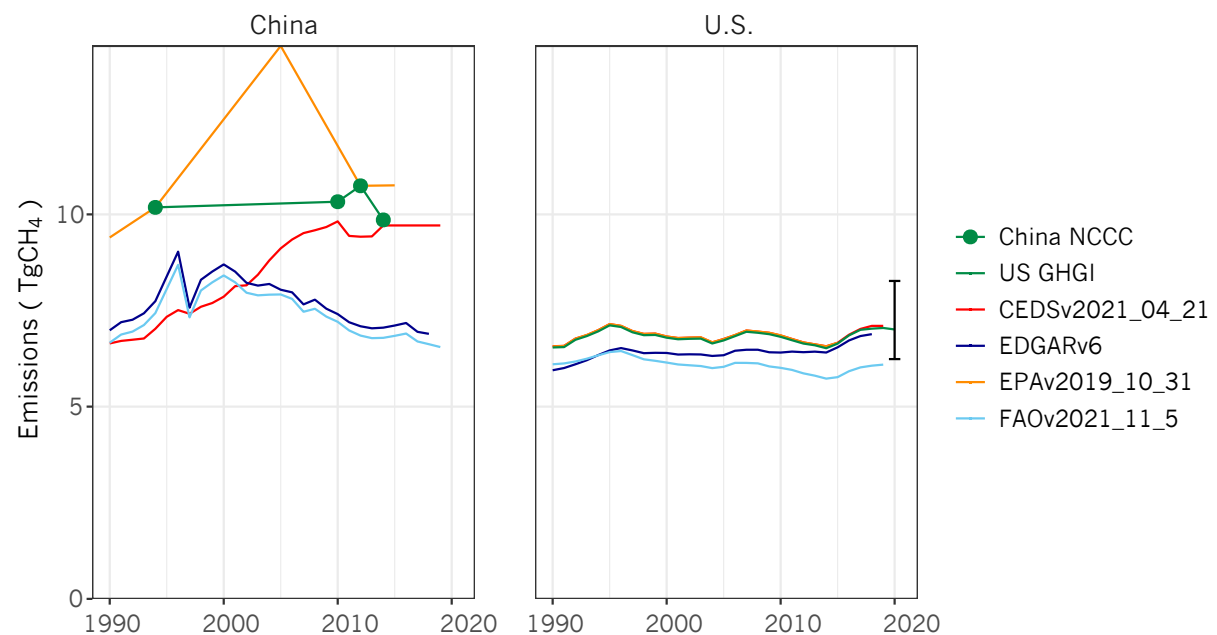


FIGURE 3.8: METHANE EMISSIONS FROM ENTERIC FERMENTATION.

The error bar for the U.S. is the EPA developed uncertainty range for enteric fermentation emissions (-11 - +18%) (EPA, 2022b). Dotted data points represent reported years from bottom-up inventories that don't report data annually.



Inventories for manure management in China report a range of values and trends. EPA and the China NCCC report a significant increase in emissions since 1990 that peaked around 2013, then began to trend downward. EDGAR, FAO, and CEDS report a slight increase in emissions from manure management between 1990 and 2015, but then estimates level off or trend downwards. Variation across inventories is attributed to discrepancies in the measurement of manure composition and variations in manure management systems, the duration of manure storage, and environmental factors, such as temperature and wind (Hristov et al., 2018). A lack of on-farm data for a variety of manure management systems under differing climatic conditions as well as a lack of knowledge of the variability of manure characteristics among farms also can contribute to differences across inventories (National Academies of Sciences, Engineering, and Medicine, 2018). Nationally reported emissions in China may exceed other inventories due to differences in emission factors

used, as activity data sources are within a 0.1-1% difference of one another (Hayek & Miller, 2021). For enteric fermentation, some inventories report an increasing trend, while others a declining trend. EPA and CEDS both show an increase in fermentation emissions from 1990-2020, though EPA shows a rapid increase, and then declining trend. EPA reports that methane emissions increased drastically between 1990 and 2005, then diminished between 2005 and 2013 before leveling off until 2015, and then increased again from 2015 to 2020. These trends are similar to the China NCCC data, which EPA uses as a source. FAO, the China NCCC and EDGAR report that emissions decreased from 1990-2020. Sources of uncertainty in methane emissions from enteric fermentation include disparities in activity data for animal inventories, feed dry matter intake, ingredient and chemical composition of the diets, and methane emission factors (Hristov et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2018).

3.5 METHANE EMISSIONS FROM WASTE MANAGEMENT

The waste management sector is a significant source of methane emissions in both the U.S. and China, primarily from wastewater and solid waste (which includes landfills). As the world's top two producers of municipal solid waste (MSW) (Nanda & Berruti, 2021), waste emissions are a key issue in both countries.

Uncertainty in Solid Waste Emissions

Methane emissions from solid waste in the U.S. ranged across inventories from 3.5 to 4.5 TgCH₄ in 2014, within the uncertainty range calculated by the EPA (Figure 3.9). Most inventories agree that methane emissions from solid waste in the U.S. have decreased significantly between 1990 and 2020. According to the EPA annual report,

the downward trend in emissions coincided with increased recycling and composting practices in MSW since 1990, and an increase in the amount of landfill gas collected. Collected landfill gas increased from 1990 to 2020, from 0.9 to 7.4 TgCH₄ for methane recovery, and from 0.7 to 1.1 TgCH₄ for methane oxidation. And in 2020, the methane recovery and methane oxidation account for 57% and 8% of total landfills methane generation, respectively (EPA, 2022b).

In China, methane emissions from solid waste management in 2014 range from 2.8 to 6.3 TgCH₄ (Figure 3.9). Emissions have increased significantly between 1990 and 2020, which can possibly be attributed to China's rapid economic growth and urbanization process (Cai et al., 2018), though inventories vary in the rate of increase. The China NCCC data shows significant

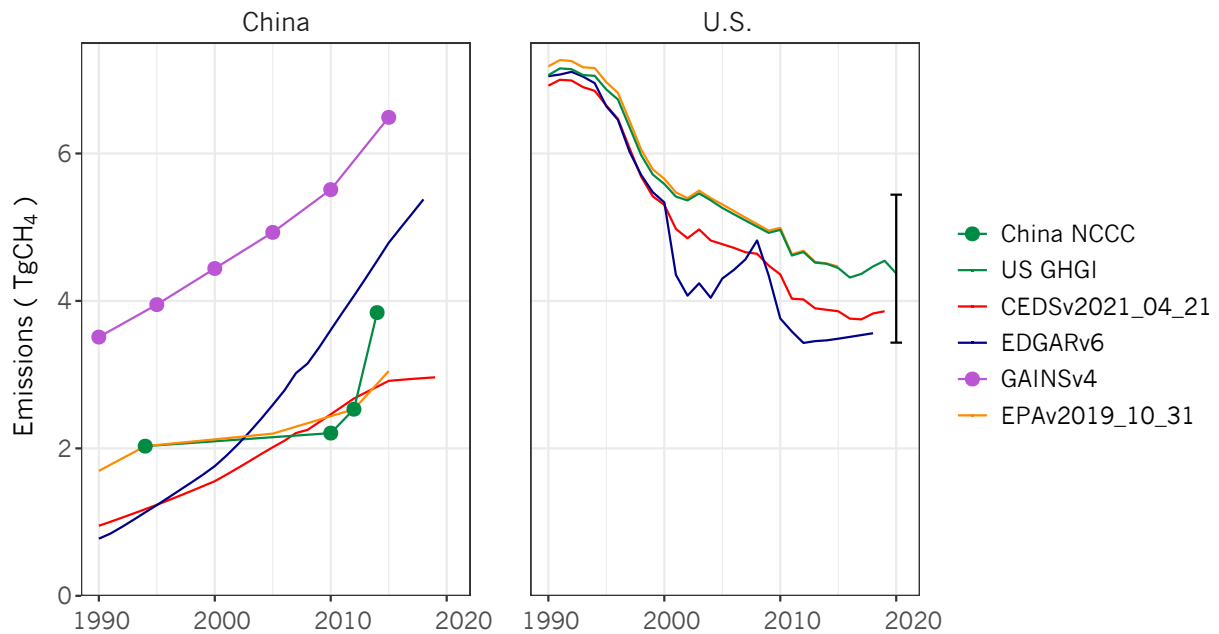
growth between 2012 and 2014, while other inventories show a more moderate increase in the near-term.

In solid waste, there are large spatial and temporal variabilities among landfills and disagreements in literature regarding assumptions in the IPCC 2006 methodology for estimating emissions from landfills. These include assuming a robust relationship between the total mass of landfilled waste and annual methane emissions and that methane generation from a given mass of waste peaks in the year of disposal and declines exponentially thereafter (National Academies of Sciences, Engineering, and Medicine, 2018;

Spokas et al., 2015). Both of these assumptions have been called into question by some recent literature, which finds that there is no statistically significant relationship between climate, site age, or status (open/closed) for landfill biogas recovery in the United States (Spokas et al., 2015). In the U.S., implementing a field-validated, process-based model to supplement the EPA Greenhouse Gas Reporting Program and updating IPCC methodologies to better reflect the site-specific drivers of methane emissions from landfills, such as cover soils and the extent of biogas recovery, can help increase confidence in solid waste emission estimates (National Academies of Sciences, Engineering, and Medicine, 2018).

FIGURE 3.9: METHANE EMISSIONS FROM SOLID WASTE.

GAINS estimates are only included for China because data is not available for the U.S. The error bar for the U.S. is the EPA developed uncertainty range for solid waste methane emissions (-23 - +22%) (EPA, 2022b). Dotted data points represent reported years from bottom-up inventories that don't report data annually.



Uncertainty in Wastewater Emissions

Methane emissions from wastewater management in 2014 in the U.S. ranged across inventories from 0.6 to 1.0 TgCH₄ (Figure 3.10), exceeding the EPA-developed uncertainty estimate. All inventories report roughly similar estimates in 1990 but diverge over time. CEDS and EDGAR report a positive trend in methane emissions from wastewater, with CEDS showing more fluctuation than EDGAR. Some literature suggests that EDGAR adopted a higher methane correction factor or a higher chemical oxygen demand for wastewater treatment plants, partially explaining the higher reported values for wastewater methane emissions in EDGAR (Peng et al., 2016). CEDS, which uses EDGAR and U.S. GHGI data to develop solid waste and wastewater estimates, reports higher emissions because of a higher ratio of emissions from wastewater than solid waste in EDGAR than in the U.S. GHGI. EPA and the U.S. GHGI report a slight negative trend between 1990 and 2019.

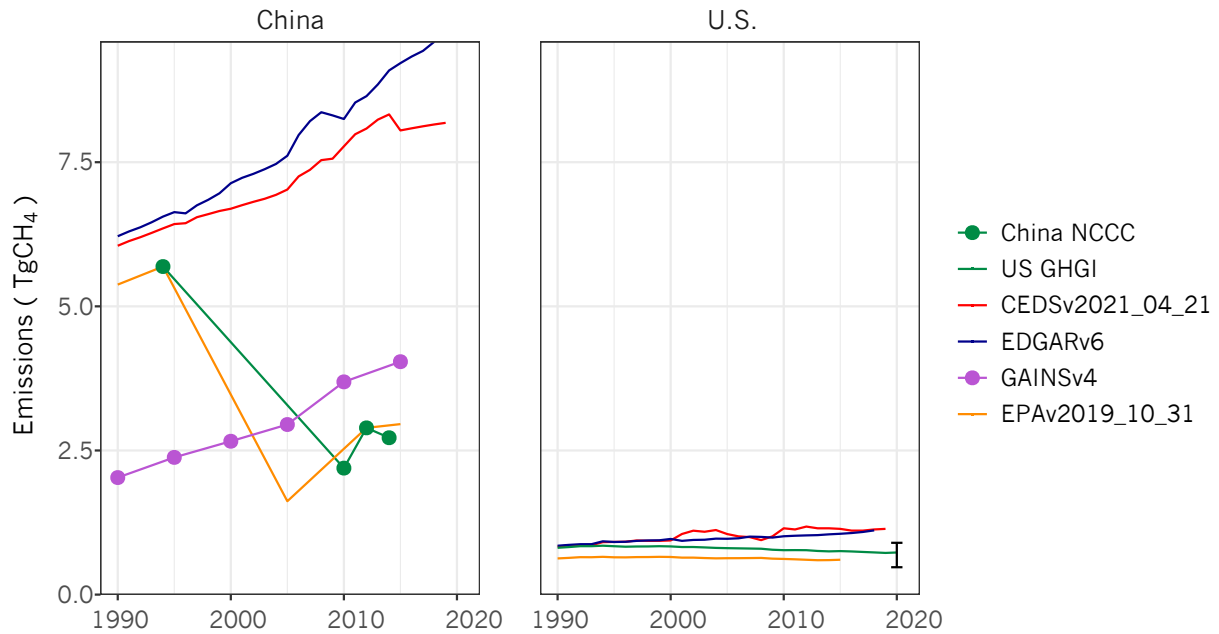
In China, emissions range from 2.7 to 9.1 TgCH₄ in 2014 (Figure 3.10). There is considerable disagreement among inventories regarding the trend of methane emissions from wastewater in China before 2010. EDGAR, CEDS, and GAINS present a mostly positive trend between 1990 and 2020, although there is a difference between the magnitude of the reported emissions in EDGAR and CEDS compared to GAINS, EPA, and the China

NCCC in 2014 (~3 TgCH₄). The China NCCC and EPA estimate overall emissions decline between 1990 and 2020 but begin increasing after 2005 or 2010. The increase in emissions from wastewater in China after 2005/2010 is due to a substantial increase in the number of wastewater treatment plants (WWTPs) as urbanization increased (Zhao et al., 2019). Between 2001-2014, the amount of treated municipal wastewater increased 10.3 times in China (Zhao et al., 2019).

Notably, methane emissions from wastewater in China are considerably greater than in the U.S. A scarcity of data for wastewater treatment, as well as the use of default emission factors in most inventories that do not account for regional variations and situational differences, contribute to uncertainty in China (Du et al., 2018). Default IPCC emission factors have also changed significantly over time, impacting inventory estimates (Wang et al., 2022a). Assumptions regarding the length of sewers, wastewater temperature due to seasonality, and nitrite concentrations in wastewater may also significantly impact methane modeling from wastewater treatment (Zhao et al., 2019). Emissions can also be impacted by pH, retention times, and phosphorus ratios (Wang et al., 2022a). Estimates may also vary in scope, as to whether they include both industrial and domestic/municipal wastewater treatment plants (Wang et al., 2022a).

FIGURE 3.10: METHANE EMISSIONS FROM WASTEWATER.

GAINS estimates are only included for China, because data is not available for the U.S. The error bar for the U.S. is the EPA developed uncertainty range for wastewater methane emissions (-35 - +23%). Dotted data points represent reported years from bottom-up inventories that don't report data annually.



3.6 SPATIAL DISTRIBUTION OF METHANE EMISSIONS

As discussed in previous sections, methane emissions vary spatially and temporally. Understanding the distribution of methane emissions is important for developing accurate historical estimates, as well as informing future policy development. Methane emissions are also dependent on several highly local characteristics, such as the flooding rate of rice paddies and the content and depth of coal mines. Incomplete spatial distribution information, such as a lack of emissions hotspots and/or heightened emissions in certain areas, can mislead or bias mitigation efforts (Lin et al., 2021). Comparing geospatial differences in inventory estimates of methane emissions enables us to visualize and compare the characteristics of various methane source sectors (Gong & Shi, 2021). In this section, we

compare several available gridded emissions datasets for a spatial analysis of methane emissions. We compared total emissions, total agricultural emissions, total waste treatment emissions, and total energy emissions between EDGARv6.0 (EDGAR), CEDSv_2021_04_21 (CEDS), and GAINS/ECLIPSE V6b (GAINS) (Crippa et al., 2021; Hoesly et al., 2018; Höglund-Isaksson et al., 2020). For more information on the inventories included in this analysis, please see the technical appendix (S1). More detailed geospatial analysis is also available in a policy brief that evaluates the spatial distribution of methane across provinces and states. Please see the Policy Brief for additional information.

In both China and the U.S., the top ten emitting major states or provinces hotspots for emissions were largely major agricultural regions, energy producing regions, and/or highly populated urban areas (Figure 3.11). In the U.S., there is significant variation in magnitude of emissions across states. In Texas and North Dakota, the first and second highest emitting states, emissions are 40-80% higher than the third-largest emitting state, California. The remaining top 10 states all emit $< \sim 1$ TgCH₄. In China, most of the high emitting provinces (> 19 TgCH₄) were mainly located in the north, central, east, and southwest of China. All inventories agree that the highest emitting province, Shanxi Province, has significantly higher emissions than other provinces, and that emissions from Shanxi range from 31-36% higher than emissions in the second highest emitting province.

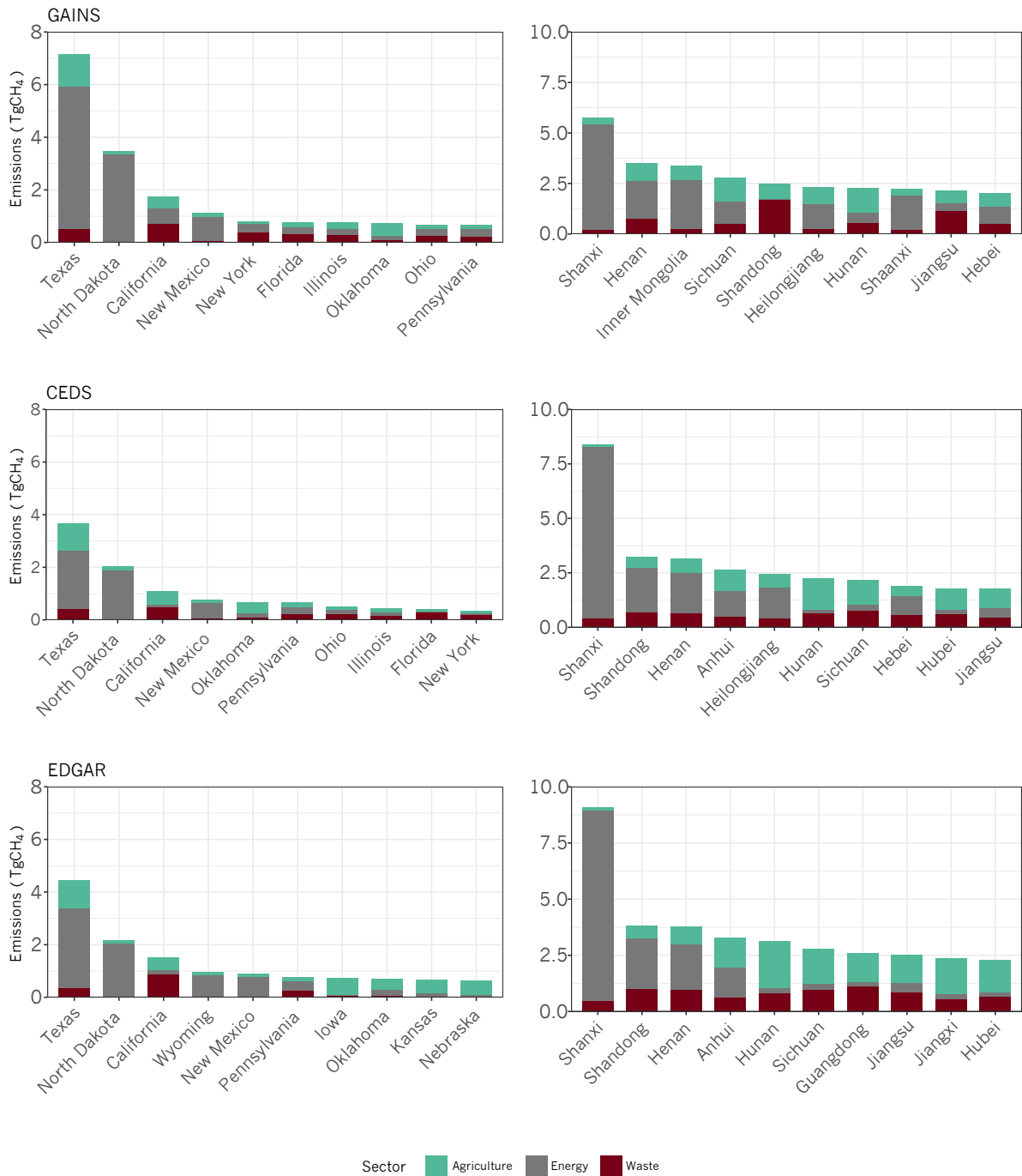
These high emitting states or provinces can have a significant impact on national total emissions. Total emissions in Texas and North Dakota, 3.7-7.3 and 2.1-3.5 TgCH₄, respectively, contribute to about 18% and 9% of total U.S. methane emissions. In China, the top 10 emitting provinces were responsible for over 56% of the country's total methane emissions across all three inventories. Shanxi Province's total emissions are 5.9-9.2 TgCH₄, accounting for more than 10% of China's total emissions. All three of these high emitting regions are energy producing hubs, with 60-74%, 90-95%, and 89-93% of emissions in Texas, North Dakota and Shanxi Province coming from the energy sector, respectively. Both Texas and North Dakota are high-ranking energy production states, especially for oil and gas production, with Texas being the top crude oil and gas producing state and North Dakota ranking second in the nation, after Texas, in crude oil reserves and third, after Texas and New Mexico, in crude oil production (EIA, 2022a). Shanxi Province is the largest coal producer in China and its economy highly depends on the fossil fuel industry (Song et al., 2020; Wang et al., 2022b). For high emitting provinces in the North of China (such as Heilongjiang, Hebei, Shandong, etc.), energy emissions account for more than 50% of the total emissions. Both the U.S. and China's spatial

distribution of total methane emissions correlates well with the spatial distribution of emissions from energy activities, indicating that energy is an important source of emissions in northern China (see the Policy Brief on Geospatial Analysis of Methane Emissions). These high emitting states and provinces present a policy opportunity for targeted, regional methane mitigation approaches in the energy sector.

Variations across inventories largely stemmed from differences in emission factors, underlying geospatial information and year of data. In the U.S., the magnitude of emissions in Texas and North Dakota varies significantly, with GAINS reporting almost twice as much emissions in Texas as CEDS or EDGAR. Additionally, energy emissions in California are much higher in GAINS than in EDGAR and CEDS, leading to higher overall emissions estimates in California. In China, all inventories agreed on the highest emitting province, Shanxi Province, but the second and third highest emitters varied. Two inventories, CEDS and EDGAR, ranked Shandong and Henan the second and third largest emitters, while another ranked Henan second, Inner Mongolia third, and Shandong fifth. This variation among top emitters across inventories is potentially due to the similar level of emissions across the remaining 9 of the top 10 emitters, as they are all hovering around 3-2.3 TgCH₄. It also could be due to the low energy emissions estimate for Shandong in GAINS inventory. GAINS energy emissions estimates for Shanxi are much lower than EDGAR and CEDS, about 62-152% less, which may be due to different data sources used for coal mine infrastructure. EDGAR also reports higher emissions across the remaining 9 highest emitting provinces than the other two inventories. These results suggest that other provinces also play a significant role in national methane emissions, and that mitigation policies should be implemented in these provinces as well as in Shanxi. To better understand methane emissions distribution across sectors and regions, future research can dive into the underlying data and inventory methodologies to investigate uncertainties across inventories and inform inventory and policy development.

FIGURE 3.11: AGRICULTURE, ENERGY AND WASTE METHANE EMISSIONS IN THE U.S. AND CHINA: TOP 10 EMITTING STATES/ PROVINCES ACROSS INVENTORIES.

We selected the top 10 provinces or states in terms of total emissions for each inventory. The charts only include emissions from energy, agriculture and waste, as other data is not available. GAINS data is from 2020 and CEDS and EDGAR data is from 2018. GAINS 2020 data is projected, not historical.



3.7 MEASUREMENT IMPROVEMENTS

To reduce uncertainty, research needs to use locally optimized emission factors, technology and operational data, and geospatial infrastructure data, and make data publicly available for comparison (Lin et al., 2021). China has a GHG reporting program scheduled for a trial run in 2023, which may increase monitoring of emissions sources and data availability (Xu & Stanway, 2022). Reducing uncertainty in coal emissions, a major source of national emissions in China, is particularly important. Measurements of the amount of methane released during coal mine operations and from abandoned coal mines is key to improving estimates. In the U.S., for example, methane data is collected quarterly by the U.S. Mine Safety and Health Administration (DOL, 2021) to assure compliance with safety regulations. The highest emitting mines are also required to report quarterly emissions from ventilation systems directly to EPA's GHG reporting program. Methane captured for energy production is subtracted from these data to determine net emissions. Overall, the U.S. EPA estimates that its estimates of coal mine emissions are accurate to within -9%/+17% in 2020 (EPA 2022a). In China, the State Administration of Coal Mine Safety collects coal mine methane emissions from underground mining facilities (Sheng et al., 2019), but only a source that used 2011 data was identified. This points to the need for publicly available mine-specific data on methane ventilation and utilization rates for more accurate emission estimates, especially since emissions can vary across coal mines due to variations in the depth and content of coal mines. In addition to active mines, better data is needed in most countries for AMM emissions (Gao et al., 2020), which are not included in the existing safety monitoring programs in the U.S. and China.

Landfill emissions depend on detailed site conditions and history, so these must be considered for accurate estimates. In the United

States, about 90% of landfills are now required to report their methane emissions to EPA using site-specific parameters, with additional reporting requirements for landfills with gas collection and control systems (which are used for a combination of safety, air pollution, odor control, and energy recovery purposes). Even with site-specific estimates for most emissions, EPA estimates overall uncertainty of municipal solid waste landfill emissions in 2020 to be -22%/+31% (EPA 2022a).

As discussed earlier, there is a large range in emission estimates from oil and gas systems. Fugitive methane emissions have been found to be “fat tailed” and a relatively small proportion of sites may contribute a large portion of emissions (Brandt et al., 2016; Irakulis-Loitxate et al., 2021). This means that relying on average parameters to estimate emissions can result in substantial emission underestimates. Emissions for production operations can be intermittent, posing additional challenges for estimation. Site-specific measurements focusing on the largest sources are needed for accurate estimation. Some inventories use the Tier 1 approach from IPCC, which is based on North American data that may not correspond to other regions (IPCC, 2021). Default IPCC emission factors may not adequately reflect different emission control technologies (Lamb et al., 2015; Collins et al., 2022; Gao et al., 2022) or temporal variability (Lavoie et al., 2017; Weller et al., 2020). Frequent measurement of emissions from oil and gas facilities is required to develop regional emission factors that reflect the variation of emissions across facilities and time. Additionally, evolving satellite capabilities (Jacob et al., 2022) may play a central role in better tracking of methane emissions from oil and gas production.

04 | MITIGATION POTENTIAL

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In addition to understanding current emissions and historical trends, evaluating methane mitigation potential and future pathways for emissions reduction is needed to inform policy making. Existing multi-model comparisons have included projected methane emissions data, including the IPCC's Sixth Assessment Report (AR6). Based on results from six models in the AR6 database with 1.5 °C consistent scenarios, assuming current policies have been implemented through 2020 and a global carbon budget of 400 GtCO₂e, methane emissions in China and the U.S. would reduce by a median of 57% and 42% by 2030 and 74% and 63% by 2050, respectively, compared to modeled 2020 levels (Figure 4.1). However, these studies are based on

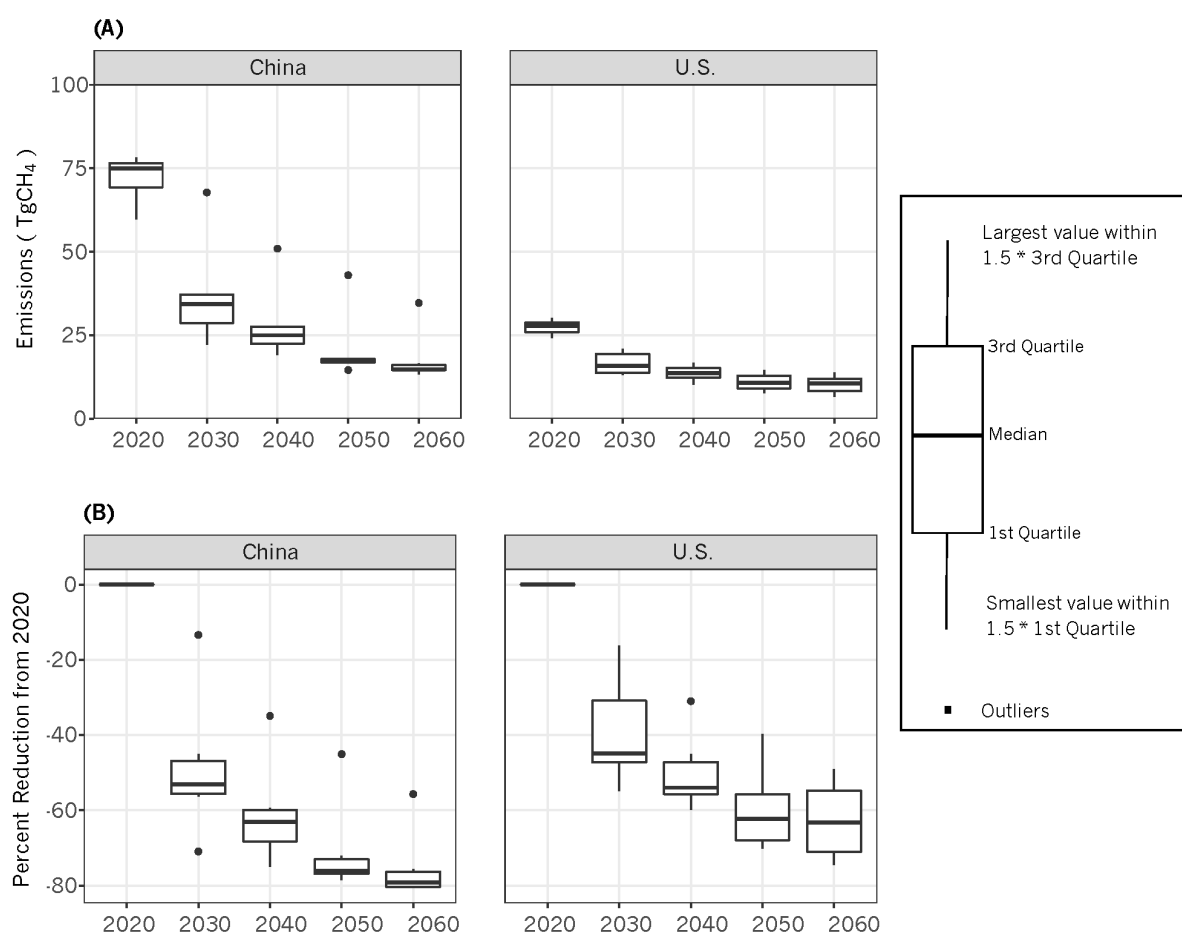
global models, often with older base-years and inventory dates, and may not reflect recent policy developments, as well as other country-specific technology conditions. Localized and updated cost data is needed to better inform the analysis of mitigation pathways. Also, these scenarios were not evaluated specifically in the context of methane mitigation and might not completely capture regional pathways. To better understand future methane emission trends across sectors, we conducted a multi-model study to further assess methane emissions reduction in China under carbon neutrality pathways and surveyed the literature to better understand methane mitigation in the U.S. under net-zero pathways.



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FIGURE 4.1: (A) TOTAL METHANE EMISSIONS AND (B) PERCENT EMISSIONS REDUCTION COMPARED TO 2020 FROM IPCC'S SIXTH ASSESSMENT REPORT (AR6) 1.5°C SCENARIOS.

Models include: Asia-Pacific Integrated Model/Computable General Equilibrium 2.2 (AIM/CGE 2.2), COmputable Framework for Energy and the Environment 1.1 (COFFEE 1.1), Model for Energy Supply Systems and their General Environmental Impact-Global Biosphere Management Model 1.1 (MESSAGEIX-GLOBIOM_1.1), POLES ENGAGE, Regional Model of Investment and Development-Model of Agricultural Production and its Impacts on the Environment 2.1-4.2 (REMIND-MagPIE2.1-4.2), and World Induced Technical Change Hybrid 5.0 (WITCH 5.0). Scenarios from AR6 return warming to 1.5°C (>50%) after a high overshoot.



4.1 METHANE MITIGATION ACROSS SECTORS IN CHINA IN CARBON NEUTRALITY SCENARIOS

Four modeling teams participated in this analysis and submitted results from the same scenario to improve comparability of results. Scenarios used in this report have CO₂ emissions peak around 2025 and reach net-zero CO₂ by 2050 and net-zero GHG by 2060, based on China's NDC and

long-term strategy targets. Given that the scenario is defined by a CO₂ and total GHG pathway, models vary in both methane peaking and net-zero time frame. Lawrence Berkeley National Laboratory (LBNL) Methane Model and Model for Energy Supply Systems and their General

Environmental Impact-China (MESSAGEix-China) have peak methane emissions in 2020, Global Change Analysis Model-China (GCAM-China) in 2025, and Asia-Pacific Integrated Model-China (AIM-China) in 2030. Both MESSAGEix-China and GCAM-China see rapid decline in emissions between 2025-2030, while LBNL Methane Model demonstrates the fastest decline between 2020-2025, and AIM-China between 2035-2040 (Figure 4.2). Models show varying rates of reduction over time: by 2030, methane emissions are reduced 31-56%⁴ from 2020; and by 2050, 46-66%⁵ from 2020. In the base-year, there is reasonable agreement among most of the models. Differences may be explained by different calibration sources and calibration data year. By 2050, models have reasonably consistent projections on remaining methane emissions (16-28 TgCH₄) (Figure 4.2).

Across sectors, models show relatively high agreement for energy (44-54%) and agriculture share (30-40%) but vary most significantly for waste (7-22%) in 2020, highlighting increased uncertainty in current emissions in this sector. Differences across models stem from differences in methodological approaches (see Box 4.1). LBNL

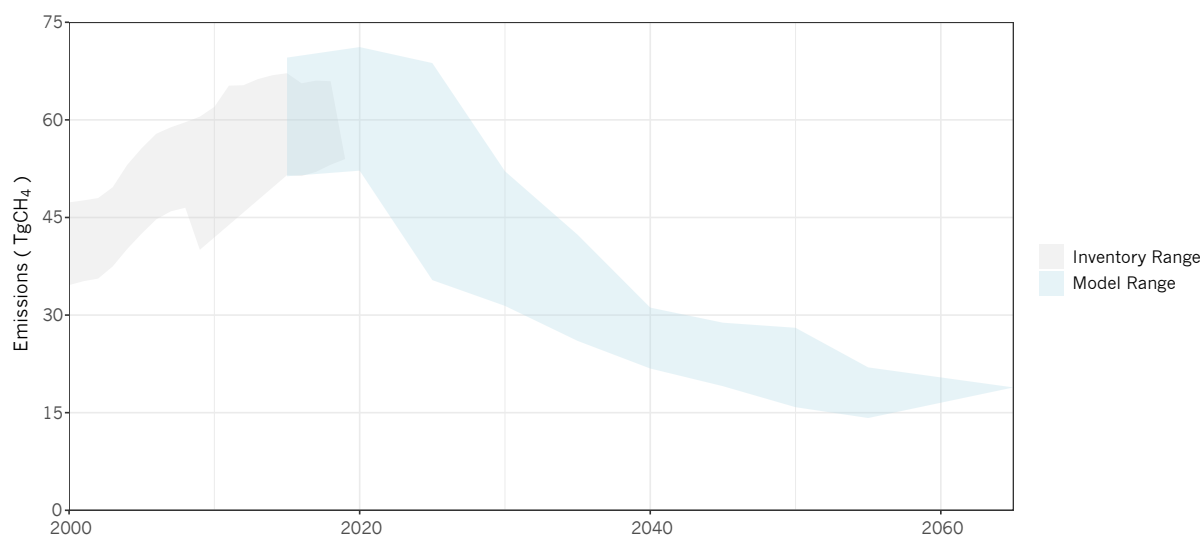
Methane Model, AIM-China, and GCAM-China have similar total emissions estimates, but vary in the make-up of emissions by sector, with AIM-China reporting higher Agriculture, Forestry and Other Land Use (AFOLU) and energy and less waste emissions, while GCAM-China and LBNL Methane Model have similar energy emissions but vary in the waste and agriculture breakdown. MESSAGEix-China shows higher emissions in all sectors than other models. Most models' emissions reduction is largely driven by reductions in emissions from coal, especially in the near-term, as it accounts for a median of 81% and 60% of total emissions reduction by 2030 and 2050, respectively (Table 4.1). In 2050, rice cultivation, enteric fermentation, and oil and gas each contribute to about 7% of total emissions reduction. Models have different mitigation potential data, and model behavior is driven by both activity data and technology change assumptions, especially in the agriculture and waste sectors. To better understand projected methane emissions reduction across models, mitigation potential assumptions will be further explored in following sections.

⁴ Range does not include one model, AIM-China, that sees a 5% reduction in emissions by 2030.

⁵ Range does not include one model, MESSAGEix-China, that sees a 78% reduction by 2050.

FIGURE 4.2: PROJECTED TOTAL METHANE EMISSIONS IN CHINA IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Model range indicates pathways of methane emissions in China across models used in this study.

**TABLE 4.1: METHANE EMISSIONS REDUCTIONS BY SECTOR IN CHINA, RELATIVE TO 2020 LEVELS, IN CARBON NEUTRALITY SCENARIO.**

(Median Values Across Models, Unit: TgCH₄)

Sector	2030	2050
Total Methane	-19	-32
Coal Mine	-14	-20
Oil and Gas	-0.6	-3.2
Rice Cultivation	-1.3	-2.7
Enteric Fermentation	+0.1	-2.5
Manure Management	-0.3	-0.9
Wastewater	+0.4	+0.2
Solid Waste	-0.9	-1.5

BOX 4.1 HOW NON-CO₂S ARE MODELED

Different approaches to modeling non-CO₂ GHGs are adopted across participating models. All models consider mitigation potential. The LBNL Methane Model calculates methane emissions using activity drivers for individual sectoral sources, multiplied by source-specific emission factors. For projections, emissions are calculated by multiplying activity data, emission factor, and reduction potential for specific non-CO₂ mitigation measures. Reduction potential is based on Marginal Abatement Cost (MAC) Curve assumptions (Lin et al., 2022). Reductions in GCAM-China are also driven by

MAC curves, based on U.S. Environmental Protection Agency technology and region-specific MAC Curves (EPA, 2019c). Modeled emissions are a function of activity level and MAC emissions reduction potential. In the MESSAGEix-China model abatement potential in the energy sector is based on abatement assumptions from GAINS. In the agriculture sector, mitigation assumptions are from the Global Biosphere Management Model (GLOBIOM) (IIASA, 2022). For AIM-China, model projections are based on exogenous technology costs, which informs model choices.

BOX 4.2 BASE-YEAR DIFFERENCES ACROSS MODELS

Base-year (2015) differences across models, as shown in Figure 4.2, are likely due to a number of differences in methodology across models, including activity data and emission factor source. As outlined in the previous chapter, there is a great deal of variation in historical methane emission estimates, so modeling discrepancies in the base-year can largely be attributed to differences in calibration sources and modeling methods. GCAM-China and MESSAGEix-China are calibrated to historical non-CO₂ emissions inventory data, and implied emission factors are calculated based on calibrated emissions and activity data. GCAM-China is calibrated to CEDS for all emissions sources except agriculture waste burning, forest fires, and deforestation, which use Global Fire Emissions Database (GFED) Land Use Land Cover (LULC) from Coupled Model Intercomparison Project 6 (CMIP6). CEDS is based on EDGARv5.0 for all sectors except agriculture, which instead uses FAO data. MESSAGEix-China is calibrated to EPA for most sectors and FAO data for the agriculture sector. MESSAGEix-China calibration is based on inventory versions

from before 2015, so base-year and inventory data may differ. LBNL Methane Model and AIM-China calculate methane emissions by multiplying activity data and source-specific emission factors. LBNL model-calculated results for 2014 are consistent with China's national GHG inventory reported by sector for that same year, with adjustments made to the model calculation method if needed.

Model differences in the base-year can impact modeling projections in the near-term and over the long-term trend. Variation in base-year and underlying inventory heightens uncertainty about near-term emissions in 2030, a key year for global climate ambition as outlined by the Paris Agreement and the Global Methane Pledge. Additionally, base-year variations across models can be so significant that it is difficult to identify a consistent long-term trend or coherent policy narrative. Increasing confidence in inventory assumptions and emission factors for historical emissions is critical for developing methane mitigation pathways.

4.2 METHANE MITIGATION FROM ENERGY ACTIVITIES IN CHINA

Methane Mitigation from Coal Production

Coal mining is a major source of methane emissions in the base-year in China, and is therefore a large source of potential methane mitigation. There's high-level agreement in base-year emissions across three out of the four models, with emissions between 20.3-20.6 TgCH₄, which is consistent with the range of inventories included in chapter 3. There's also reasonable agreement across all four models on production base-year values (2505-2715 Mtce). Base-year emissions in the MESSAGEix-China model are calibrated to the EPA inventory, which is on the higher end of the inventory range for coal mining emissions. There is also some variation in the trend of coal production between 2015-2020 across models, with AIM-China and LBNL Methane Model projecting production peaking in 2020, and GCAM-China and MESSAGEix-China in 2015. Given that the nationally reported statistics document increasing emissions through 2020, models may be overestimating near-term reduction in coal emissions and production. By 2030, most models see a 72-82% reduction in coal emissions

compared to 2020, except one model, AIM-China, which only demonstrates an 18% decrease. By 2050, all models foresee coal emissions reductions of 93-100% from 2020 (Figure 4.3). Emissions across all models eventually reach <1.4 TgCH₄ in 2050.

Implied emission factors were calculated using activity data and emissions projections for models (Figure 4.4) to compare the impact of activity level and technology changes on emissions reduction over time. Near-term mitigation is driven by technology changes in most models, but activity level becomes an increasingly larger driver over time. By 2050, activity data is the primary driver for emissions reduction in coal production. While all models see coal production as a major source of emissions reduction potential and are fairly aligned on magnitude of emissions reduction in the coal sector, models may be overestimating potential, especially in the near-term, as three models do not consider AMM. While helpful for understanding how two factors may be contributing to assumptions across models, understanding mitigation in policy and real-world context is critical for informing policy-making.



FIGURE 4.3: CHINA COAL MINE METHANE EMISSIONS AND COAL PRODUCTION IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and production (Mtce) on the right. Historical production data was collected from the 2021 Chinese Energy Statistical Yearbook (CESY) (NBS, 2021).

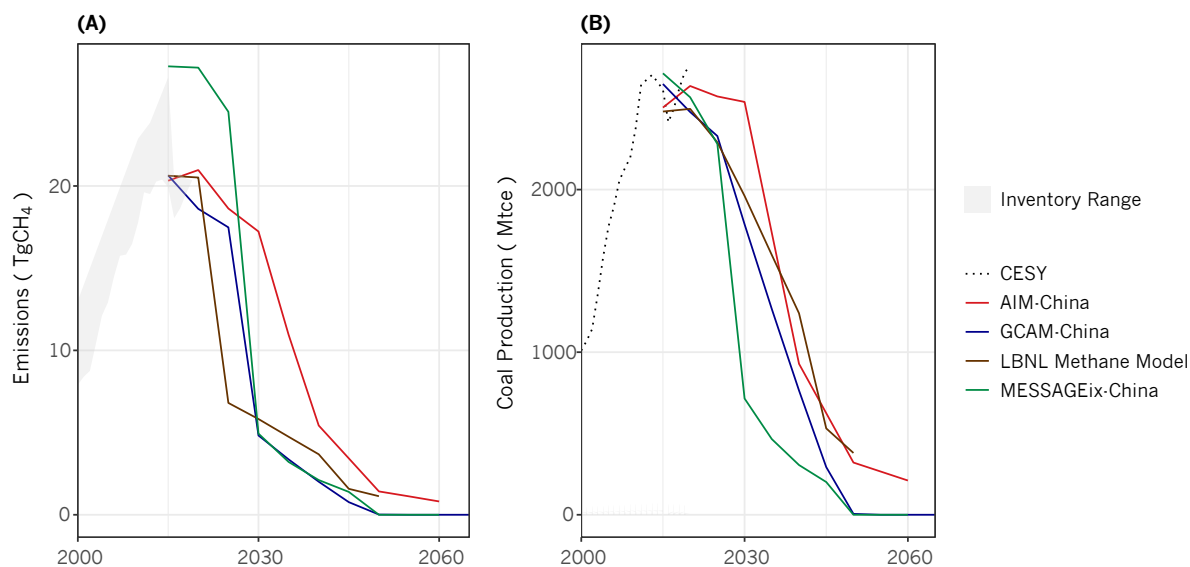
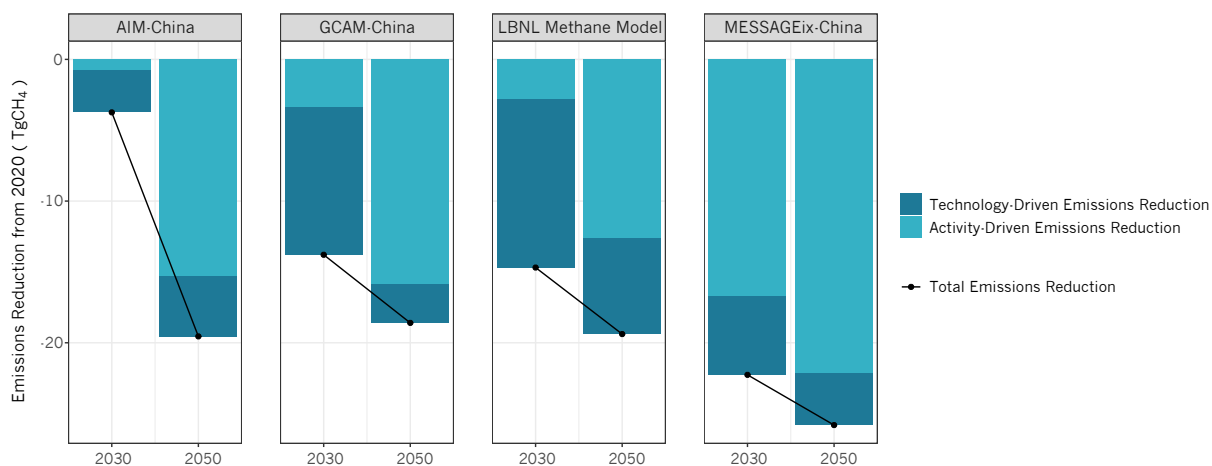


FIGURE 4.4: CONTRIBUTIONS OF ACTIVITY LEVEL AND TECHNOLOGY CHANGE TO METHANE EMISSIONS REDUCTION IN THE COAL MINE SECTOR IN CARBON NEUTRALITY SCENARIOS.

For MESSAGEix-China, 2045 data is used instead of 2050, since emissions and production are 0 in 2050.



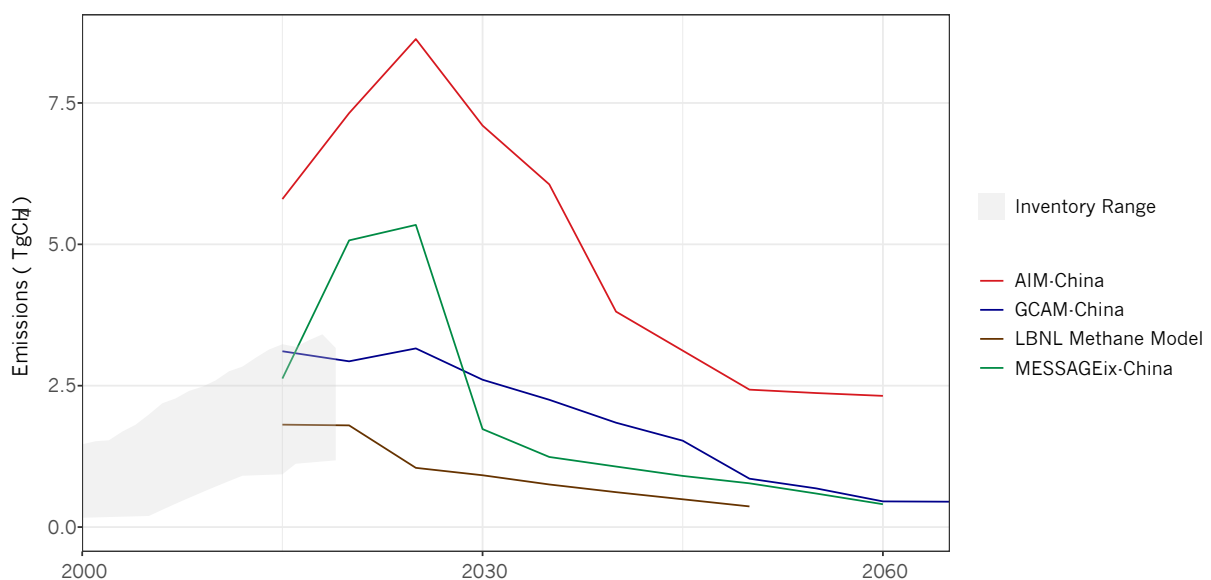
Methane Mitigation from Oil and Gas Production

Oil and gas production is not as large a source of current methane emissions in China as coal, but results from prior inventory analysis suggest there are high levels of uncertainty in oil and gas methane emissions in China and that emissions have been increasing, potentially making oil and

gas methane emissions a more important sector for mitigation in the future. Differences across base-year model emission estimates range from 2-6 TgCH₄ in 2015 (Figure 4.5), with one model exceeding the inventory range. These differences are likely caused by different emission factors or inventory data used for base-year calibration by models.

FIGURE 4.5: CHINA OIL AND GAS METHANE EMISSIONS IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Historical production data was collected from the 2021 Chinese Energy Statistical Yearbook (CESY) (NBS, 2021).



Looking at natural gas production and emissions separately from oil, we can better understand some of the differences across models. While gas production in the base-year has reasonable agreement across models, projections about production after 2015 vary significantly. Long-term trends for most models are consistent – peaking in 2015 or 2025, followed by significant reductions in production and emissions, so that emissions are less than 2.5 TgCH₄ in 2050 (Figure 4.6). Emissions in GCAM-China decline between 2015-2020, potentially accounting for COVID impacts on production and economy. While

GCAM-China, AIM-China and MESSAGEix-China all demonstrate increasing emissions from 2015 to 2025, the projected increase in production from 2015-2025 varies between models, from a ~35 Mtce to a ~250 Mtce increase, with one model, MESSAGEix-China, almost doubling 2015 production estimates by 2025. Most models project a decline in gas production by 2040, suggesting that the modeled rapid increase in natural gas by 2025 may serve to replace coal during a near-term phase-down of coal in compliance with the 2030 NDC target. AIM-China shows less production decline after 2025

than other models, as gas production peaks in 2035, declines somewhat after 2035, but remains around 260 Mtce in 2060, while other models estimate production will be approximately less than 50 Mtce. Differences in model projections for gas production highlight the uncertainty of the role natural gas will play to meet carbon neutrality goals in China. Nationally reported gas production data shows increasing production from 2015-2020 (NBS, 2021), suggesting near-term growth of gas production and corresponding emissions in China is likely.

For oil production, we see fairly consistent base-year production estimates across models, but a wide range of emissions in 2015 (0.1-4 TgCH₄) (Figure 4.7). All models show a similar long-term trend, with a 2025 or 2020 peak and near-zero emissions (<1 TgCH₄), in 2050 and similar 2015 oil production estimates, which range from 280-335 Mtce. The emission range in the base-year across models for oil emissions is relatively higher than oil production, suggesting that model variation in oil emissions may stem from different emission factors used across models, not from differences in projections about oil production behavior.

FIGURE 4.6: CHINA GAS METHANE EMISSIONS AND GAS PRODUCTION IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and production (Mtce) on the right. Historical production data was collected from the 2021 Chinese Energy Statistical Yearbook (CESY) (NBS, 2021).

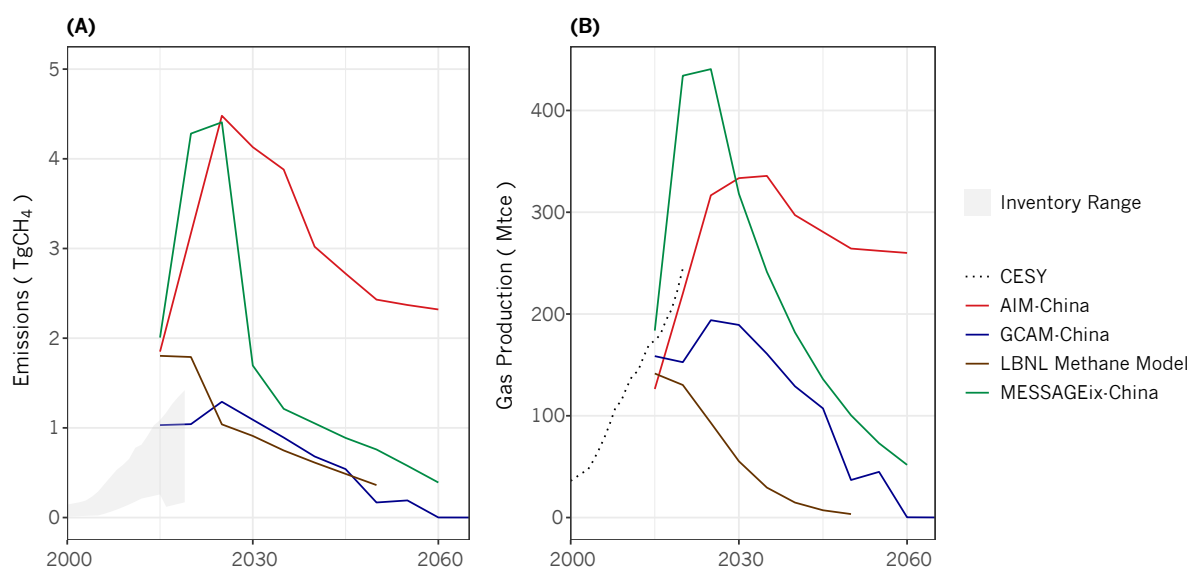
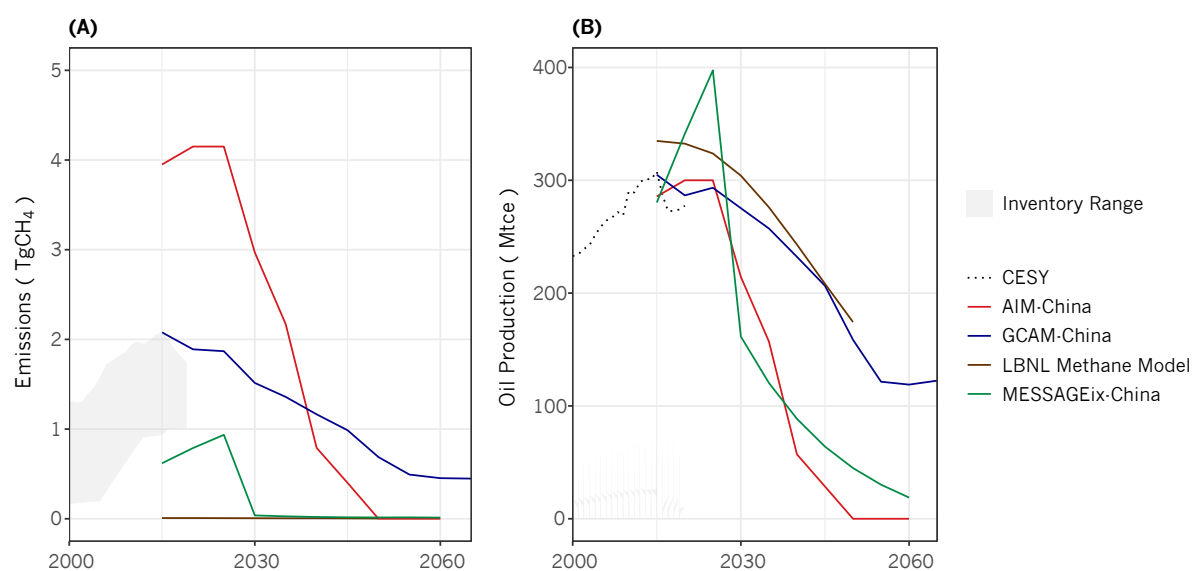


FIGURE 4.7: CHINA OIL METHANE EMISSIONS AND OIL PRODUCTION IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and production (Mtce) on the right. Historical production data was collected from the 2021 Chinese Energy Statistical Yearbook (CESY) (NBS, 2021).

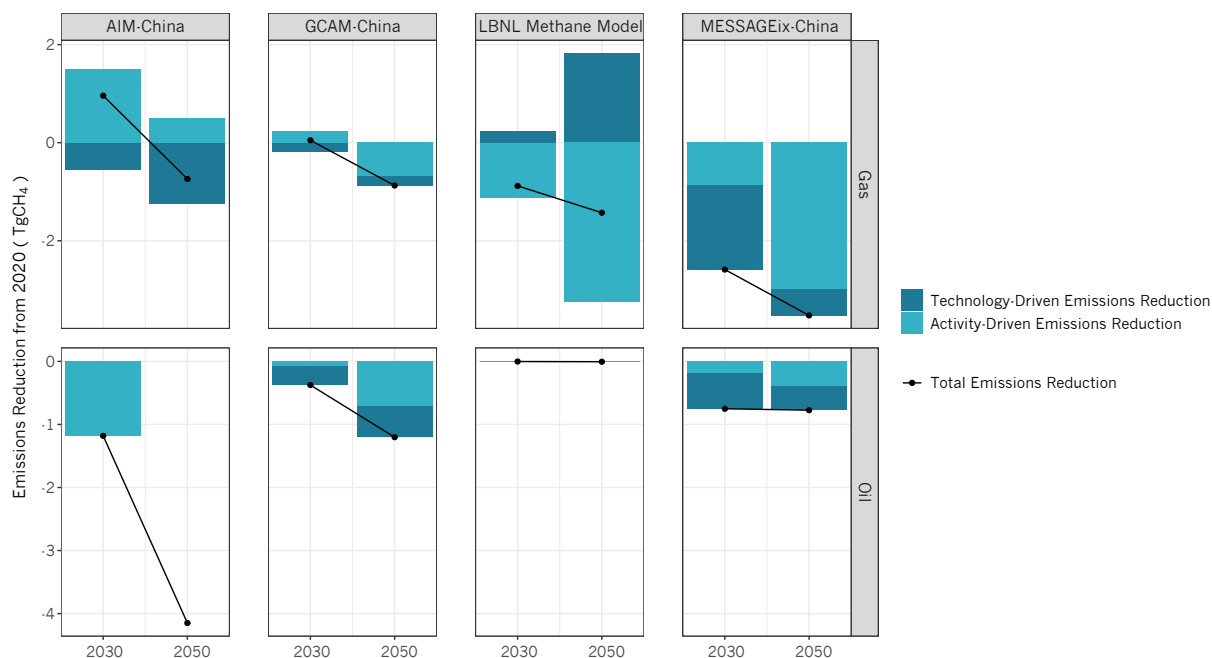


Implied emission factors were calculated using activity data and emissions projections for models (Figure 4.8) to compare the impact of activity data and technology changes on emissions reduction over time. For oil, most models project that activity level reductions will play an important role in emissions reduction by 2050, but the magnitude of emissions reduction and technology change contribution varies across models. Both GCAM-China and MESSAGEix-China show moderate emissions reductions, with contribution from both activity level and technology change. AIM-China foresees significant reductions in emissions almost entirely from activity level but has a significantly higher 2020 emissions starting point than the other models. All models have similar 2050 emissions, so this may not represent differences in mitigation potential, as much as uncertainty in base-year emissions.

Gas production activity level and technology change capability are both highly uncertain, especially in China, as gas production may play an increasingly important role as other fossil fuels, such as coal, are phased out rapidly (Figure 4.8). But one model, AIM-China, foresees technology improvement helping to drive down emissions from gas even while production increases, showing technology change as a larger factor in emissions reduction by 2050 than activity level decline. Modeled measures that are helping to drive emissions reduction include leakage control for mining equipment and sealing technology in gas production. The LBNL Methane Model shows declining improvements in gas production technology after 2030 because emission factors are held constant after 2030, based on the assumption that full mitigation technology deployment for gas production occurs by 2030.

FIGURE 4.8: CONTRIBUTIONS OF ACTIVITY LEVEL AND TECHNOLOGY CHANGE TO METHANE EMISSIONS REDUCTION IN OIL AND GAS SECTOR IN CARBON NEUTRALITY SCENARIOS.

For AIM-China oil, 2045 data is used instead of 2050, since emissions and production are 0 in 2050. The LBNL Methane Model assumes very little oil emissions and production in China in 2020, and relatively constant production in the future.



4.3 METHANE MITIGATION FROM AGRICULTURAL ACTIVITIES IN CHINA

Methane Mitigation from Rice Cultivation

There is a high level of uncertainty in rice cultivation emissions in China (Cheewaphongphan et al., 2019), but there is relatively reasonable agreement across three models in base-year behavior (~7 TgCH₄). All models are on the lower estimate of the inventory range in 2015, suggesting that emissions in this sector may be underrepresented. However, the high-end of the inventory range may be overestimating emissions, due to higher flooding assumptions and/or inclusion of aquaculture emissions used in some inventories. See Chapter 3.4.1 for further analysis of the rice cultivation emissions inventory range.

Most models project emissions peak in 2025, with one model peaking in 2015, followed by a fairly rapid decline from peaking year to 2030. AIM-China results demonstrate a slower emissions reduction rate from peaking in 2030 to 2045, as the harvested area for rice cultivation grows from 2020-2055. The LBNL Methane Model shows a slight decline in harvested area but overall, a constant amount around ~32 million ha, while GCAM-China demonstrates a more dramatic decline in harvested area by 2050 (~6 million ha). The LBNL Methane Model, GCAM-China, and AIM-China models have similar estimates of base-year harvested area of ~31-34 million ha.

FIGURE 4.9: CHINA RICE CULTIVATION METHANE EMISSIONS AND HARVESTED RICE AREA IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and harvested land area (million ha) on the right. Historical harvested area was collected from the FAO (FAOSTAT, 2021a). GCAM-China assumed two harvests on every ha used for rice cultivation.

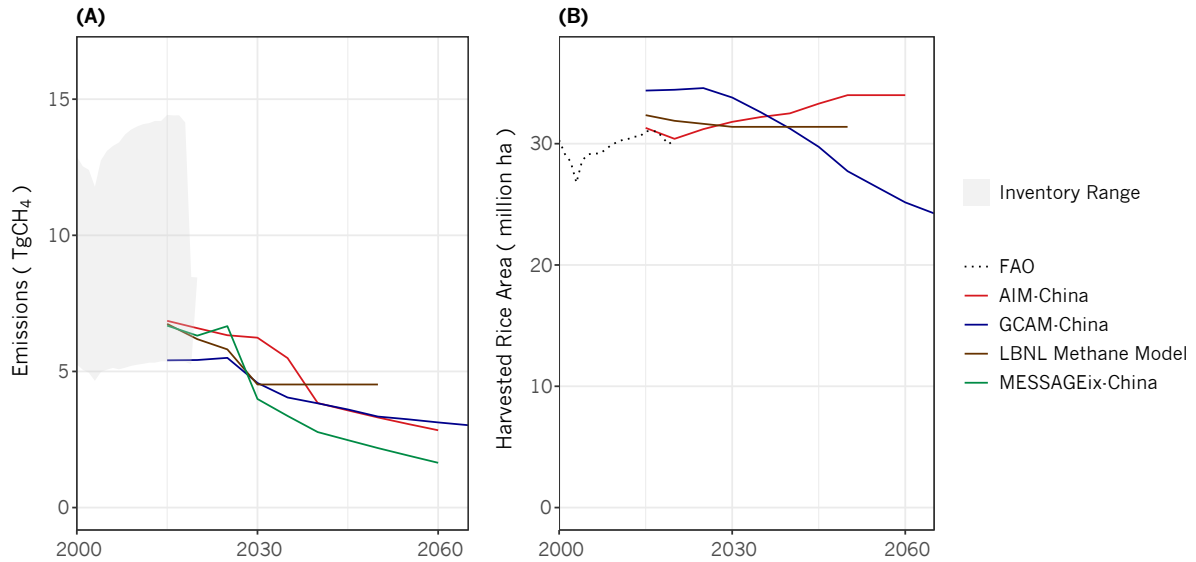
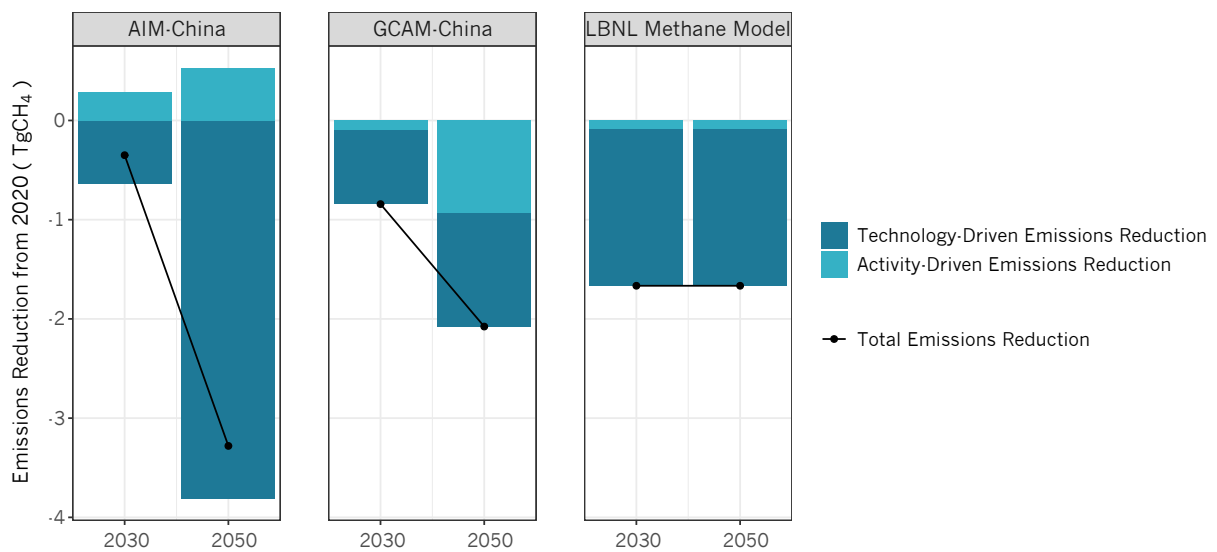


FIGURE 4.10: CONTRIBUTIONS OF ACTIVITY LEVEL AND TECHNOLOGY CHANGE TO METHANE EMISSIONS REDUCTION IN THE RICE CULTIVATION SUBSECTOR IN CARBON NEUTRALITY SCENARIOS.



Mitigation potential results show variation across models in terms of magnitude and mechanism of emissions reduction (Figure 4.10). For both AIM-China and LBNL Methane Model, rice cultivation emissions reduction is driven more by technology change than activity level. Only one model suggests that declining cultivation area will be the primary driver of emissions reduction in 2050. Another anticipates increasing cultivation by 2050, with significant emissions reduction (>3 TgCH₄) due to improved irrigation technology and agricultural management practices. The LBNL Methane Model assumes emissions reduction, activity data and technology change remain constant from 2030 to 2050, as full mitigation measures are implemented in 2030 and activity level does not change.

Methane Mitigation from Livestock Production

There is disparity between models and inventory estimates of enteric fermentation emissions in the base-year, as two models exceed the inventory range (Figure 4.11). Differences in underlying livestock production data may explain some of the differences, as only one model, AIM-China, is consistent with the FAO historical data in 2015.

Emission factors may also play a role, as AIM-China and GCAM-China base-year emission projections are very similar, despite differences in production estimates. All models show a near-term emissions increase, from 2015-2020/2025/2030. There are also varied mitigation assumptions, as two models show more rapid reduction from 2020 (AIM-China and MESSAGEix-China decline by 40-45% by 2050), while the LBNL Methane Model projects only a 9% reduction in emissions by 2050, and GCAM-China emissions increase by 9%, though by 2060, emissions begin to decline as livestock production declines.

For manure management, all models are within the inventory range (1.3-3.3 TgCH₄), but mitigation behavior varies by model (Figure 4.12). Similar to fermentation, MESSAGEix-China and AIM-China assume increasing emissions in the near-term followed by rapid reduction. One model projects that 80% of emissions will be reduced by 2050 compared to 2020, while remaining models only foresee 26-41% of emissions being reduced. The LBNL Methane Model demonstrates near-term emission decline, as mitigation measures are implemented through 2030, while GCAM-China projects limited emissions reduction in the manure management sector.

FIGURE 4.11: CHINA ENTERIC FERMENTATION METHANE EMISSIONS AND LIVESTOCK PRODUCTION IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and livestock (Mt) on the right. Livestock production includes duck, chicken, cattle for meat, pig, sheep and goat. Historical production data was collected from the FAO (FAOSTAT, 2021a), and was used to separate poultry livestock production for meat and eggs for GCAM-China. Total livestock production in the LBNL Methane Model does not include poultry.

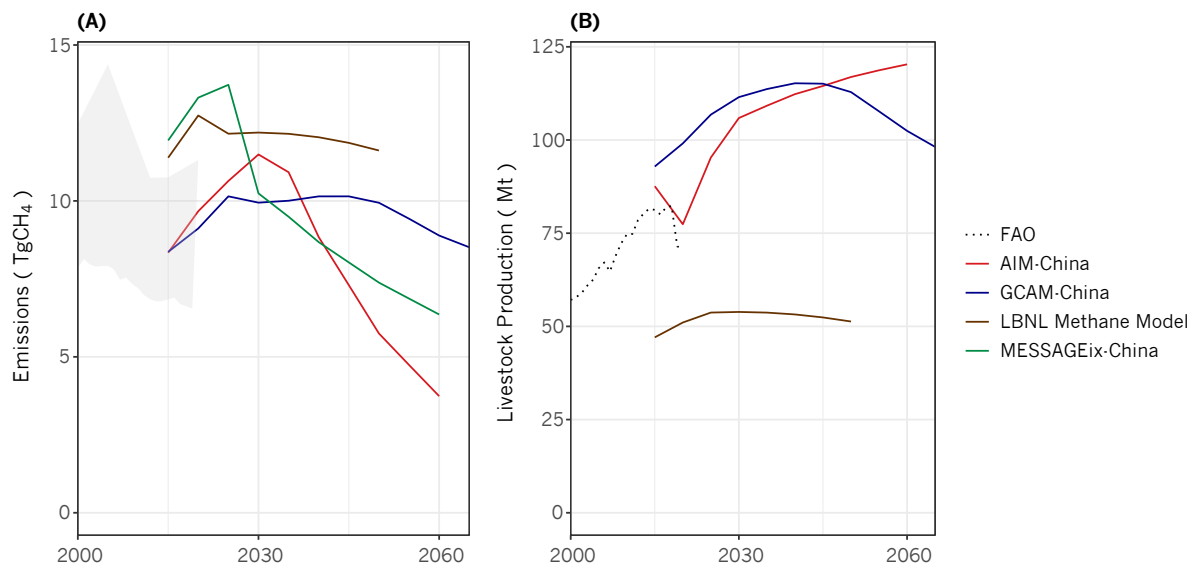


FIGURE 4.12: CHINA MANURE MANAGEMENT METHANE EMISSIONS AND LIVESTOCK PRODUCTION IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. Units of panels are different, with emissions on the left (TgCH₄) and Livestock Production (Mt) on the right. Total livestock production in the LBNL Methane Model does not include poultry.

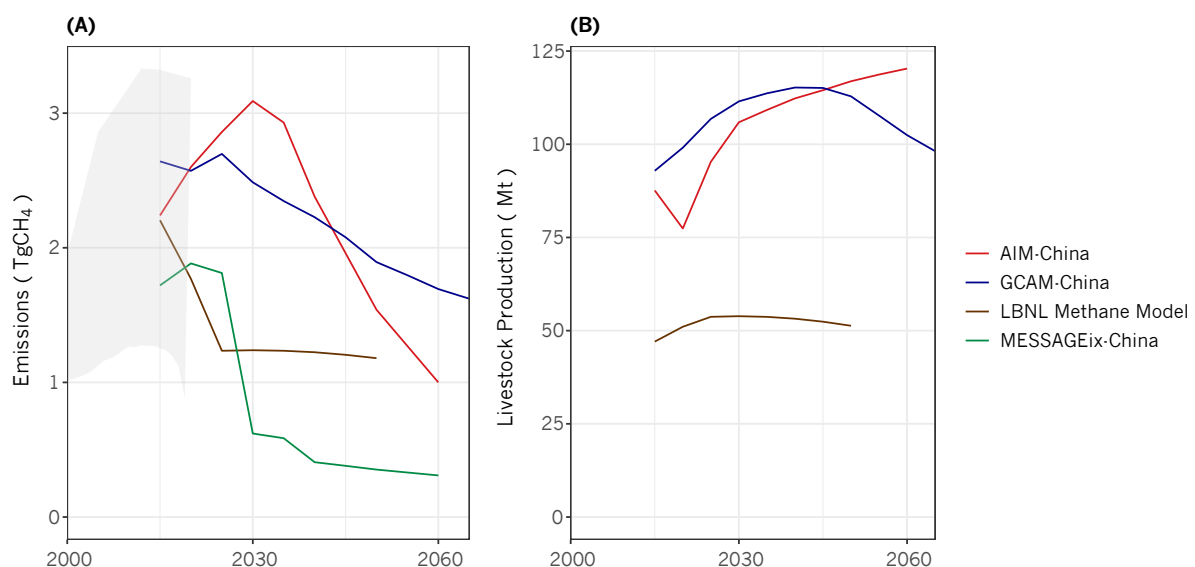
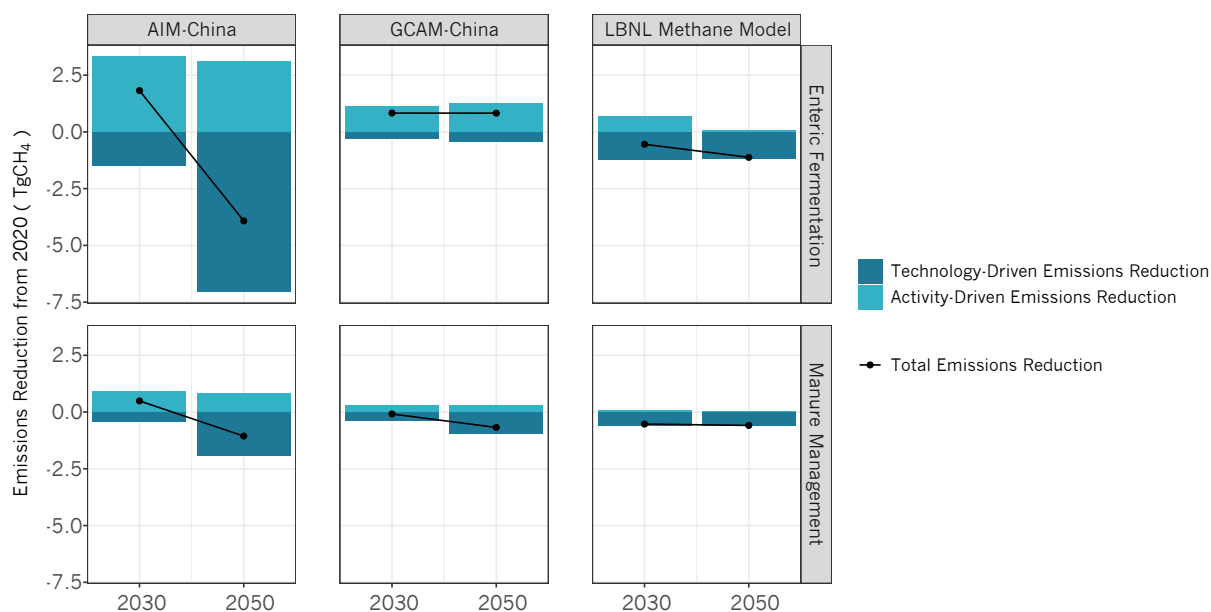


FIGURE 4.13: CONTRIBUTIONS OF ACTIVITY LEVEL AND TECHNOLOGY CHANGE TO METHANE EMISSIONS REDUCTION IN LIVESTOCK SUBSECTORS IN CARBON NEUTRALITY SCENARIOS.



Overall, the livestock sector is more driven by technology change than the energy sector. Both LBNL Methane Model and AIM-China show technology change having a significant impact on emission reduction for both livestock sectors (Figure 4.13). Most models see an increase in livestock production-driven emissions in 2030 from 2020, with both GCAM-China and AIM-China projecting increasing emissions, while the LBNL Methane Model foresees technology change helping to reduce emissions by 2030. By 2050, the LBNL Methane Model foresees no emissions change driven by activity level, just technology change for enteric fermentation. In manure management, GCAM-China and AIM-China show increasing emissions from increasing activity levels, while the LBNL Methane Model foresees no activity-level driven increase in emissions.

One model with significant mitigation potential projected in the livestock sector, AIM-China, assumed improved management of livestock, including cattle breeding, cattle feed and animal manure management improvements, as well as increased waste utilization in the cattle and pig sectors. In the model, the ratio of improved cattle breeding and feeding management increases from ~10%-25% by 2030 to ~85%-100% by 2050. Waste utilization rates in the cattle/pig raising process are also assumed to reach 100% by 2050. MESSAGEix-China assumes the adoption of non-intensive feeding patterns increases over time, based on socio-development changes, reducing methane emissions from both the enteric fermentation and manure management subsectors. Both GCAM-China's and LBNL Methane Model's underlying Marginal Abatement Cost (MAC) curves project limited opportunities for methane emission mitigation in the livestock sector.

4.4 METHANE MITIGATION FROM WASTE MANAGEMENT IN CHINA

Waste is a significant source of methane emissions in China, making up 12% of nationally reported emissions in 2014. Base-year emissions vary across models, ranging from 3.8-13.6 TgCH₄, with all but one model within the inventory range (Figure 4.14). Post-2015, one model foresees increasing emissions, another relatively constant emissions, and the two models with the largest base-year estimates (GCAM-China and MESSAGEix-China) foresee relatively significant reductions by 2050 – 40% and 66% compared to 2020, respectively.

Looking at some of the major components of the waste sector, we see agreement among models in the base-year in solid waste, with 2015 estimates between 2.8-3.6 TgCH₄, and a relatively consistent downward trend across models (Figure 4.15). However, the emissions reduction potential varies across models, as models demonstrate a range of 34-76% emissions reduction by 2050 compared to 2020, with one model projecting fairly constant emissions after 2025. Two of the three models that reported this variable are within the inventory range, while another, AIM-China, is below the

estimated range. Differences in the base-year are likely due to differences in methodologies across models, as two teams calibrate or confirm results with inventory reported values, while AIM-China uses activity data and emission factors to come up with their estimate.

As discussed in the previous chapter, historical estimates in the wastewater sector have very high uncertainty (Figure 4.15). Activity data and emission factors vary significantly because of limited data on emissions from wastewater treatment plants. One model, GCAM-China, projects significant emission reductions based on EPA MAC curves, which shows significant opportunities (~39 MtCO₂e) for wastewater mitigation at low-cost, including replacing latrines, open sewers, and septic tank use with anaerobic WWTPs (EPA, 2019b). The LBNL Methane Model also considers open sewer replacement for mitigation potential, but assumes less potential from these mitigation measures for China (Lin et al., 2022). Emissions are projected to increase in this model, as activity level increases over time, and low-cost mitigation opportunities are limited.

FIGURE 4.14: CHINA WASTE METHANE EMISSIONS IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3.

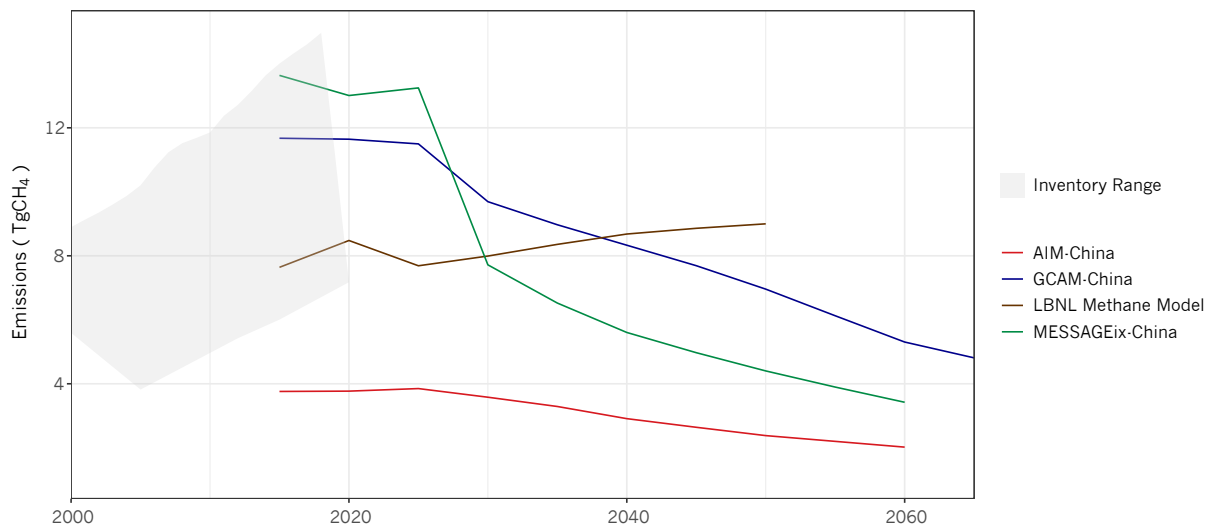
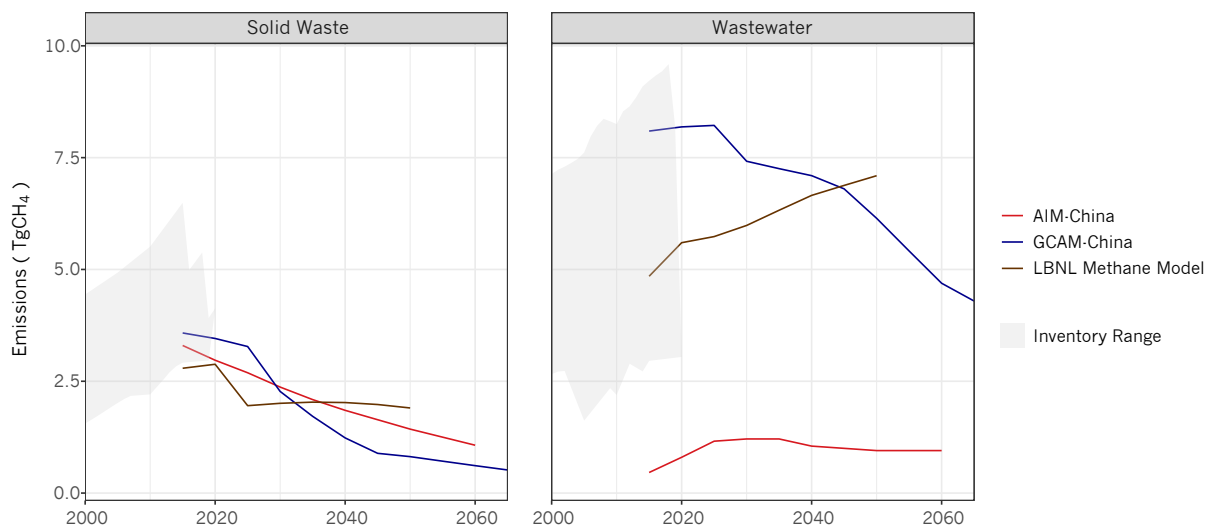


FIGURE 4.15: SOLID WASTE AND WASTEWATER METHANE EMISSIONS IN CHINA IN CARBON NEUTRALITY SCENARIOS.

Inventory range for emissions includes estimates from all inventories included in Chapter 3. GCAM-China estimates include waste incineration.



4.5 METHANE MITIGATION IN THE UNITED STATES

Methane emissions currently account for 11% of U.S. GHG emissions (EPA, 2022b). To meet the U.S. climate pledge of reaching net-zero GHG

emissions by 2050, a significant portion of non-CO₂ emissions, including methane emissions, need to be reduced, while remaining methane and

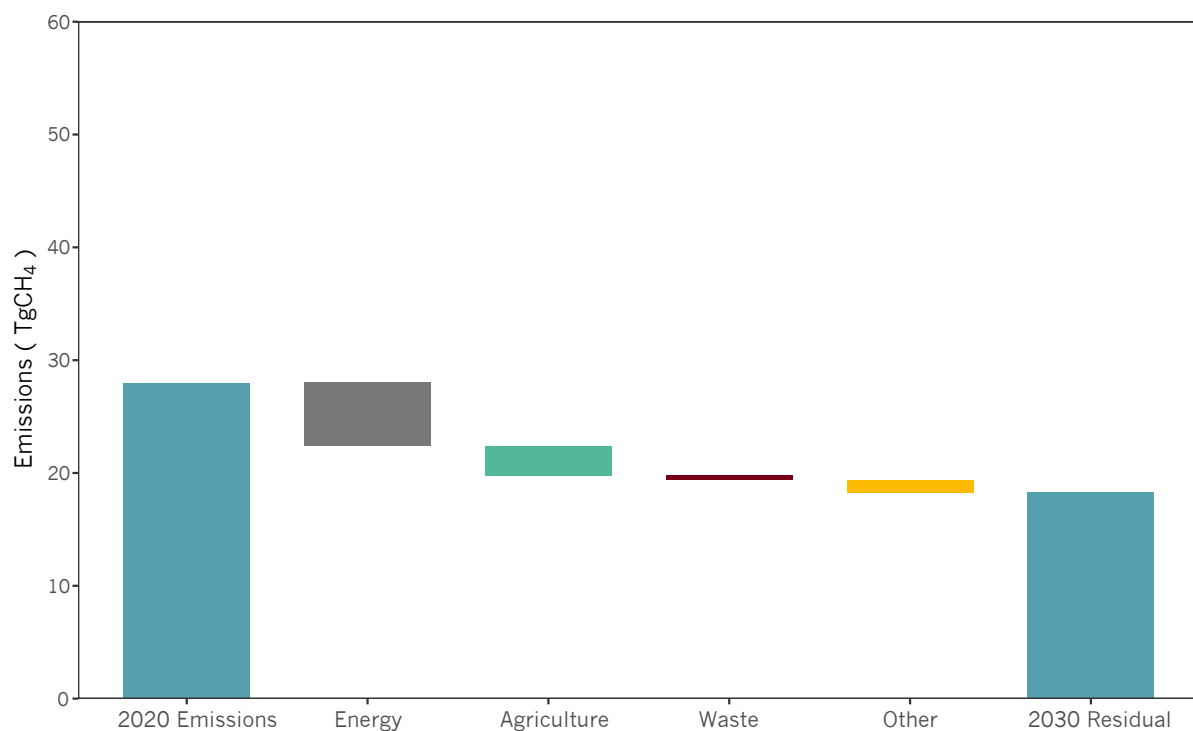
other non-CO₂ emissions will need to be offset by negative emissions. The U.S. Long-Term Strategy estimates that to reach net-zero greenhouse gas emissions by 2050, U.S. methane emissions need to be reduced by 30% by 2030 and up to 40% by 2050, compared to 2020 levels (U.S. Department of State, 2021). Most emissions reductions come from the energy sector, driven by reduction in the use of fossil fuels and improvement in technologies.

Most recent analysis indicates that with an all-of-society climate strategy from the United States, combining actions from the federal government with actions from states, cities, and businesses,

including the methane fee from IRA, the United States can potentially reduce its methane emissions by 9 TgCH₄, or more than 30% below 2020 levels by 2030 (Zhao et al., 2022) (Figure 4.16). Most emissions reductions come from the energy sector, followed by the agriculture sector and the waste sector. With robust climate actions, energy sector methane emissions can be reduced by 44% between 2020 and 2030. These emissions reductions can be achieved by adopting standards on existing and new oil and gas sources, implementing extensive leak detection and repair requirements, limiting venting and flaring, and taking actions to reduce methane emissions from active and abandoned coal mines.

FIGURE 4.16: METHANE EMISSIONS REDUCTIONS BY SECTOR IN THE UNITED STATES BETWEEN 2020 AND 2030 WITH FEDERAL, STATE, LOCAL, AND BUSINESS ACTIONS.

Based on the analysis of Zhao et al. (2022), comprehensive U.S. actions can lead to significant reductions in methane emissions between 2020 and 2030, driven by emissions reductions in the energy and agriculture sectors. Note that the U.S. analysis in this figure (Zhao et al., 2022) and the analysis of methane mitigation in China shown in previous sections are country-specific and based on different modeling analyses and scenarios.



4.6 MITIGATION COSTS AND TECHNOLOGY POTENTIAL ACROSS SECTORS

Models have varying assumptions about mitigation potential across sectors and adopt different modeling methodologies for developing methane emissions projections. In this report, we were not able to directly compare the different underlying marginal abatement cost assumptions across all models and technologies. To better understand mitigation potential, we evaluated the EPA MAC curves in 2030 and 2050 and found that in both the U.S. and China low-cost mitigation potential opportunities are primarily in the energy sector (Figure 4.17).

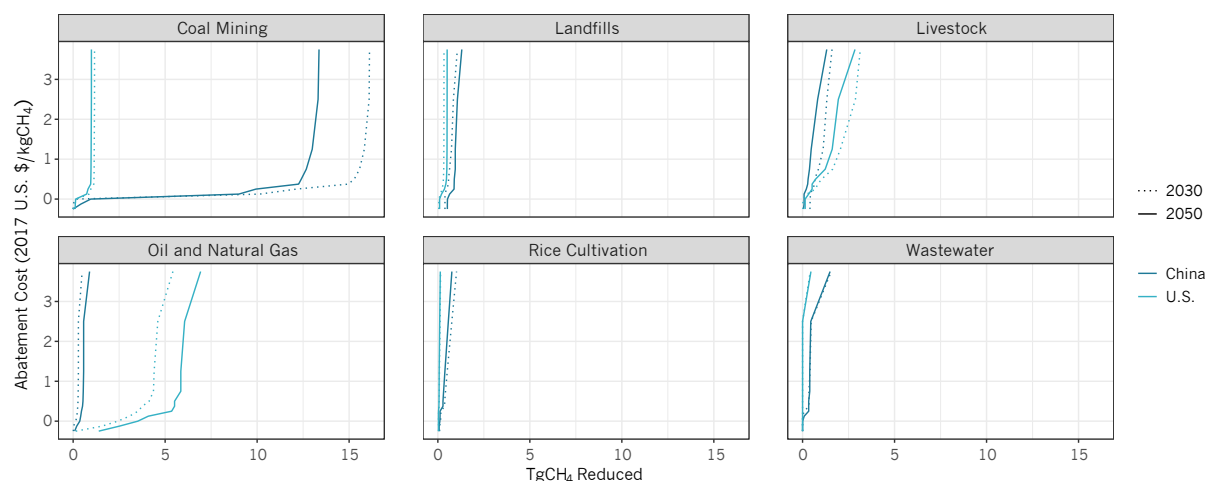
Energy sector mitigation is a key area for collaboration. The majority of emissions from coal mines in China and oil and gas in the U.S. can be

reduced by low-cost technologies. Additionally, for rice cultivation, coal mines, and livestock production, emissions potential is greater in 2030 than 2050 in China. This emphasizes the need for near-term action on methane mitigation.

These estimates for emissions reduction are based on engineering estimates, but real-world factors, as well as future research on new mitigation technologies, could impact these results. EPA MAC Curves did not make assumptions about policy context in determining mitigation potential (EPA, 2019b). In the next chapter, we review policy barriers and opportunities for methane mitigation in both countries.

FIGURE 4.17: U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA) MAC CURVES IN 2030 AND 2050 IN THE U.S. AND CHINA (EPA, 2019b).

The U.S. EPA MAC curve was used in the GCAM model to project emissions reduction potential.



05 | CHALLENGES AND OPPORTUNITIES

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5.1 BARRIERS AND OBSTACLES

Given existing policy gaps, numerous challenges exist that could halt ambitious actions toward methane mitigation in both the U.S. and China. Four key challenges related to techno-economic uncertainties, market mechanisms, policy effectiveness, and institutional capacity are identified and summarized across the methane

emissions sectors. However, both countries and each of the sectors may encounter these barriers to varying degrees due to differences in their development stages and level of attention from policymakers. Key issues for each sector in the U.S. and China are listed in Table 5.1.

TABLE 5.1: IDENTIFIED KEY ISSUES IN THE U.S. AND CHINA BY SECTOR.

	U.S.	China
Coal Mine	<ul style="list-style-type: none"> ▶ AMM has not been addressed adequately in existing policy frameworks ▶ Lack of effective market mechanisms/financial support for low-concentration methane recovery and commercialization, specifically for VAM ▶ Overlapping licenses between coal mines and CMM/CBM/AMM ▶ Inherent physical and geological challenges for CMM/CBM extraction and profitability 	
	<ul style="list-style-type: none"> ▶ Lack of federal policies/regulations for methane reduction or utilization in the coal mine sector ▶ Institutional barriers related to land ownership and abandoned coal mine ownership 	<ul style="list-style-type: none"> ▶ Insufficient/inaccurate techno-economic data for inventory, abatement costs and potential ▶ Underreporting of CMM data by coal mine companies ▶ Lack of gas transmission facilities especially for medium and small coal mines ▶ Existing supporting policies for CMM/CBM are not effective enough ▶ Strengthened coal demand and uncertain coal retirement plans
Oil & Gas	<ul style="list-style-type: none"> ▶ Oil and gas companies are underperforming in addressing methane emissions leaks ▶ Institutional barriers related to land or mineral ownership ▶ Methane emissions from orphan wells are understated in the existing policy framework 	
	<ul style="list-style-type: none"> ▶ Emissions from this sector appear to be underreported ▶ Small wells have not yet been fully covered by current regulations ▶ Small or less well-financed companies may not be able to afford to plug abandoned wells or use other costly methane abatement methods ▶ Ineffective policy implementation of Bureau of Land Management (BLM) waste prevention regulations - BLM never implemented the gas capture requirement due to legal challenges (GAO, 2022) ▶ Inflexibility of EPA regulations for approving alternative technologies (GAO, 2022) ▶ The Federal Energy Regulatory Commission (FERC) has no specific plans to address pipeline leakage (Daly, 2022) ▶ Concerns about encouraging oil and gas production due to the new leasing arrangements for wind power in the IRA 	<ul style="list-style-type: none"> ▶ Insufficient techno-economic data for inventory, abatement costs and potential ▶ Inadequate regulations for oil and gas methane emissions ▶ No official methane mitigation targets at the national level ▶ Some technological options are not cost-effective, requiring more capital investment/financial support

	U.S.	China
Landfills	<ul style="list-style-type: none"> ▶ Inadequate regulations for direct methane emissions reduction in this sector rather than biogas industrial policies 	<ul style="list-style-type: none"> ▶ Large uncertainties exist in techno-economic data for inventory, abatement costs and potential ▶ Challenges of scaling up biogas production sites and commercialization ▶ Landfill gas collection devices are not fully deployed in the existing landfill sites ▶ Waste management in rural areas is facing challenges in waste collection, sorting and transportation
	<ul style="list-style-type: none"> ▶ Landfill methane emissions have not attracted enough attention from policy makers and investors ▶ Existing regulations do not cover small landfill sites, therefore, only half of the landfills in the U.S. have gas recovery systems (RRS, 2021) ▶ The smaller landfills (with a capacity of 1k-100k tons per year) contribute the majority of methane emissions of the sector (RRS, 2021) ▶ Other barriers to increased methane recovery at landfills include informational issues related to site potential, permitting issues, financing issues, and difficulties in finding energy customers 	
Wastewater	<ul style="list-style-type: none"> ▶ Inadequate methane emissions regulations for wastewater treatment ▶ Challenges of commercializing wastewater methane recovery due to high capital cost 	<ul style="list-style-type: none"> ▶ Large uncertainties exist in techno-economic data for inventory, abatement costs and potential ▶ The increased number and capacity of municipal wastewater treatment plants (WWTPs) in China have driven methane emissions (Zhao et al., 2019) ▶ Methane emissions are substantial but vary greatly depending on regional and technological differences (Zhang et al., 2021a) ▶ Rural wastewater treatment is still underdeveloped and leaves great uncertainties in methane mitigation (Xu et al., 2020)
	<ul style="list-style-type: none"> ▶ Methane emissions from wastewater treatment facilities are often flared or burned - very little is recovered and utilized (Ha et al., 2022) ▶ Biogas is not recognized as a renewable energy source across all states' Renewable Portfolio Standards (RPS) programs (Ha et al., 2022) ▶ Financial and budget hurdles are often high for aging WWTPs' maintenance and operation (Seiple et al., 2020) ▶ The benefit of methane recovery technologies is poorly communicated to the decision-makers and the public (Ha et al., 2022) 	
Manure Management	<ul style="list-style-type: none"> ▶ Challenges of scaling up anaerobic digesters and commercializing biogas production 	<ul style="list-style-type: none"> ▶ Lack of policies for direct methane emissions reduction other than biogas industrial policies ▶ Biogas facilities are underused in many rural areas despite massive deployment and economic incentives ▶ Insufficient techno-economic data for inventory, abatement costs and potential
	<ul style="list-style-type: none"> ▶ Biogas is not recognized as a renewable energy source across all states' Renewable Portfolio Standards (RPS) programs ▶ Inadequate regulations for methane emissions reduction in this sector 	

	U.S.	China
Enteric Fermentation	<ul style="list-style-type: none"> ▶ Feed additives and manure processing systems can be expensive ▶ Less addressed in the existing policy framework and business practices 	
	<ul style="list-style-type: none"> ▶ Innovative solutions are needed to push forward the deployment of technological options, such as the development of enteric methane inhibitors, which need regulatory procedures for drugs (Tricarico et al., 2022) 	<ul style="list-style-type: none"> ▶ Less addressed in the existing policy framework and business practices ▶ Feed additives and manure processing systems can be expensive ▶ Huge uncertainties exist in technological and governance options
Rice Cultivation	<ul style="list-style-type: none"> ▶ Not included in the national policy agenda yet 	
	<ul style="list-style-type: none"> ▶ Absent from IRA and overall national strategies 	<ul style="list-style-type: none"> ▶ Methane mitigation in this sector will have conflict with the objective of food security ▶ Lack of incentives for local policy implementation ▶ It is a diffuse source which requires effective and strong rural governance capacity and innovative policy instrument ▶ The economic and technological feasibility and governance models in this sector are still underexplored

Insufficient Techno-Economic Information

Compared to CO₂ mitigation, techno-economic data on methane mitigation – such as well-grounded inventory data, reported emissions (e.g., transmission, storage, distribution), and technological potential and costs – are highly inadequate. A large gap remains in the data collection process, and there are a lot of uncertainties in terms of data accuracy, especially for China. This is important, because data accuracy lays a concrete foundation for policy-making and business investment. It can help policymakers assess mitigation opportunities so they can design more effective policies (UNECE, 2021).

Insufficient and inaccurate inventory information.

For example, based on various inventories, coal mining emissions made up 34%-45% of the total methane emissions in China in 2014. The discrepancy of historical emissions data is largely due to their high dependence on assumptions

and estimates of production activities and emission factors, rather than on real-time, on-site measurements, which can help obtain more accurate and detailed emissions data (UNECE, 2021). For instance, China's GHG inventory for the oil and gas sector at the company, subnational and national levels are all generally calculated based on the emission factors provided by the Guidance of GHG Emissions Accounting Methods and Reporting for the Oil and Gas Companies in China, in which the estimated emission factors play a significant role and create large uncertainties in the estimation of emissions data (Zhong et al., 2021). More importantly, a monitoring and reporting system is largely absent from the agriculture sector.

The U.S. has better performance on emissions data availability, due to its more established mandatory GHG emissions reporting schemes – the GHGRP – for most of the emissions sectors, including coal mines, oil and gas, landfills and wastewater. The U.S. methane inventory in the

coal mine sector is based on measured data for ventilation emissions, gas drainage system emissions, and emission reductions taken at the gassiest underground mines and reported to the EPA portal to comply with the GHGRP (UNECE, 2021). China has not yet established a systematic monitoring and reporting scheme for methane emissions, even for the coal mine sector, which has a relatively comprehensive policy framework regarding methane emissions. Coal mine operators only need to report safety-related methane emissions data, such as the concentration volume, to the local emergency management agency. Even then, the data may not be accurate, because of data underreporting, often done to avoid safety regulation penalty and equipment insufficiency or deterioration (Zhang, 2021).

There are data shortcomings in the U.S. Even with GHGRP, emissions levels are often underestimated in some sectors. For example, landfills were found to be the largest methane emission sources in California, leaking at rates as high as six times greater than the EPA estimation (Groom, 2021; Duren et al., 2019). Similarly, a recent investigation found that methane emissions from the oil and gas industry in the U.S. are underreported. Industry actors fail to identify and track super-emitting leaks and assess how much the leaks contribute to their total methane emissions. In fact, oil and gas companies have internal data showing that methane emission rates from the sector may be significantly higher than official data reported to the EPA (U.S. House of Representative Committee on Science, 2022).

Moreover, both the U.S. and China do not mandate monitoring of emissions from abandoned coal mines, helping to create non-negligible uncertainty about emissions data of the coal mine sector. Specifically, China has taken the initiative to cut excessive coal production capacity since 2016. Numerous medium and small coal mines were closed under this policy. China phased out 5,500 coal mines during the 13th Five-Year Plan period (2016-2020) (Ding, 2021), but these abandoned mines are seldom addressed for methane emissions reduction.

Uncertainty of the technological costs and potential. In addition to the inventory and projected emissions data, uncertainties remain for the technological costs and abatement potential of methane mitigation. First, inherent technical limitations exist for producing the marginal abatement cost curves (MAC curves). For example, transaction costs, such as negotiation or regulatory costs, are often not included in the MAC curve studies, yet they can significantly increase the unit cost of an abatement project (EPA, 2019b). Consequently, the abatement costs of reducing GHG emissions may be underestimated (Mundaca T et al., 2013). Second, country-specific data may be controversial and inaccurate without comprehensive investigation throughout the emissions sectors (EPA, 2019b). The costs and potential data can vary significantly across different studies. Some of the mitigation potentials are not as effective as what the models indicate, due to implicit market failures, such as monopoly (e.g., monopolized transmission of the recovered CMM can significantly increase the overall mitigation costs) and information asymmetry. Third, differences in the physical and geological endowments of coal mines (e.g., underground coal mines vs. surface coal mines) across countries or regions can also lead to large variations in the mitigation costs. For example, it is widely recognized by the coal industry that the uniqueness of CMM/CBM endowments in China due to geological movement have limited the technological options for the extraction of CMM/CBM. Technologies that are feasible for North America or Australia may not be applicable to China (Yang et al., 2021).

Uncertainty of future activities. The projected activities and associated methane emissions also face large uncertainty. As discussed in Chapter 4, sectoral activities, such as coal production and solid waste generation, are major drivers of methane emissions, despite the fact that emission factors are determined by technological potential. Expanding activities drive up methane emissions and hold back mitigation efforts. Therefore, a fundamental solution is to slow down the accelerated growth of these activities and eventually turn them into a declining trend.



For example, phasing down coal production will significantly contribute to methane emissions reduction in China. However, the level of these activities and their trends, such as the expansion of natural gas production in China, are determined by complex socioeconomic and sociopolitical factors and associated policies that are often hard to predict and will inevitably create significant uncertainty in methane emissions.

Lack of Market-Based Solutions

Market-based solutions that can incentivize methane mitigation efforts, such as forging market mechanisms and developing business models are essential, as they can be highly useful for minimizing the social costs of methane emissions. Methane gas can be either a public bad or a private good, depending on whether methane emissions can be commercially utilized as energy or industrial raw material, or traded as carbon assets and liabilities. In the end, it comes down to one basic question: Who bears the cost? Economic incentives already exist to turn methane emissions into marketable resources. For example, CMM, landfill gas and biogas recovery and utilization have long been developed in both the U.S. and China. However, current market mechanisms, including carbon offset markets, to harness these incentives are either not fully functioning or absent from some of the emission sectors, such as the enteric fermentation and rice cultivation sectors in both countries. In addition, market mechanisms to prevent methane emissions directly instead of encouraging the usual “emit and recover” actions have been underexplored. Both the U.S. and China have seen pitfalls in these mechanisms. Generally, well-functioning market mechanisms can: (1) support methane recovery and utilization businesses; (2) accelerate innovation and deployment of cost-effective mitigation technologies; (3) incentivize direct methane emissions reduction efforts. The basic idea is to make methane mitigation economically viable. That requires sustainable financing channels and robust supply chains that include developers, equipment manufacturers, service providers (e.g., transmission and distribution), material suppliers

and customers. Methane recovery and utilization is not only about methane production. It needs supporting markets, such as the electrical power industry, for utilization (Evans & Roshchanka, 2013).

Insufficient market mechanisms/business models for less cost-effective technology deployment.

For example, the recovery and utilization of low-concentration methane, particularly ventilation air methane (VAM), with a concentration lower than 0.4%, are economically challenging worldwide. But because VAM usually makes up around 70% of total CMM emissions, failing to address this will fundamentally impede methane mitigation in the coal sector. The lack of market mechanisms to drive down technological costs and improve productivity for VAM recovery has been a major challenge for CMM mitigation. Currently, all VAM projects worldwide (only 5 projects by 2018) rely on Regenerative Thermal Oxidation (RTO) technology. These projects are, in general, highly expensive, and VAM manufacturers have few incentives for further Research and Development (R&D) to improve designs and reduce costs without confirmed markets (CSIRO & GMI, 2018).

In China, high concentration CMM/CBM recovery and utilization projects have largely achieved commercialization, with subsidies and tax exemptions provided by the government. However, low-concentration emissions are struggling with cost-effective recovery methods. Especially in recent years, financial support for CMM has decreased due to the reduced subsidies for CMM/CBM production and suspension of the Clean Development Mechanism (CDM), which was the primary financing mechanism for CMM mitigation in China. There has been a growing concern for the business and financial models of VAM recovery and utilization projects. In the U.S., VAM projects are benefited by adoption of carbon markets with carbon prices that can sustain a VAM project (CSIRO & GMI, 2018). However, as of 2018, only one VAM project - Murray Energy's Marshall County Mine in West Virginia - was successfully operating in the U.S. (EPA, 2019a).

Business models are seldom explored and less understood in the enteric fermentation and rice cultivation sectors. In both the U.S. and China, methane emissions in these two sectors are discussed more intensively in academic research (mostly from a scientific and technical perspective) rather than in policy processes and business practices. While two U.S. carbon markets now cover methane emissions from these sectors, few business models exist in China. Moreover, market-based solutions other than carbon markets are still less understood compared to other sectors. One of the biggest challenges is the difficulty in recovering those methane emissions, because a lot of market incentives come from methane gas utilization besides carbon offset markets. Therefore, methane mitigation efforts for emissions from enteric fermentation and rice cultivation are solely a form of public good provision rather than attainment of private gains. In addition, many of the technological options for methane mitigation in these sectors are ex-ante actions, such as changing feed additives and rice types to prevent methane emissions from the beginning. Few incentives would exist if the ranch owners and farmers are the only ones paying and receiving no rewards in return (Searchinger & Waite, 2014; Foster, 2022). There is also a significant challenge for increasing financial investments for enteric methane mitigation options, since private firms would be investing in mitigation options without clear goals on how and when the investment can be monetized, particularly if the options do not have additional economic benefits (Tricarico et al., 2022).

A lack of financing mechanisms poses a greater threat to smaller business actors, who may have a larger impact on methane emissions. The costs associated with methane mitigation are an extra expense for business owners. Their ability to undertake the cost varies, depending on their financial and budget conditions and technological capabilities. Many small businesses, such as landfill sites or wastewater treatment plants with smaller capacity, face higher financial constraints and tighter budgets. They are most likely to be affected by methane mitigation requirements without proper market, financing, and technical

assistance mechanisms to help them stay in business. However, smaller operation capacity does not necessarily mean trivial impacts on methane emissions. On the contrary, some small operations contribute significantly to the methane problem. For example, data shows that in the U.S., small-scale landfills (with a capacity of 1K-100K tons) emit the majority of methane gas because they are not regulated by current EPA rules. Therefore, only half of the landfills in the U.S. are equipped with gas recovery systems (RRS, 2021). Abandoned oil and gas wells also can create a significant amount of methane leaks if they are not plugged. Even if legal obligations were imposed, small oil and gas companies may not be able to afford the costs. Some might have to abandon their drilling operations due to bankruptcy. Current financial assurances, such as bonds, are often insufficient for coping with such challenges (Wolf, 2021). Therefore, targeting sources of methane emissions from small-scale facilities with outsized methane emissions could have a significant impact on overall emissions reduction.

Ineffective Policies

Despite a large number of methane-related policies in both countries, the existing policy frameworks for methane mitigation do not necessarily lead to desired outcomes. A recent study found that China's coal mine methane regulations have not curbed growing emissions (Miller et al., 2019). In addition to the policy gaps summarized in Chapter 2, two other major challenges undermine the policy effectiveness of methane mitigation.

Ambiguous principles for developing policy toolkits. A basic question for the adoption of effective methane mitigation policies is: to what extent should methane emissions be treated as hazards/pollutants and to what extent as resources? Additionally, should the government encourage and reward emitters to cut off methane emissions or penalize them for not doing so? The answers to these questions are ambiguous for both countries. If methane



emissions are considered as resources, policies will naturally be focused on supporting methane recovery and utilization. On the one hand, this approach forges stronger market incentives and mechanisms for methane mitigation and provides new opportunities for economic growth. A large amount of methane emissions might be avoided in the short term if effective market mechanisms are implemented. On the other hand, it focuses on methane gas production rather than methane emissions reduction. As a result, there could be a higher demand for methane production activities, which may lead to an increase in methane emissions in the long run.

For example, CMM recovery/utilization is a useful tool for methane mitigation in the coal mine sector. In fact, it significantly contributed to the establishment of China's methane policy framework. However, the CMM policies in China were primarily designed to support the development of CBM as an unconventional natural gas industry. These policies, including subsidies, feed-in-tariffs, and tax exemptions, have not only encouraged CMM recovery from existing coal mines, but also incentivized new coal mine activities that could have been avoided, to produce CBM. Similar to conventional natural gas production, there are also methane leak and flaring issues in CBM operations (Li, 2021). In addition, the recovered methane emissions, including CMM, CBM and biogas, are utilized predominantly as fossil fuels, which produce carbon dioxide emissions.

If methane emissions are treated as hazards/pollutants, policy design and adoption should follow the "regulation-compliance" framework. Emitters would be mandated by regulations (e.g., laws and rules) to reduce emissions and would be penalized if they fail to comply. According to our analysis in Chapter 2, the U.S. favored this rationale in methane policy-making, whereas China preferred resource-oriented policies. The EPA and other government authorities have enacted multiple rules to mandate methane emissions reporting and reduction directly or indirectly in various sectors.

Regulations can contribute directly to reducing methane emissions without creating new emissions sources. Using this premise, methane recovery and utilization would not be an end, but a means, to methane mitigation. A properly designed regulatory framework can even incentivize emitters to phase down emission sources or adopt technologies that can prevent methane production instead of the conventional "emit and recover" approaches (e.g., LDAR technologies in oil and gas operations; aerobic bioreactor technology in landfill management instead of anaerobic bioreactors, which are the most common way to recover biogas).

There are obvious costs that go along with regulations. Passing regulations can be difficult and time-consuming. It requires extensive political, administrative, and legislative procedures to finalize those regulations. In addition, regulations are often strongly opposed by interested parties. They may not be ideally enacted, or even aborted, as a result of that opposition. Regulations also may be poorly implemented, since they increase the cost of compliance and enforcement. The emitters may take the risk of noncompliance to avoid the mitigation costs mandated by the regulations (IEA, 2021a). For example, the U.S. oil and gas industry was found to underreport their GHG emissions data to the EPA (U.S. House of Representative Committee on Science, 2022). Landfills were found to violate EPA rules on emissions (Allen, 2021). In China, even though coal mine safety has been heavily regulated, violations and wrongdoing by coal mine owners, including the manipulation of CMM monitoring and alarming devices to avoid penalties, are still commonly witnessed (Zhang, 2021). Except for carbon markets, fewer business models or financing mechanisms can be established if there are limited market incentives for methane mitigation.

In addition to the resource-versus-pollution dichotomy, there is a debate on whether the government should reward those who reduce methane emissions by "carrot" policies (e.g., preferential policies, subsidies, and tax exemptions) to encourage methane emissions

reduction or penalize those who do not reduce emissions by “stick” policies (e.g., taxes, fines, and other penalties). This creates distinctive incentives for methane mitigation and may lead to different outcomes (IEA, 2021a). For example, a study investigated the possible impacts of taxing the number of cattle to reduce beef demand and, consequently, methane emissions (Bonnet et al., 2018). Although the study indicated that a beef tax was the most market-friendly policy option, it was notorious for being politically difficult to support. Also, without a consistent multi-national policy, such a tax in one country will result in emissions leakage as production shifts elsewhere (Fellmann, 2018). As a result, no country currently adopts taxes as a way to reduce enteric fermentation methane emissions (Baker, 2021).

In summary, both principles have pros and cons and may be considered in future policy designs for methane mitigation in the U.S. and China. The challenge is to balance and set boundaries between the two principles, and to decide when “carrots,” rather than “sticks,” should be used, and vice-versa.

Problems with policy implementation. In addition to choosing the right policy instruments, some existing policies have not been well implemented. In the U.S., EPA and BLM have encountered administrative and legal challenges in implementing rules for methane emissions in the oil and gas sector. First, the 2016 EPA rule that established national standards for methane emissions was curtailed in 2020, but then reinstated in 2021. Frequently changed regulations inevitably create chaotic situations and compliance issues during implementation. Second, the current EPA rule, in fact, limits voluntary actions by industry actors to reduce methane emissions. Some operators use aircraft and satellites to detect emissions, which are not devices required by the EPA rule, yet they may be more efficient than the required ones. However, few operators have applied for the EPA's approval in using alternative technologies due to the inflexibility of the approval process. Third, a 2016 BLM rule required operators to submit waste minimization plans when applying

for permits to drill new wells. However, this requirement was never implemented due to legal concerns. After the rule was enacted, industry groups immediately asked for a review of the rule. As a result, the requirements of the 2016 rule were mostly rescinded in another 2018 rule. After another round of legal rulings, in 2020, the 2016 regulations were vacated by the U.S. District Court for the District of Wyoming (GAO, 2022). It is also too early to understand the overall implementation strategy and ultimate emissions reductions outcomes from various IRA provisions.

In China, implementation issues have been related mostly to CMM recovery and utilization, as well as biogas recovery in terms of manure management in rural areas. China has set the CMM utilization rate as a major target in the FYPs for CBM development since 2011. For both 11th FYP and 12th FYP, the goal was to reach a minimum CMM utilization rate of 60% nationwide. The 13th FYP for CBM lowered the target to 50%. However, the targets have never been met due to various and persisting challenges, including technical difficulties, low profitability, inadequate supporting facilities (e.g., lack of access to transmission networks and pipelines), and administrative barriers (Lau et al., 2017; Tao et al., 2019; Yang, 2009).

GHG emissions reduction, including methane mitigation, is particularly challenging in China's agriculture sector, due to the complexity and sensitivity of rural affairs in China. The agricultural stakeholders in China are often small-scale and geologically diversified and dispersed, factors that complicate the implementation of climate policies. For example, biogas has been strongly promoted across rural areas for decades as a major approach to manure management. The government has provided numerous subsidies and financial support to help rural households install anaerobic manure digesters (Yin et al., 2017). From 2001-2010, the central government has invested around \$3 billion (18.1 billion RMB) in rural biogas infrastructure. However, despite 1 billion worth of financial resources invested in rural biogas facilities, biogas accounts for merely 1% of energy consumption in rural China,



and the utilization rate of biogas is decreasing (Chen et al., 2020). The effectiveness of these supporting policies has been controversial, even questioned by the media and researchers. The cost of building and maintaining the digesters has been increasing as the prices of raw materials rise (Yin et al., 2017). The lack of more robust financial mechanisms makes manure digester deployment increasingly cost-ineffective. Also, the manure sources for biogas generation may not be sufficient for some households. The other major issue for rural biogas development is the obsolescence of manure digesters across many regions in China (Qiu et al., 2013). For example, a study showed that 40% of the biogas facilities installed in Shaanxi province were idled (Shaanxi Province Department of Agriculture, 2011). This has been attributed to several factors: (1) a lack of rural labor force to operate manure digesters. As a large number of young people migrate from rural to urban areas for work, leaving elderly parents and young children to stay at home, less able-bodied workers are available to operate and maintain the facilities (Yin et al., 2017); (2) inadequate training for operation (Huang et al., 2022); (3) existing rural biogas technology does not fit every region and condition. In addition, the massive expansion of biogas facilities does not take regional differences, such as weather/temperature, into consideration (Yin et al., 2017). For example, in regions with long periods of extremely cold weather (e.g., northeastern China), biogas facilities may not be well-functioning, which leads to their abandonment.

Institutional Barriers

Institutional barriers are systemic challenges embedded in existing institutions (e.g., political systems, administrative arrangements, land property rights) and will most likely prevail unless fundamental changes are made. Whereas policies can, in principle, be altered in a relatively short period of time, institutional changes are usually difficult. Methane mitigation in the U.S. and China has encountered multiple institutional barriers, which require more strenuous efforts to overcome.

Land and mining ownership. One major challenge for both the U.S. and China is associated with land ownership and mining rights, which would have a significant impact on methane recovery and utilization in the energy sector. Ownership that is not clearly defined can cause various conflicts among resource owners and hinder methane mitigation efforts. The mining rights of CMM and coal mines are usually separated in the current mining regulatory systems of both countries (Banks, 2012; Denysenko et al., 2019). This means that the owners of coal mines do not inherently obtain the mining rights of CMM/CBM. The rationale behind this is the recognition that coal mining and CMM recovery belong to two different mineral categories – coal and natural gas – that require different sets of expertise and mining licenses.

However, this separation increases the transaction cost of CMM recovery and utilization, as the owner of CMM/CBM (usually natural gas companies) needs to constantly coordinate with the owner of the coal mines (usually coal companies). Ineffective coordination may pose a threat to coal mine safety and result in lower CMM/CBM productivity. China has faced a larger challenge with respect to CMM recovery compared to the U.S., since coal production is central to China's energy system. It is common that coal mine owners control CMM/CBM resources associated with their coal mines without getting approval for the CBM ownership rights (CMM use does not require a CBM license), which hinders the business opportunities of CMM (natural gas) developers. There are also numerous cases where natural gas developers gain CMM ownership rights first, then impede coal mining activities because of their business's strategic concerns. Overlapping mining ownership causes serious conflicts between coal industry owners and natural gas companies. As a result, CMM ownership accounts for less than 16% of the total resource potential in China (Zhu, 2021).

AMM ownership is another major regulatory obstacle (Denysenko et al., 2019). In the U.S., the governance of AMM ownership varies across federal and state governments. AMM capture

and utilization can be difficult to accomplish on federal lands, as resource rights may be divided among multiple lessees. On private lands, AMM ownership rights are directly granted to coal mine owners. The deployment of AMM projects has been given particular preference in states where coal owners have the right to capture and utilize AMM, rather than natural gas developers. However, in most of the cases, a methane lease expires when the associated coal mine lease expires. In China, there has been an unclear regulatory environment with respect to AMM ownership after coal mine closure (Creedy, 2019). The other issue with AMM development is the lack of incentives to reopen coal mines once they have been closed due to high costs.

Land ownership rights also have a significant impact on the effectiveness of methane mitigation. In China, land is mostly state-owned (there are also collectively-owned lands), and all mineral mines are state-owned. Developers in China can only obtain development permits instead of property rights. The legal and administrative procedures of mining and land-related activities (e.g., building pipelines and transmission facilities) are mostly determined by the central government, with a few adjustments at the provincial/local level. Therefore, methane mitigation policies in the coal mine and oil and gas sectors can be implemented from the top-down, if necessary, without land ownership and jurisdictional concerns. The situation is more complicated in the U.S., where land and mineral resources have much more complex ownership structures, including federal and tribal ownership, state ownership, and private ownership. The U.S. regulatory frameworks for land use and mining activities, including coal mining and oil and gas operations, vary across jurisdictions. In addition, interjurisdictional activities are even more challenging. However, the impact of ownership complexity on methane emissions has been little explored.

Some questions have been raised about whether specific leasing provisions in the Inflation Reduction Act of 2022 (§ 50265) could partially offset the benefits of emissions reductions (Bittle,

2022; Brown & Phillis, 2022). For example, issuance of federal wind and solar development rights are linked to those for oil and gas leases for a 10-year period. The provision forbids the Department of Interior (DOI) to issue offshore wind leases before it offers 60 million acres on the Outer Continental Shelf for sale in offshore oil and gas leases during the previous one-year period. It also limits the issuance of rights-of-way and certain leases for wind and solar development on federal land before an onshore oil and gas lease sale takes place during a 120-day period before the right-of-way is granted. On the other hand, impacts of these provisions are likely to be small compared to overall reductions from other IRA provisions (Mahajan et al., 2022).

Socio-economic gaps and regional and urban-rural inequality. The effectiveness of methane mitigation not only relies on cost-effective technologies, but also depends on the capacity of enabling entities to carry out designated activities. The capacity of methane mitigation varies due to large socio-economic gaps and inequalities. Regions that are economically underperformed might be less capable of delivering ideal policy outcomes because of insufficient financial and human resources, and a lack of robust governing institutions. These challenges would prevail unless efforts are made to close the socio-economic gaps. On the other hand, while it is also important to understand if methane mitigation practices can benefit regional development and alleviate inequality, both mechanisms are seldom explored and understood.

This institutional barrier is particularly highlighted by the emission sectors that are closely related to China's rural areas, including rural landfills, rural wastewater, manure management and enteric fermentation, and rice cultivation. In fact, the majority of China's most challenging methane issues are associated with rural development. Compared to the U.S., the urban-rural gaps in China are large in terms of development levels. The key to tackling those challenges and raising ambitions is to strengthen rural governance and build stronger capacities for methane mitigation actions. For example, whereas municipal solid



waste and wastewater are regulated mostly for pollution reduction, rural landfills and wastewater are still loosely managed. In many of the areas, untreated landfills and wastewater are left unattended or discharged directly into the natural environment, which can result in surface and groundwater degradation. Pit latrines – a commonly used toilet system in rural areas – are significant sources of methane emissions globally (Reid et al., 2014). EPA estimates that methane emissions from latrines account for 74% of China’s domestic emissions from wastewater (Brink et al., 2013). Urbanization in China can significantly reduce methane emissions from rural wastewater. Research projected that urbanization in China could largely contribute to the decrease of global anthropogenic emissions by ~2% to ~1% between 2000 and 2015 (Reid et al., 2014).

In addition, mitigating methane emissions from enteric fermentation and rice cultivation requires fundamental changes of current livestock feed types, cultivation practices, and rice varieties. The challenge is to make the change happen, since these technological options often come with high costs, and the benefits for these changes are not well understood. Existing research primarily focuses on the technological details of methane mitigation of these sectors; few have investigated the issue from a governance perspective.

Social acceptance and political economy. It is essential to identify the relevant stakeholders and the political economy factors that affect progress on methane emissions reduction.

Raising ambitions for methane mitigation will inevitably create winners and losers in the short term because of the associated costs. A key question is: Who bears these costs? Those who would be potentially worse off by the mitigation policies may be strongly against the policy-making. In addition, many of the challenges are not technical, but are sociopolitical barriers that generate implicit costs for methane mitigation. For instance, concerns for food security have been raised in discussions of methane mitigation in rice cultivation and have become one of the

greatest challenges for this sector.

Making changes in China’s CMM/CBM industry is also much more complicated than simply deploying cost-effective technologies. The effectiveness of CMM/CBM capture and utilization is largely determined by interactions among various stakeholders, including state-owned or private coal mine owners, local state-owned and central state-owned CMM/CBM developers, local government authorities, the power grid and pipeline companies, which are usually the largest oil and gas state-owned enterprises and major developers of CMM/CBM in China. Conflicts between coal mine developers and CMM/CBM developers have been intensified by the unique political economy of central-local relationship in China, where the interests of local governments and central state-owned CMM/CBM developers were not aligned (Guo, 2011).

In the U.S., politics dominates legislation on climate issues. The cost of climate mitigation has been a major concern in the political arena and will potentially have a significant impact on the policy-making process for methane mitigation (Baker, 2021). One example has been Republican lawmakers’ argument of the high costs associated with the Green New Deal. In addition to the view of politicians, public opinion also tends to be hesitant about funding large-scale emissions reduction programs (Hamel et al., 2019). Another example has been the degree of public acceptance on some technological options for methane mitigation. For instance, landfill incinerators have proven to be effective for cutting landfill methane emissions. However, the “not in my backyard” (NIMBY) issue has been a major challenge for the deployment of incinerators across many countries. The U.S. has a long history of NIMBY problems with respect to the installation of landfill incinerators, driven by air quality and health concerns (Dunphy & Lin, 1991). Therefore, the technology will be much less favorable despite its effectiveness on methane emissions reduction. Political feasibility must be examined along with technological and financial feasibility.

5.2 OPPORTUNITIES

Identifying Sectoral Priorities Based on Technological Abatement Potential and Costs

This section further analyzes sectoral priorities and “low hanging fruit” (LHF) – i.e., sectors with large emissions reduction potential and low technological costs for methane mitigation, based on the 2030 MAC curves developed in Chapter 4 (Figure 5.1). Mitigation priorities are evaluated based on the potential contribution of each sector to the country’s total emissions reduction. All six sectors are ranked and categorized according to two criteria: (1) **The impact of each sector on overall methane emissions**, measured by the share of the emissions of each sector as a fraction of overall methane emissions; (2) **The contribution of low-cost technologies of each sector to methane emissions reduction**, measured by the amount of low-cost abatement potential in each sector (here defined as technologies with costs of \$0.25/kgCH₄ or \$10/tCO₂ and below).

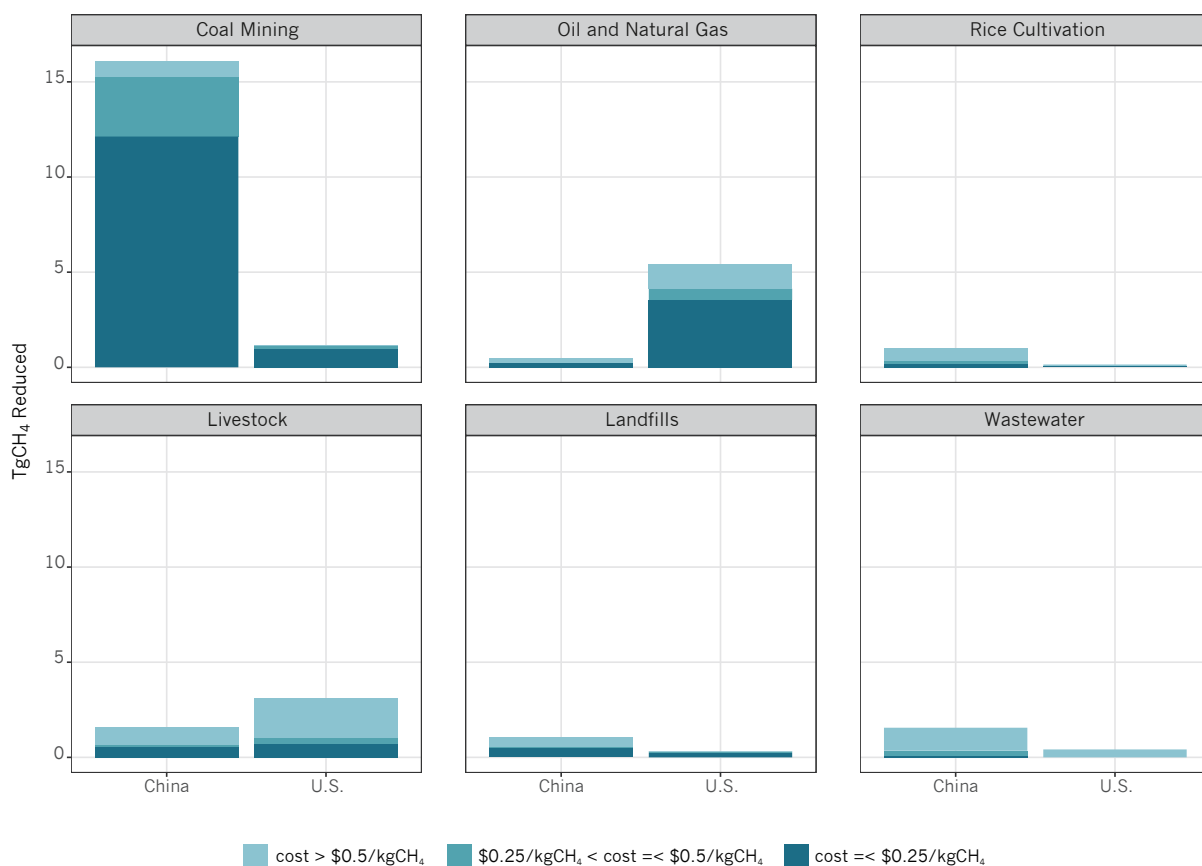
The LHF sector(s) should have a large impact on total methane emissions, as well as a large abatement potential at a low-cost level, indicating that the sector(s) can contribute significantly to methane emissions reduction with low-cost technology, therefore must be prioritized. The most challenging sectors are the ones that have a large impact on total emissions but with little abatement potential at a low-cost level, indicating that low-cost technologies barely contribute to emissions reduction from the baseline and that more efforts must be made to increase the abatement potential or to reduce the emission activities⁶. For sectors where impact on total methane emissions are relatively small, the tasks are less urgent, even though efforts in those sectors should still be made as much as possible.

⁶ In terms of the categories, based on the rankings from high to low, the first two sectors are considered as high impact/potential. The following two sectors are considered as medium impact/potential. And the last two sectors are considered as impact/low potential.



FIGURE 5.1: METHANE MITIGATION TECHNICAL POTENTIAL BY SECTOR IN THE U.S. AND CHINA IN 2030 (TgCH₄).

This figure shows potential methane emissions reductions in 2030 by mitigation cost ranges (USD/kgCH₄). It is constructed from abatement cost curves using different technologies. Low-cost technologies are defined here as cost equal to or lower than \$0.25/kgCH₄ (\$10/MtCO₂e using 100-year Global Warming Potential (GWP) coefficient from AR4). Data from EPA Non-CO₂ Greenhouse Gas Data Tool (EPA, 2022c).



The United States

Overall, low-cost technologies contribute to 51% of the total abatement potential. That implies that the U.S. should not only focus on the implementation of existing low-cost technologies, but, more importantly, pay more attention to fostering business models and crafting effective policies to drive down the technological costs of methane mitigation.

The oil & gas and coal mine sectors are LHF.

Based on the evaluation, both the oil and gas and coal mine sectors are LHF. The oil and gas industry will largely determine the overall performance of methane mitigation actions in the U.S. These sectors have high emission levels, however, 65% of the sectoral mitigation

potential – the emissions that can be reduced by existing technologies – can be realized with costs of \$0.25/kgCH₄ and below by 2030. Although the mitigation potential of the coal mine sector is far less than the oil and gas sector, 83% of the potential mitigation can be achieved with low-cost technologies. Deploying these low-cost technologies in the oil and gas and coal mine sectors could result in a reduction of 4.5 TgCH₄ emissions, which is greater than the total abatement potential at any cost of the wastewater, landfill and rice cultivation sectors combined.

The livestock and landfill sectors have promising opportunities, yet challenges need to be addressed with respect to technological options. Methane emissions from the livestock

sector will account for around one third of the total U.S. methane emissions by 2030. It is one of the nation's largest methane emissions sources. Though only 22% of sectoral potential can be achieved at a low-cost level, the absolute amount of methane emissions which can be reduced in this sector with low-cost technologies is comparatively large – a reduction of 0.7 TgCH₄ emissions can be achieved in a low-cost range. However, challenges need to be addressed regarding technological costs, as 67% of the total abatement potential is contributed by technologies which cost more than \$0.5/kgCH₄. Therefore, for the livestock sector, it is important to explore business models and policies that can more effectively reduce technological costs.

The U.S. landfill sector accounts for a moderate share of total methane emissions. The total abatement potential is relatively small compared to its emissions level, which means a large number of the emissions from this sector cannot be mitigated by technological options by 2030. Even so, 69% of the sectoral abatement potential can be achieved at a low-cost level, resulting in a reduction of 0.2 TgCH₄, which is still a relatively large amount of emissions. Therefore, for the landfill sector, actions must be taken to encourage technological improvements and innovation, and to reduce emission activities.

The wastewater and rice cultivation sectors are less urgent, however efforts can be made when possible. Both sectors account for a small share of total methane emissions, and the abatement potential is limited and expensive. Therefore, these sectors might not be a priority for the U.S. in methane mitigation. However, actions can be taken to address some of these challenges when possible.

China

Overall, low-cost technologies play a predominant role in mitigation potential. About 62% of the total abatement potential can be mitigated by 2030 using low-cost technologies. This indicates a promising trend in which a large amount of methane emissions can be reduced if the existing

cost-effective technologies are properly deployed.

The coal mine sector is a LHF. Among all the sectors, coal mine methane has the highest cost-effective abatement potential. It not only makes up 74% of China's total mitigation potential across all sectors but also can be largely mitigated at a low-cost level – i.e., 75% of the sectoral abatement potential can be actualized with costs no higher than \$0.25/kgCH₄. Therefore, the coal mine sector is a low-hanging fruit for methane mitigation and therefore can be prioritized in China's overarching mitigation strategy.

A comparatively large amount of emissions can be reduced in the landfill and livestock sectors at a low-cost level, however, challenges need to be addressed to increase the sectoral abatement potential and lower the technological costs.

The absolute amount of the low-cost mitigation potential is comparably large – about 0.5 TgCH₄ for each of the landfill and livestock sectors. The sum of the mitigation potential is more than twice that of total oil and gas abatement potential in China. For both sectors, one solution could be landfill gas/biogas recovery and utilization, which has already been implemented as a key policy for promoting rural development and environmental protection and municipal solid waste management in China. In addition, waste incineration is a direct way to reduce methane emissions, yet the NIMBY issue is a global challenge for building incinerators. Meanwhile, the low-cost abatement potential of the livestock and the landfill sectors contribute to only 34% and 44% of the sectoral potential respectively. The total abatement potential of these two sectors occupies only a small fraction of the sectoral methane emissions. Therefore, further actions should be taken to drive down the technological costs and to accelerate technological innovation and reduce emissions-related activities.

The oil and gas sector has a limited impact on total emissions, but has promising opportunities.

This sector has the least methane emissions among all of China's sectors. Around half of the emissions can be mitigated by existing technologies, and 47% of the abatement



potential is contributed to low-cost technological opportunities. Therefore, it is important to make sure those technologies can be fully implemented and to continue reducing technological costs for methane mitigation in this sector.

Methane mitigation in the wastewater and rice cultivation sectors is costly. Most of the sectoral mitigation potential of these two sectors can be achieved only by high-cost technologies. For the wastewater sector, 78% of the total mitigation potential in 2030 is associated with technological costs above \$0.5/kgCH₄. The low-cost mitigation potential for the rice cultivation sector is only 16%, with 63% of total abatement potential stemming from costs over \$0.5/kgCH₄. Despite the high technological costs, the total abatement potential is only 1.6 TgCH₄ and 1.0 TgCH₄ for wastewater and rice cultivation, respectively, accounting for a small proportion of each sectors' emissions. Therefore, technology innovation and mechanisms to drive down costs are particularly crucial to enhance the mitigation potential of both sectors.

Assessing U.S.-China Collaboration Readiness and Potential

This section identifies the sectors and policy areas that the U.S. and China are most ready to adopt and that have the greatest potential for collaboration in the near-term. We selected a set of indicators to assess the level of readiness and potential for each of the subsectors, including coal mine, oil and gas, landfills, wastewater, manure management, enteric fermentation, and rice cultivation. Four indicators are considered:

Research collaboration. This indicator represents the extent to which researchers from the U.S. and China have collaborated on methane emissions. It indicates the scientific foundation and communication the two countries have established on this topic. The indicator is measured by the number of peer-reviewed journal articles co-authored by researchers from institutions in the U.S. and China. The data was obtained from the Web of Science and was current as of June 17, 2022.

Partnership opportunities. This indicator shows the established or intended business or non-business partnerships between the two countries on methane mitigation. It indicates the level of interest in each sector and the foundation for advancing future collaboration. It is measured as the presence or absence of existing U.S.-China engagement activities and the number of business or non-profit opportunities in each subsector. The data for this indicator was obtained from the Global Methane Initiative (GMI, 2022c) and EPA (EPA, 2022a).

International engagement. Due to the different international contexts and socio-political characteristics of the two countries, this indicator focuses only on how much China has been involved in international methane mitigation activities. More international engagement experience equips state and non-state actors with better knowledge and abilities to forge future collaboration at the global level. It also makes these actors more comfortable communicating with international communities. This indicator serves as the proxy for the level of willingness and capacity of the actors in China to engage with their counterparts in the U.S. on methane mitigation. This indicator can be measured by the number of international projects that the actors in China have participated in and whether these actors have been involved in major international coalitions or industrial organizations. The data was obtained from the CDM project database (UNFCCC, 2022), the World Bank project database (The World Bank, 2022), the United Nations Economic Commission for Europe (UNECE), and the Oil and Gas Climate Initiative (OGCI).

Sectoral methane emissions. This indicator represents the combined sectoral methane emissions of the U.S. and China. U.S.-China collaboration may better contribute to methane mitigation if it effectively targets the sectors with the highest methane emissions. Therefore, combined sectoral emissions are considered as an indicator of collaboration priorities in the near-term.

The data is processed and normalized with a min-max approach, in which the normalized score for each indicator ranges from 0 to 1 and is transformed to a 0-100 range for better

visualization (by multiplying 100). The final score of collaboration readiness and potential is the sum of the scores of all four indicators, which are equally weighted (Table 5.2).

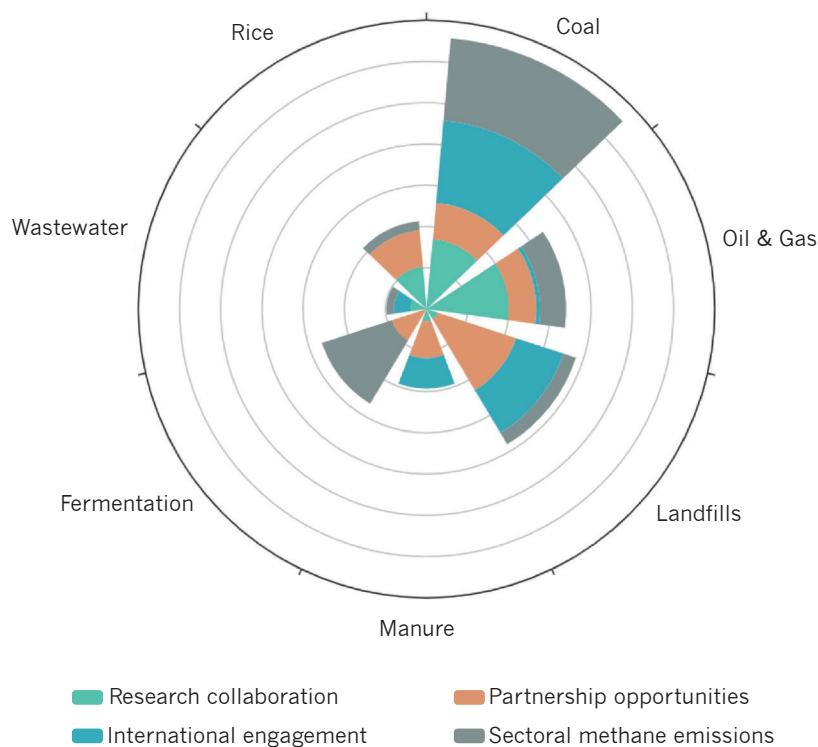
TABLE 5.2: INDICATORS FOR ASSESSING U.S.-CHINA COLLABORATION READINESS AND POTENTIAL DATA DESCRIPTION.

Indicator	Description	Measurement	Data source
Research collaboration	Research conducted together by researchers from the U.S. and China on the methane topic	# of peer-reviewed journal publications co-authored by researchers from institutions in the U.S. and China	Web of Science
Partnership opportunities	The established or intended business and non-business partnerships on methane mitigation between the U.S. and China	# of business or non-business methane-related partnership opportunities, weighted by the existing number of partnerships with the U.S.	Global Methane Initiative; EPA
International engagement	The extent to which China has been involved in international methane mitigation activities	# international projects on methane mitigation that actors in China have participated in, weighted by international coalition membership	CDM; UNECE; OGCI; World Bank
Sectoral methane emissions	The combined sectoral emissions of the U.S. and China	The amount of U.S.-China combined sectoral methane emissions in 2020	This study



FIGURE 5.2: U.S.-CHINA COLLABORATION POTENTIAL BY SECTOR.

The four indicators include research collaboration – measured by the number of peer-reviewed journal articles co-authored by researchers from institutions in the U.S. and China; partnership opportunity – measured as the presence or absence of existing U.S.-China engagement activities and the number of business or non-profit opportunities in each subsector; international engagement – measured by the number of international projects/ industrial organizations in the sector; and U.S.-China combined sectoral methane emissions in 2020. The indicators are normalized with a min-max approach and transformed to a 0-100 range. The final score of the collaboration potential is the sum of the four indicators. The size of the shade indicates the score.



The results show that, overall, the coal mine sector is most ready for the two countries to collaborate (Figure 5.2). The oil and gas and landfills sectors are the next most ready. The coal mine sector has already attracted extensive research collaborations between the two countries. This sector also has a relatively high number of partnership opportunities between the U.S. and China. The EPA participated in and supported CMM methane mitigation demonstration projects in China through the Coalbed Methane Outreach Program (CMOP) as early as the 1990s. China's coal mine industry also has a high level of international engagement, as there were 84 CMM mitigation projects supported by the CDM, nearly 30% of the total number of CDM projects associated with methane mitigation. Additionally, the coal mine sector in China has been deeply involved with international communities such as UNECE.

The oil and gas and landfill sectors are also well-prepared for U.S.-China collaboration. Comparatively, the oil and gas sector has the highest research collaboration score. The landfill sector has more U.S.-China partnership opportunities and stronger international engagement experience. Most of the CDM projects for methane mitigation focused on landfills. However, the combined landfill methane emissions of the two countries account for a smaller share of total emissions, and there have not been many scientific research collaborations in this sector. Enteric fermentation is one of the least ready sectors for U.S.-China collaboration. There have been only six collaborative peer-reviewed publications by researchers from the two countries, and China has little international engagement experience in this sector. However, enteric fermentation

emits a significant amount of methane emissions. Initiating U.S.-China collaboration in this sector has great potential to push forward methane mitigation efforts. According to this assessment, the U.S.-China collaboration in the manure management, wastewater and rice cultivation sectors can be optional. The shares of emissions are comparatively low in these sectors. Nevertheless, there have been opportunities for the two countries to collaborate in the manure management and rice cultivation sectors. Pilot and/or demonstration projects and research opportunities should be further explored in these areas.

In summary, U.S.-China collaboration on methane mitigation can focus on the following, ranked in terms of readiness: **the coal mine sector**, which has a concrete foundation, large potential, and is well prepared for future collaboration; **the oil and gas sector**, for which the U.S. and China have already conducted extensive research collaborations; **the landfill sector**, which has significant potential opportunities for U.S.-China collaboration despite its comparatively low emissions level. Notably, the **enteric fermentation sector** can be highlighted as a potential focus because of its high level of methane emissions, despite the fact that existing mitigation efforts have so far been limited.

Co-Benefits of Methane Mitigation

Methane mitigation has multiple co-benefits that contribute to human and socioeconomic well-being. It can help lower ozone concentration, improve air quality and public health, strengthen food and energy security, enhance coal mine safety, and create job opportunities (Bollen et al., 2009; CCAC, 2021). These co-benefits can serve as facilitators of more ambitious methane mitigation actions for both countries.

Impact on ozone, air quality and health. Methane is an important precursor of tropospheric ozone (O₃), also known as ground-level ozone, which is both a greenhouse gas and a powerful air pollutant that endangers the earth's atmosphere,

air quality, and human health (CCAC & UNEP, 2021b). Exposures to ozone can significantly increase the risk of premature death (Malley et al., 2017). Methane oxidizes to form ground-level ozone (West & Fior, 2005; Sarofim et al., 2015), and contributes to the reaction around six times more than anthropogenic non-methane volatile organic compounds (NMVOCs) to the development of ground-zone level ozone (West & Fior, 2005). Therefore, methane mitigation can help to reduce ozone-related environment and health risks. In addition to ozone, some methane mitigation options can contribute indirectly to better air quality by reducing fossil fuel use, the combustion of which generates many air pollutants, including particulate matter (PM₁₀ and PM_{2.5}), nitrogen dioxide (NO₂), carbon monoxide (CO), and sulfur dioxide (SO₂) (WHO, 2021).

The co-benefits of methane emission reduction on public health are closely related to air quality improvement. For example, PM_{2.5} increases the risk of death by causing cardiovascular, respiratory, and metabolic diseases. Ozone exposures increase the risk of death by causing chronic obstructive pulmonary disease. Recent studies have found that short-term exposure to NO₂ also increases the risk of death from cardiovascular and respiratory diseases (CCAPP, 2021). In addition to air quality related co-benefits, methane mitigation in rice cultivation, such as improving irrigation systems, can contribute to reducing arsenic - a notable toxic substance for human health - in rice (Minamikawa et al., 2015; Yang et al., 2017).

Some research has quantified the co-benefits of methane mitigation on public health. One study shows that PM_{2.5} and O₃ reduction through methane mitigation measures can lead to the avoidance of 0.6-4.4 and 0.04-0.52 million annual premature deaths globally in 2030, from PM_{2.5} and O₃ reduction respectively (Anenberg et al., 2012). The model developed by West et al., estimates that reducing methane emissions by 20% can prevent 30,000 premature all-cause deaths globally in 2030 and approximately 370,000 mortalities between 2010 and 2030 (Bollen et al., 2009).



Impact on food security. Ground-level ozone also causes crop yield loss, which can be greatly avoided by methane mitigation. Through ozone-related effects, methane contributes to 15% annual yield losses of soy, wheat, rice, and maize (CCAC, 2022; West & Fior, 2005). Studies show that implementing methane abatement measures can increase crop yields, forestry and vegetation quality and productivity by reducing tropospheric ozone (Abernethy et al., 2021; CCAC, 2022; Shindell et al., 2017). In addition, methane mitigation practices for rice paddy, such as rice intensification and alternative crops, also contribute to a more climate-resilient agricultural system (Shah & Otterpohl, 2016).

Studies show that existing methane mitigation measures can prevent more than 26 million tons of crop losses annually – equivalent to 2% of production in 2000 – and is worth \$3.5 billion (2000 constant USD) (Monaco et al., 2021; Avnery et al., 2012). According to Global Methane Assessment, 134 TgCH₄ emissions reduction can avoid yield losses of 7.46 Mt of wheat; 2.23 Mt of soybeans; 5.58 Mt of maize; and 4.20 Mt of rice (CCAC & UNEP, 2021b). In addition, applying improved agricultural practices to reduce methane emissions can increase crop yields, especially when using measures that specifically focus on improving efficiency (Monaco et al., 2021).

Impact on coal mine safety. Methane is a major threat to coal mine safety. An explosive gas, it severely endangers coal mine workers' working conditions, health, and lives. This hazard can be addressed by effectively controlling CMM emissions. For example, the pre-mining degasification of surface and underground coal mines has been successfully employed in many countries (UNEP, 2011). The idea is to reduce the risk of methane-related explosions by preventing the buildup and migration of in-mine methane. More methane recovery and utilization technologies are introduced in the article of Karacan et al. (2011). Another study shows that a 1% increase of per ton CMM drainage volume can reduce 1.9% of per million ton coal methane-related accidents and 5.5%-7.4% of per million ton mortality rate (Xu & Wang, 2017).

Impact on employment & industry development.

Methane mitigation has a great potential to boost economic development and provide better job opportunities (EDF, 2022; Parikh, 2021). The oil and gas sector emitted 7.7 million tons of methane per year, resulting in \$1.8 billion of company revenue losses (EDF, 2014). Fugitive methane mitigation can save extra gas that would have been wasted (Clark et al., 2021). If the wasted methane can be captured, natural gas producers in the U.S. could increase their revenues by \$188 million per year (Silverstein, 2021).

For industry development, in the U.S. the methane mitigation service sector has nearly doubled since 2017, and the methane mitigation manufacturing industry has grown by one third since 2014 (Lowe & Skillern, 2021). There are more than 225 manufacturing and service companies with nearly 1,000 employee locations across the U.S. (Lowe & Skillern, 2021). 70% of this emerging methane mitigation industry consists of small businesses, which represents an upward mobility of the whole industry (Lowe & Skillern, 2021).

In terms of job creation, with the development of the industry and relevant methane techniques and solutions, new jobs for skilled workers can be created (Stokes et al., 2014). 75% of manufacturing firms and 88% of service firms in the U.S. are reported to have created more jobs under the national methane mitigation strategy (Lowe & Skillern, 2021). The implementation of identified methane mitigation measures could create around 85,000 jobs annually in the U.S. oil and gas sector through 2015-2019 (Keyser et al., 2015).

In addition, the salary levels of these new jobs are likely to be higher than the conventional jobs in the related sectors. Data shows that the entry level salary for methane mitigation jobs is up to 10% higher than the national average wage, and the industry can offer up to \$140,000 annual wage (EDF, 2022). Moreover, the median hourly salary for workers in the leak control sector of the methane mitigation industry is \$30.88 (Stokes et al., 2014). Therefore, methane mitigation is expected to have substantial economic benefits,

boost the growth of new industries, and create more well-paid positions.

We estimated the co-benefits of methane mitigation in terms of ozone, health, pollution-related premature deaths, crop yields, coal mine mortality, and employment, when all the baseline methane emissions of a country are reduced to zero in a given year. 2030 baseline emissions came from the EPA for the U.S., and from participating models in this study for China. The

median across models was used for estimating 2030 emissions and coal production in China. Most of the co-benefit coefficients, except those for coal mine mortality and employment, came from the data tool “Assessment of Environmental and Societal Benefits of Methane Reductions,” developed by the Climate & Clean Air Coalition (CCAC) and United Nations Environment Programme (UNEP). The coal mine mortality and employment co-benefits were calculated using different methodologies⁷ (Table 5.3).

TABLE 5.3: COEFFICIENTS OF CO-BENEFITS (CO-BENEFIT/ TgCH₄).

Source: Co-benefit coefficients from Climate & Clean Air Coalition (CCAC & UNEP, 2021a).

Impacts	Coefficient (U.S.)	Coefficient (China)
Reduction in Ground-level Ozone (ppb)	0.017	0.017
Reduced Premature Deaths Due to Ozone Exposure (number of persons)	76.037	297.082
Reduced Asthma-related Emergency Room Visits due to Ozone Exposure (number of visits)	11.344	53.991
Increase in Crop Yield due to Climate and Ozone Response to Methane (kt)	29.362	31.122

(1) Ground-level ozone. The quantified co-benefits are shown in Figure 5.3. For ground-level ozone, by mitigating 1 TgCH₄ per year, the ground-level ozone in the U.S. and China can be reduced by 0.017 ppb. The 2030 emissions baseline is 27.34 TgCH₄ and 32.41 TgCH₄ in the U.S. and China, respectively. In 2021, the level of tropospheric ozone is around 44 ppb (daily maximum 8-h) in the U.S. and in China, 64 ppb (EPA, 2021b; MEE, 2022). If all the methane emissions in 2030 were mitigated, the reduced ground-level ozone that year would be around 0.5 ppb in the U.S. and 0.6 ppb in China, equal to 1% and 0.9%, respectively, of the average 2021 tropospheric ozone level.

(2) Asthma-related emergency room visits. A reduction in ozone level would potentially reduce the number asthma-induced hospital visits (CCAC & UNEP, 2021a). Reducing 1 TgCH₄ can avoid 11 and 54 hospital visits in the U.S. and China, respectively. If the 2030 baseline emissions in both countries were reduced to zero, around 300 and 1,800 asthma-related emergency room visits could be avoided, in the U.S. and China, respectively.

(3) Premature deaths. Ozone exposure can lead to premature deaths (CCAC & UNEP, 2021a). Reducing emissions by 1 TgCH₄ contributes to a decrease of 76 and 297 premature mortalities in the U.S. and China, respectively.

⁷ Due to limited data availability, we calculated the coal mine mortality co-benefits only for China and the employment co-benefits for the U.S. For coal mine mortality co-benefits in China, we used the median across participating models in this study for 2030 coal mine production.



If all methane emissions were mitigated in 2030, around 2,100 and 9,600 premature deaths in the U.S. and China, respectively, could be prevented. By cutting methane emissions thousands of lives can be saved not only in the U.S. and China, but globally.

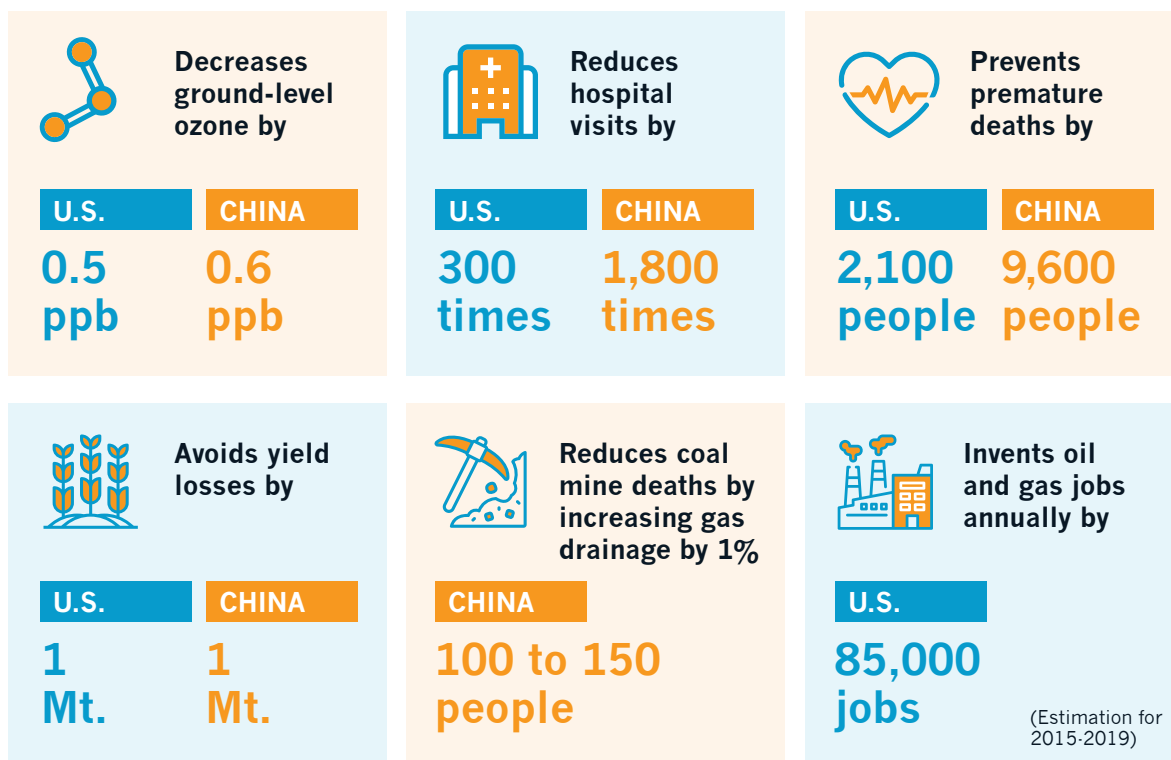
(4) Crop yields. Reducing methane emissions by 1 TgCH₄ helps to avoid 29.36 and 31.12 kt of crop losses in the U.S. and China, respectively. Based on this assumption, both the U.S. and China can avoid around 1 Mt crop yield losses in 2030, respectively. The avoided yield losses of the U.S. and China, combined, in 2030 are estimated to be able to feed 25.5 million people in the U.S. for a year (USDA, 2021).

(5) Coal mine safety. Based on the results of

the four models participating in this study, a median of 1,874 million tons of coal is estimated to be produced in 2030 in China. A 1% increase of CMM drainage is estimated to decrease the per million tons coal mine mortality rate by 5.6-7.4% (Xu & Wang, 2017). As a result, around 100-150 coal mine deaths in China can be avoided if the CMM drainage rate increases by 1% in 2030.

(6) Employment. The economic co-benefits of methane mitigation also can be seen in several key sectors. In the U.S., it has been estimated that reducing methane emissions from the oil and gas sector can create approximately 85,000 jobs annually for the sector (Keyser et al., 2015).

FIGURE 5.3: CO-BENEFITS OF METHANE MITIGATION IN 2030 ASSUMING ZERO METHANE EMISSIONS⁸.



⁸ We calculated co-benefits from methane mitigation by assuming that baseline total emissions in 2030 are mitigated to 0. Co-benefits for ground-level ozone, yield losses, hospital visits, and premature death = impact coefficient * baseline total methane emissions in 2030. Co-benefits for coal mine safety = fatality rate per million tons reduction by increasing 1% gas drainage * coal production in 2030.

5.3 POLICY OPTIONS

Based on the review and analyses of the previous sections, we identify a set of policy recommendations to address current gaps, sectoral priorities and options, and collaborative opportunities for the U.S. and China.

Recommendations for Current Gaps and Challenges

- ▶ **Fill existing policy gaps.** Both countries need to pay more attention to the sectors that have not been well-covered by existing policy frameworks (federal/central-level). Immediate actions should be taken to initiate or accelerate the policy-making or legislative process for these sectors. Both the U.S. and China should fill the policy gaps for abandoned coal mine methane, enteric fermentation and rice cultivation, and adopt more policies that directly address methane emissions reduction for climate mitigation purposes. Specifically, the U.S. should pay greater attention to coal mine methane, strengthen regulations on small and orphan wells, and improve MRV in the agriculture sector. In particular, the support for methane mitigation in the agriculture sector should be further specified, despite the significant amount of funding appropriated to the agricultural climate actions by the Inflation Reduction Act of 2022. For China, future policy making should put more emphasis on the oil and gas, and rural landfills and wastewater sectors. In addition, it is urgent to develop comprehensive and robust greenhouse gas reporting mechanisms and MRV systems across sectors, as well as to incorporate methane into the national carbon emissions trading scheme.
- ▶ **Better quantify methane mitigation targets.** Both countries should set more direct and quantifiable targets for methane emissions reduction. However, it is also urgent to establish more quantifiable technology-based standards that can be implemented in the absence of quantitative targets. Currently, both countries do not have economy-wide methane emissions reduction targets. Few sectoral emissions reduction targets exist except for the oil and gas sector in which both countries have some level of quantified methane emissions reduction mandates.
- ▶ **Reinforce the co-benefits of methane mitigation and demonstrate higher ambition through more climate change-oriented policies.** Co-benefits of methane mitigation, such as environmental quality, mining safety, and industrial development, have been primary drivers of existing actions toward methane emissions reduction. It is essential to reinforce those co-benefits to create larger social benefits, mobilize as many resources as possible, and alleviate political obstacles for methane mitigation. Nevertheless, more climate change-oriented policies for methane mitigation are needed for both countries, in contrast to the safety and pollution-oriented regulations that are already largely available in both countries (while still recognizing the importance and political feasibility of addressing those co-benefits). Climate change-oriented policies for methane mitigation can serve as a demonstration of higher ambitions and would provide different incentives for further actions.
- ▶ **Improve techno-economic information quality.** Both countries need to improve the accuracy of techno-economic information, including inventory data and mitigation costs and potential. It is essential to increase confidence in historical emission estimates through enhanced transparency of data sources and development of localized, technology-specific emission factors. Increasing reporting requirements in both countries for coal mines, wastewater treatment plants, landfills and oil and gas production equipment will help develop better emission factors and estimates of historical emissions. Making activity data



and emission factors publicly available can help better understand differences among inventories. Utilizing granular emission factors and activity data, based on specific technologies and facility-level conditions, can help improve accuracy of estimates. Finding synergies between public health and safety outcomes (i.e., U.S. coal mining compliance measurements) and improved monitoring can help realize policy action and methane mitigation co-benefits. This does not mean we should wait for improved data; immediate actions should be taken by incorporating those uncertainties into consideration.

- For the U.S.: (1) The compliance of the mandatory GHG reporting scheme can be strengthened, as underreporting of emissions data has been seen in the oil and gas sector. Additionally, methane emissions from landfills in the U.S. may also be underestimated. (2) Tracking methane emissions from the agriculture sector should be encouraged and can be incorporated into the existing GHG reporting scheme. (3) Increasing monitoring for unintended, short-term emission events from oil and gas production facilities.
- For China: (1) A methane emissions measurement, reporting and verification (MRV) scheme should be built across all the emission sectors as soon as possible. Currently there is no system to monitor methane emissions in China. (2) Improving the compliance of data reporting is also important, as underreporting of methane concentration data is still common in coal mine operations, which are already relatively well-prepared for methane mitigation in China. (3) Thorough field investigations on the abatement costs for methane mitigation are crucial, since non-technical and transaction costs can be large and may not be comprehensively considered. (4) Monitoring of emissions from abandoned coal mines.

- Both countries should take physical/geological factors, transaction costs, and field investigation into consideration to improve the accuracy of inventory and mitigation costs and potential. Both countries should deal with data underreporting.

▶ **Strengthen market mechanisms and infrastructures for methane-related transformation and technological innovation.**

Market mechanisms and robust supply chains for methane mitigation need to be further developed and improved for both countries.

- Carbon markets in China should open to methane emissions. Specifically, CCER should be restored as soon as possible. The carbon markets in the U.S. cover all the methane emissions sectors and have proven to be effective in forging better market mechanisms for methane mitigation. For both countries, carbon offset markets need to be further developed for methane emissions that are physically difficult to recover, such as the emissions from enteric fermentation and rice cultivation.
- More business models should be explored to support methane emissions with great utilization potential, but which are not yet fully cost-effective. For example, low-concentrated CMM, such as VAM, as well as sectors without clear market incentives, could present opportunities. Closer attention should be paid to the financial conditions and constraints of small business owners associated with methane emissions.
- Supporting facilities, among other supply chain steps, need to be strengthened to reduce transaction costs for methane mitigation and ensure easy access for methane recovery and utilization with respect to pipeline networks and electrical power transmission. For example, in China, pipelines and electrical power

transmission are largely monopolized by state-owned enterprises, which may create shortages and higher costs for necessary access to, and distribution of, recovered methane emissions.

- Mobilize private sector investments, such as venture capital and public-private partnerships in technologies that can prevent or directly capture and reduce methane emissions, such as special feed additives for cattle. In particular, public-private partnerships have been identified as one of the most attractive opportunities for the development of enteric methane mitigation options. Collaboration between the private and public sectors is critical for identifying mitigation options and encouraging action by dairy sector participants, while continuing to improve the availability of safe and nutritious milk and dairy products. For example, the U.S. has a program called “The Greener Cattle Initiative,” that contributes to advancing the voluntary greenhouse gas reduction goals established by the U.S. and global dairy sectors (Tricarico et al., 2022).
- ▶ **Focus on “super emitters” and small but high-emitting sites.** Both countries should pay significant attention to the “super emitters”, as well as the small but high-emitting sites that are not well covered by the existing regulatory framework, such as small landfills and small or orphan gas wells in the U.S. Small sites can also contribute a large share of methane emissions, as seen in some cases in the U.S. in gas and oil production regions, as well as landfill sites. However, they are often the sites lacking technical resources for accurate estimation, and are more affected by market risks and bankruptcy, which could lead to a large amount of unattended methane emissions.
- ▶ **Clarify the rationale for selecting policy toolkits and improve implementation.** More efforts are needed to improve the policy effectiveness of methane mitigation.

The selection of policy toolkits needs to be carefully examined: (1) **Resources or pollutants.** It is important to balance supporting policies that encourage methane utilization as an alternative fossil fuel with the regulatory policies that disincentivize/penalize methane-emitting behaviors; (2) **“Carrots” or “sticks”.** It is essential to understand the effects of using “carrot” policies, such as subsidies and tax exemptions, to encourage methane emissions reduction, as opposed to using “sticks” policies, such as taxes and fees, to penalize and disincentivize methane emissions.

Policy implementation for oil and gas sector emissions in the U.S., and for CMM and biogas recovery from livestock manure in China should be improved as soon as possible.

- ▶ Tackle institutional barriers. Both countries should make more effort in dealing with institutional barriers:

 - Resolving conflicts associated with **land and mining ownership** by eliminating restrictions on transferring rights to gas, regardless of whether it will be sold as gas or converted to electricity.
 - **Building capacities for less-developed regions and communities to ensure robust and just methane mitigation actions.** In particular for China, robust rural governance and institutions are key to many of the methane challenges, including rural landfills and wastewater treatment, manure management, enteric fermentation, and rice cultivation. Policies should also emphasize improving benefits for the lower income communities.
 - Understanding the **societal and political economy challenges.** It is necessary to conduct a stakeholder analysis before policy-making to reduce potential opposition to further actions.



- ▶ **Incorporate local contexts and encourage policy experiments.** There is “no one-size fits all” for methane mitigation. The policy agenda and policy processes should not simply follow a top-down approach. Rather, it is important to motivate subnational and nonstate actors to take initiatives. Policies will be most effective if they are tailored to local situations, including the political and regulatory context, the nature of the industry, the size and location of emissions sources, and the jurisdiction’s policy goals. Policymakers need to understand how these circumstances play out within the local context (IEA, 2021a). Policy experiments, such as demonstration projects, voluntary programs, and pilot cities, should be encouraged to explore the best practices for methane mitigation by taking local contexts into account.

Recommendations for Sectoral Priorities

- ▶ **For the U.S., the oil and gas sector and coal mine sector are low-hanging fruits for methane mitigation;** the livestock and landfill sectors have promising opportunities to reduce a comparatively large amount of methane emissions at a low-cost level. Yet it can be challenging because of the high cost of taking further technological actions (livestock) or low sectoral mitigation potential (landfills). Methane emissions from rice cultivation and wastewater are expensive to mitigate; however, these two sectors account for only a small proportion of total methane emissions in the U.S.
- ▶ **For China, the coal mine sector is a low-hanging fruit.** The livestock and landfill sectors can also reduce a comparatively large amount of methane emissions at a low-cost level. However, more efforts should be made to reduce technological costs and accelerate innovation for better mitigation options. Methane emissions from the rice cultivation and wastewater sectors are most challenging since the mitigation costs are high and the

total mitigation potential is relatively low compared to the emissions level.

- ▶ Regarding the modeling uncertainties of the abatement costs and potential, general suggestions on sectoral mitigation strategies are identified:
 - ◎ For low-hanging fruit sectors, the strategy should be to ensure effective deployment and implementation of existing technological options.
 - ◎ For sectors with high mitigation potential and high mitigation costs, the key strategy is to develop business models and proper policies to drive down mitigation costs.
 - ◎ For sectors with low technological mitigation potential, the key strategy is to encourage technological innovation and reduce/slow emissions activities as soon as possible.

Recommendations for U.S.-China Collaboration

- ▶ **Prioritize sectors based on collaboration readiness and mitigation potential.** U.S.-China collaboration on methane mitigation should prioritize collaborative opportunities in the coal mine, oil and gas, landfill, and enteric fermentation sectors based on the assessment of collaboration readiness and potential.
- ▶ **Circular economy (CE) can be a key collaborative area.** Most CE-related methane mitigation opportunities are in bioenergy/bioeconomy, particularly in the waste and agriculture sectors. Biogas derived from organics in landfills, wastewater, and livestock manure are directly associated with the application of CE as a way to minimize waste and improve utilization. Waste-to-biogas-based circular economy requires an integration of waste management, biogas production, and utilization and policy support (Kapoor et al., 2020). The other way that CE can help with

methane emissions reduction in landfills is to use technologies such as aerobic bioreactor or semi-aerobic bioreactor to prevent methane production. There are several potential mechanisms by which CE may contribute to GHG emissions reduction and methane mitigation:

- Carbon sequestration and limiting methane emissions through regenerative agriculture, which builds up both organic soil carbon and nitrogen stocks, while reducing nitrogen losses with proper management. The livestock management system under regenerative agriculture is also effective at reducing methane emissions by more effective manure management, and, more importantly, from enteric fermentation by providing high-quality feed that is easier for livestock to digest and decreases the need for antibiotics.
- Recycling carbon through circular carbon economy (CCE). The concept and framework are a recent development of CE and have high-potential application for carbon-intensive economies. The core idea is to take carbon emissions as a material that can be reduced, reused, recycled, and removed within a closed-loop system in which carbon emissions can be fully captured and sequestered, then chemically transformed into new products. With respect to methane mitigation, coal mines and the oil and gas sectors are the major methane emission sources for both the U.S. and China. The CCE framework has the potential to catalyze waste gas reduction and recovery in these sectors. This framework has already been adopted by Saudi Arabia and has the potential to

be applied in other countries, including China.

- ▶ **Forge conversations on policy instruments selection and regulatory frameworks.** The U.S. and China have different strengths and weaknesses in terms of policy-making strategies. The U.S. has preferred regulations, including rules and laws for methane mitigation, whereas China has taken an industrial policy approach for methane recovery and utilization. In addition, both countries can collaborate on measures that can improve techno-economic data accuracy, such as MRV. Policy learning is important for the effectiveness of methane governance and policy frameworks and may be achieved through extensive conversations and communication between the U.S. and China.
- ▶ Encourage subnational and non-state collaborations between the two countries, including cities, industries, NGOs, and research institutes. The U.S. and China already have significant experience in climate cooperation. Among other outcomes, the U.S.-China Joint Announcement on Climate Change in 2014 and the establishment of the U.S.-China Clean Energy Research Center (CERC) were major achievements of the U.S.-China collaboration on climate change. There are both positive and negative lessons to be learned, reflecting successes as well as missteps, in the collaboration. For instance, at the subnational level, the state of California has developed extensive cooperation on low-carbon city strategies with China. Future U.S.-China cooperation on methane can build on these experiences and platforms in a variety of ways, such as sharing best practices on just transition and upskilling.

5.4 INTERNATIONAL PRACTICES

In addition to the U.S. and China, other countries have taken actions on key methane mitigation issues. This section introduces some of the practices that several pioneering countries and regions, including Canada, Australia, New Zealand, Brazil, and the European Union (EU), have adopted. Among these, the Canada case study is elaborated in greater detail because of its long history and outstanding performance in methane mitigation.

Canada: Oil and Gas Sector

In 2020, four of the five largest methane-emitting countries in the oil and gas sector were also on the list of the top-five oil and gas producers: Russia, the U.S., China, and Canada (IG, 2021; Statista, 2022). Canada had the lowest methane emissions per unit of oil production score out of the countries, with emissions per unit in Canada one-third of Russia's and one-half of China's⁹.

Methane is Canada's second largest source of greenhouse gas emissions, making up 13% of national GHG emissions (Environment and Climate Change Canada, 2020). Among all methane-emitting sectors, oil and gas facilities were the main industrial emitters of methane in Canada, contributing the largest share of national methane emissions. In 2017, they released 44% of Canada's methane emissions (Government of Canada, 2020). Canadian governments, both federal and provincial, have been actively regulating methane emissions from the oil and gas sector.

Policies and Actions

Canada's regulation of methane emissions can be dated back to 1999, when methane

was considered toxic under the Canadian Environmental Protection Act, 1999 (CEPA) (Government of Canada, 2021). Methane was regulated as a GHG in 2016, when Canada signed a joint statement with the U.S. and Mexico, pledging to reduce emissions by 40-45% below 2012 levels by 2025 (Government of Canada, 2016). At the federal and provincial levels, Canada has deployed different policy frameworks to mitigate methane.

Federal level

In 2016, the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) included new regulations to reduce methane emissions from the oil and gas sector and confirmed the 40-45% reduction target (IEA, 2022). The PCF was updated in late 2020 with a plan called "A Healthy Environment and a Healthy Economy" (HEHE). HEHE indicates that the federal government will help accelerate the reduction of methane emissions with the \$750 million Emissions Reduction Fund (ERF), which provides repayable funding to oil and gas companies (Government of Canada, 2022b). A portion of the funding can be forgiven based on the cost per tonne of emissions reductions.

In June 2021, Canada launched a federal review of its national approach to reducing oil and gas methane, indicating that the federal government will refocus ERF to drive additional methane emissions reductions and continue to improve the quantification of fugitive methane emissions (Government of Canada, 2022a). In October 2021, the Government of Canada confirmed its support for the Global Methane Pledge, committed to developing regulations that reduce oil and gas methane emissions by at least 75% below 2012 levels by 2030 (Government of Canada, 2022a).

⁹ In 2020, the oil production of Russia, China, and Canada was 11.49, 4.89 and 5.5 million bpd respectively, while the methane emissions from oil and gas of these three countries are 12,898, 3,379 and 2,093 kt, so the methane emissions per unit of oil production sources for them are 1122.54, 630.04 and 380.55 kt/million bpd (IG, 2021; Statista, 2022).

In March 2022, the federal government published Canada's 2030 Emissions Reduction Plan, highlighting the role played by science and clean technology innovation in facilitating mitigating methane emissions (Environment and Climate Change Canada, 2022).

The federal government has avowed that it is making its best efforts to reduce methane emissions. However, the situation still varies across provinces. To avoid duplication of regulations, the federal government announced that it had finalized equivalency agreements with the provinces of Alberta, British Columbia (B.C.), and Saskatchewan in 2020, allowing their provincial methane regulations to replace federal regulations as long as federal methane goals are met (Dobson et al., 2021).

Provincial level

The provinces of Alberta, British Columbia, and Saskatchewan are the top three methane contributors in the oil and gas sector. Each has established provincial methane regulations.

The Alberta Energy Regulator finalized its provincial methane regulations in 2018 by making amendments to Directive 060 and Directive 017. Compared with federal level regulations, Alberta has more stringent controls and specific requirements for glycol dehydrators. However, for routine venting and pneumatic pumps, Alberta has weaker standards (Government of Canada, 2022a). Additionally, its reported methane emissions are highly underestimated, and the carbon pricing system it has used to abate GHG was not designed for methane and does not have strong measurement and reporting requirements (Gorski & Kenyon, 2018; MacKay et al., 2021).

British Columbia (B.C.) amended its Drilling and Production Regulation in December 2018 to improve control of methane emissions from the oil and gas sector (BC Oil and Gas Commission, 2019). B.C.'s control measures are more stringent for new facilities but have lower leak detection frequency for some facility types (Government of Canada, 2022a). B.C. also includes a thrice-yearly

inspection requirement for gas processing plants, compressor stations and some batteries, which is more stringent than federal standards (Clean Air Institution et al., 2019).

Saskatchewan enacted the Oil and Gas Emissions Management Regulations (OGEMR) in 2019, which focuses mainly on company-level venting and flaring methane emissions from oil facilities (Government of Saskatchewan, 2021). OGEMR sets the provincial goal of reducing methane emissions by over 40% between 2020-2025 (Government of Saskatchewan, 2021). In March 2020, the provincial government amended Directive PNG036 and added LDAR (regular leak detection and repair) provisions, requiring companies to implement relevant programs for gas facilities (Government of Saskatchewan, 2021).

Problems and Best Practices

At all levels of government, Canada has focused mainly on a bottom-up approach to reduce methane emissions by establishing requirements and regulations on components, activities, specific production, transition, and storage steps. These include targeted interventions, like routing emissions, replacing or controlling high emission components, and inspecting equipment to prevent methane leaks (Konschnik & Reuland, 2020).

The federal government has recently been considering a market-based approach and launched the Greenhouse Gas Offset Credit System in June 2022. However, instead of targeting oil and gas methane emissions, it has mainly focused on livestock and landfills (Government of Canada, 2022c). At the provincial level, both B.C. and Alberta have launched relevant GHG offset programs, but still lack regulations modified specifically for methane (BIC, 2019; Province of British Columbia, 2022).

Another successful and potentially instructive experience from Canada regulation of methane is the interactions between national and provincial rules. Although the federal and provincial governments share authority over environmental



matters, the methane rules, with the help of equivalency agreements, managed to avoid regulatory overlap.

[Emissions Reduction Fund \(ERF\)](#)

In 2020, the federal government launched the \$750 million Emissions Reduction Fund (ERF) to help onshore and offshore oil & gas companies reduce methane and other GHG emissions and to retain jobs in the sector threatened by impacts of the COVID-19 pandemic (Government of Canada, 2022b).

[Methane Mitigation in Alberta](#)

In Alberta, one organization, Bluesource, has delivered recommendations and consultancy services to reduce and eliminate methane emissions from pneumatic equipment. So far, 68,000 tCH₄¹⁰ has been reduced by mitigating methane from pneumatic controller retrofits, instrument air, chemical pumps, and vent gas capture (Bluesource, 2021).

Case Studies of Brazil, Australia, New Zealand and European Union

Other countries and regions have methane regulation experiences across different sectors, such as New Zealand, Brazil, Australia, and the European Union (EU). New Zealand is an example of effective mitigation in the livestock sector. Although it ranks 12th and 13th globally in the inventory of cattle and sheep, New Zealand was only 22nd and 23rd, respectively, in terms of emissions from manure management and enteric fermentation (Cook, 2022; EDGAR, 2018; NationMaster, 2019). Brazil launched the National Zero Methane Program in March 2022, which has provided a valuable reference for developing countries. Australia is the world's fifth largest coal mine producer and implements a number of policies that can serve as a reference for other countries, especially major coal producers. Finally,

the EU promulgated its Methane Strategy in 2020, which is the first world's state-level methane mitigation plan.

[New Zealand: Livestock Sector](#)

Biogenic methane emissions have been New Zealand's largest contribution to climate change since 1840 (Reisinger & Leahy, 2019). Its population of cattle and sheep is seven times its human population. Methane emissions from agriculture and waste account for over 40% of current emissions (Brown, 2022; Climate Action Tracker, 2021). New Zealand has made some progress in terms of methane-related research but has often been criticized for its unambitious targets.

Methane, especially agricultural methane, has attracted increasing government attention in New Zealand. In 2002, the Ministry for the Environment passed the Climate Change Response Act, which regulated the methodology of methane calculation. This act was amended in 2019, providing a definition of biogenic methane covering all methane produced from the agriculture and waste sectors (New Zealand Ministry for the Environment, 2021). Additionally, the methane mitigation target was advanced, aimed at reducing biological methane by 10% by 2030 and by 24-47% by 2050. However, their net-zero by 2050 target includes CO₂ and other non-CO₂ gases, but not methane. In 2020, the Climate Change Act was amended for the second time and the ministers for environment and agriculture were directed to prepare a report that outlines a system to price emissions from agricultural activities as an alternative to the emission trading scheme (ETS) by the end of 2022 (New Zealand Ministry for the Environment, 2021). The 2020 amendment provides financial incentives for New Zealand's agricultural methane mitigation, bridging a gap in the ETS that left out agricultural methane (Climate Action Tracker, 2021).

Overall, New Zealand's methane mitigation

¹⁰ Using 100-year GWP from AR4 for conversion between CO₂e and CH₄.

strategies have been criticized by the Climate Action Tracker as “not covered by significant policies” and the current climate targets “highly insufficient” (Climate Action Tracker, 2021), in large part due to its low climate ambition and lack of policies. Nonetheless, the country has successfully identified its main methane emissions sources and addressed them with financial incentives. New Zealand’s related research has provided lessons for other countries. For instance, New Zealand’s research on livestock methane mitigation has been relatively comprehensive, covering breeding, feeds, inhibitors, vaccines, and manure, which is helpful to reduce the production of methane in the rumen (NZAGRC, 2021).

Brazil: Waste Sector

Brazil is the world’s fifth largest methane emitter (Climate Watch, 2020). In 2020, Brazil emitted around 402,000 million metric tons of CO₂e (2% of total world emissions) (GMI, 2022a). According to the World Bank, Brazil has produced one-third more waste since 2003; approximately 216,000 tons of trash are collected each day. This waste is estimated to produce over 1.88 TgCH₄ annually, equivalent to the GHG emissions from 10 million vehicles (The World Bank, 2020).

Brazil published the Zero Methane Act in 2022, only the third state-level methane mitigation plan after the EU and the U.S. Unlike those comprehensive plans, Brazil’s Zero Methane Act focuses on biogas and biomethane from urban and rural organic waste (Ran & Zhang, 2022). Brazil has taken comprehensive actions on the utilization of this kind of biogas and biomethane, including public policies, international projects, and market incentives.

Dating back to 2004, Brazil joined the Global Methane Initiative (GMI) as a partner country and worked with GMI on many projects to reduce barriers to the use of methane as a clean energy source in the waste sector (GMI, 2022a). In 2010, Brazil finalized its National Solid Waste Policy, aiming to reduce total waste production at the national level and promote the sustainability of waste management locally and nationally (Brazil

Ministry of Environment, 2012). In 2012, the World Bank’s Carbon Partnership Facility built cooperation with Caixa Econômica Federal (CAIXA), the second largest public bank in Brazil, offering beneficial financing channels for companies to manage and regulate landfills (The World Bank, 2020). In 2013, the Brazilian government published The Atlas of Energy Potential of Solid Waste, which aims to support the production of electricity through the recycling of solid waste (Abrelpe, 2013). In 2017, Brazil launched the National Biofuels Policy (RenovaBio), which became a key tool in reducing GHGs emissions and helped Brazil fulfill its commitments under the Paris Climate Agreement (Brazil Ministry of Mines and Energy, 2021). RenovaBio, as a state policy, framed a strategy that recognizes the integral roles of all types of biofuels, including biomethane, and introduced market mechanisms to value the contribution of each biofuel in reducing emissions (Brazil Ministry of Environment, 2021).

In 2021, following the Glasgow Climate Change Conference (COP 26), Brazil signed the Global Methane Pledge, making it the second largest emitter after the U.S. to join the collective commitment to slash emissions 30% below the 2020 levels by 2030 (Global Methane Pledge, 2021). In 2022, Brazil launched the National Zero Methane Program, along with incentives to encourage methane reduction (Bezerra et al., 2022). The incentive package, “Federal Strategy of Incentive to the Sustainable Use of Biogas and Biomethane” focuses mainly on: (1) promoting the development of carbon markets, in particular adding a specifically designed methane credit to the current carbon market; (2) supporting R&D of new technologies that facilitate the reduction of methane emissions and the more sustainable use of energy sources, including biogas and biomethane; (3) encouraging national and international cooperation for actions on methane reduction (Trench Rossi Watanabe, 2022).

Brazil is on track to achieve its 2030 methane target. The country has focused its policy on biomethane emission mitigation. In the initial stage, Brazil regulated methane with other GHGs



and controlled biomethane mainly for resource-saving and energy-reuse. But recently, in close international cooperation with organizations and other countries, Brazil has launched more specific methane mitigation policies. Today, Brazil has a relatively comprehensive methane pricing mechanism to stimulate business activity in reducing emissions and to underscore the role of technology with funding and policy support.

Australia: Coal Sector

Coal mines in Australia are one of the country's primary methane-emitting sectors. In 2019, coal mines released 68% of total energy-sector emissions (Assan, 2022). Australia is the world's sixth largest contributor of coal mine methane emissions (Assan, 2022). Although it did not join the Global Methane Pledge, Australia has committed to achieving net-zero by 2050, and has committed to reduce CO₂ emissions by 26-28% by 2030, under its NDC. To achieve this goal, Australia has taken a number of policy actions.

The NGER scheme, established by the National Greenhouse and Energy Reporting Act 2007 (NGER Act), is a single national framework for reporting and disseminating company information about GHG emissions. It requires direct measurement of the amount of methane emitted by underground mines and the estimates of methane emission by surface mines, using emissions factors (NGER, 2019).

In July 2011, Australia launched the Clean Energy Future Plan, which provides an overall framework for emissions abatement, including methane mitigation. The plan includes the implementation of a carbon-pricing mechanism, providing incentives for businesses to engage in activities that will reduce their emissions (GMI, 2011). The government has also developed a transitional assistance package, Coal Mining Abatement Technology Support Package (CMATSP), to support funding for technology innovation.

The New South Wales government has also imposed regulations on coal mine methane. The new amendment of the Mineral Resources Act

1989 requires that pre- and post-drainage methane either be used or flared, rather than simply vented (State of Queensland, 2021).

Australia is making progress on methane mitigation in the coal sector to meet its NDC. In addition to policy implementation, the country has also carried out extensive research and cooperated with specific companies and projects on methane mitigation in the coal sector (GMI, 2011). However, Australia also has problems in underestimating emissions, a lack of relevant policies, and insufficient international cooperation, which need to be improved in the future to meet its emissions targets (Morton, 2022).

European Union: All Sectors

The EU's climate goal is to reduce 55% of its GHGs compared to 1990 levels by 2030, and to achieve carbon neutrality by 2050; these targets became legally binding in 2021 (Finland Ministry of Environment, 2021).

In November 2019, the European Commission published its plans for a European Green Deal, making methane reduction a priority initiative (EU, 2022; European Commission, 2019). In October 2020, the EU published the EU Methane Strategy, the first plan specifically addressing methane emissions since 1996. This Strategy covers all sectors, but focuses on energy, agriculture, and waste. A key goal is to improve the measurement and reporting of methane emissions (EU, 2022; European Commission, 2019). In December 2021, the European Commission passed a proposal for regulation aimed at reducing methane emissions in the energy sector. This new act provides for: 1) improved MRV of methane emissions from the energy sector; and 2) direct emissions abatement, through compulsory detection and repair of fugitive methane, and prohibition of methane venting and flaring (EU, 2021b, 2022).

The EU also has worked with international partners to reduce methane emissions. The EU is actively involved in several international initiatives, such as the Climate & Clean Air Coalition (CCAC), under which the CCAC Mineral Methane Initiative

provides an ambitious methane emissions measurement and reporting framework (CCAC, 2015; EU, 2022). The European Commission also contributes to global methane research that aims to address a lack of global measurement data in the oil and gas sector. For example, it has worked with CCAC, the Environmental Defense Fund (EDF), and the Oil and Gas Climate Initiative (OGCI) on a series of peer-reviewed scientific studies to measure methane emissions in the oil and gas sector (EU, 2022). The EU also supported the establishment of an International Methane Emission Observatory (IMEO) with the UNEP, CCAC, and the International Energy Agency (IEA) in October 2021. This collaboration aims to ensure public transparency of anthropogenic methane emissions reporting (EU, 2021a, 2022).

The EU's advantages lie in its broad network of relationships with many countries, regions, and organizations, smoothing the way for policies and initiatives. This network also creates opportunities to share best practices.

Summary of International Best Practices

Ensure legislative coordination. Policy-making should be based on the specific context of different jurisdictions to avoid policy overlap or contradiction. Canada, as a federal state, put forward equivalency agreements to coordinate differences in methane mitigation policies between the federal and provincial levels. In the EU, this role was played by the European Commission.

Focus on low-hanging fruits. As shown in the above cases, all five countries and regions placed significant attention on the sectors which contributed the most to methane

emissions. Although the EU Methane Strategy is a comprehensive plan, it recognizes three priority sectors. This approach can help realize the greatest methane reduction in the shortest amount of time.

Respect technological innovation. Technological innovation has been an important component of methane reduction policies in all five of the case countries and regions. Therefore, R&D costs will be a key issue, and countries at different levels of development and with different political economies will have differential capacities. The earlier a country adopts effective technologies, the more benefits it will achieve from methane mitigation.

Take advantage of market mechanisms. Methane, as both a GHG and a potential energy resource, can be abated using economic incentives. The case studies have shown different forms of such incentives, including market-based offset credits, emissions trading schemes, and carbon taxes.

Develop multidimensional cooperation.

Cooperation enables different jurisdictions to learn from each other to more effectively meet global climate goals. Cooperation exists among different countries and organizations (the latter includes the Climate & Clean Air Coalition and Global Methane Initiative). Cooperation can also be established across different sectors within a country. The most typical is cooperation across governments, companies, and the research community. Australia, New Zealand, and the EU have all underlined such cooperation in their methane mitigation policies.



06 | CONCLUSIONS

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Rapid, economy-wide reductions in methane emissions will be critical for the world to achieve a 1.5°C pathway. Both the United States and China have highlighted the urgency of reducing methane emissions in the Glasgow Joint Declaration. However, ambitious actions by both countries to reduce methane will be needed to deliver reductions needed to support this high-ambition global outcome. As two of the top three methane emitters in the world, China and the United States are well positioned to lead global methane mitigation efforts and collaborate on methane policies, technologies, and strategies. Several challenges present obstacles for enhanced methane abatement, including uncertainty in historical emissions estimates and mitigation potential, limited market mechanisms, and institutional barriers. However, there are opportunities for collaborative action, including identifying low-hanging fruit abatement opportunities and realizing co-benefits to methane emissions reduction, such as improved air quality and public health.

Our results suggest prioritizing mitigation measures in coal and oil and gas production, for China and the United States, respectively, as these are low-cost, high mitigation potential sources that contribute to over one third of each country's total methane emissions. Key areas for collaboration between countries are improving monitoring and measurement of methane emissions, developing methane emission recovery markets, and engaging in cross-country subnational and national conversations on regulatory frameworks for mitigation. The United States and China can collaborate on strategies for emissions sources prevalent in both countries that have high mitigation potential, and act to rapidly reduce methane emissions to improve our chances of limiting global temperature rise to 1.5°C.

Areas of Future Research

While this study evaluated estimates across several inventories, further research is needed to fully understand inventory differences. We did not evaluate the underlying assumptions for China's National Communication on Climate Change estimates, and therefore cannot fully identify the reasons for differences between these estimates and other inventories. Comparing activity data, emissions factors, and proxy geospatial data across inventories would help to better outline differences and increase certainty in emissions estimates. Additionally, developing an uncertainty estimate across sectors, based on collected inventories, would help to understand how variation across inventories translates emissions estimates today. While we were able to use the EPA's estimate of uncertainty for the U.S., we were not able to find an analogous estimate for China. Developing sectoral uncertainty estimates in China would help to inform future policy targets.

This study used results from four modeling teams that had national level results for China, but we did not conduct a multi-model exercise for the U.S. Future research could evaluate pathways for emissions reduction in the U.S. and identify areas of uncertainty. For our results in China, we were unable to compare marginal abatement cost assumptions across models, which would be helpful for understanding differences in model behavior. We did identify significant differences across modeling teams for projections about gas production in China and the mitigation potential in the wastewater and livestock sectors. Future research should evaluate these sectors in particular in China to better understand the role technology change can play in emissions reduction and how activity levels will change over time.



REFERENCES

1. Abernethy, S., O'Conno, F. M., Jones, C. D., & Jackson, R. B. (2021, June 2). Methane Removal and the Proportional Reductions in Surface Temperature and Ozone. <https://doi.org/10.1098/rsta.2021.0104>
2. Abrelpe. (2013). Atlas of GHS Emission and Energy Potential. <https://www.waste.ccacoalition.org/document/atlas-ghg-emission-and-energy-potential-waste-destination-brazil>
3. Agency of Environmental Protection. (1997, July 2). Standard for Pollution Control on the Landfill Site for Domestic Waste. <https://img.antpedia.com/standard/pdf/Z70/1703/GB%2016889-1997.PDF>
4. Allen, G. (2021). Landfill Fined by EPA after Violating Federal Clean Air Act. <https://pamplinmedia.com/nbg/142-news/529174-423075-landfill-fined-by-epa-after-violating-federal-clean-air-act-pwoff>
5. Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasackers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., ... Hamburg, S. P. (2018). Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain. *Science*, 361(6398), 186–188. <https://doi.org/10.1126/science.aar7204>
6. Anenberg, S. C., Schwartz, J., Shindell, D., Amann, M., Faluvegi, G., Klimont, Z., Janssens, -Maenhout Greet, Pozzoli, L., Van, D. R., Vignati, E., Emberson, L., Muller, N. Z., West, J. J., Williams, M., Demkine, V., Hicks, W. K., Kuylenstierna, J., Raes, F., & Ramanathan, V. (2012). Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, 120(6), 831–839. <https://doi.org/10.1289/ehp.1104301>
7. Assan, S. (2022). Tackling Australia's Coal Mine Methane Problem. <https://ember-climate.org/app/uploads/2022/06/Ember-Tackling-Australias-Coal-Mine-Methane-Problem-2.pdf>
8. Avnery, S., Mauzerall, D. L., & Fiore, A. M. (2012, December 8). Increasing Global Agricultural Production by Reducing Ozone Damages Via Methane Emission Controls and Ozone - Resistant Cultivar Selection. <https://onlinelibrary.wiley.com/doi/10.1111/gcb.12118>
9. Bai, C., Wang, X., & Zhong, X. (2012). Regulation or Property Rights: The Effect of China's Coal Mine Shutdown Policy on Work Safety. *China Economist*, 7(3), 114–127. <https://www.proquest.com/openview/6d072b80a31d4e678b1500d797b5ad84/1?cbl=1806366&parentSessionId=3QD4Kq428Sh%2BFdvhk1ZzmfFYU55INPFxF0II0G6XMUE%3D&pq-origsite=gscholar&parentSessionId=1Zfu7XC8ot-IMfII9eKWbdlu3d0%2FdoWpDUOD9LFYoS0U%3D>
10. Baker, P. (2021). Government Subsidization and the Reduction of Enteric Emissions in the United States: Is Implementing a Policy of National Enteric Emissions Standards a Feasible National Policy Option to Reduce Methane Emissions in the United States? *Consilience*, 23, 59–64. <https://www.jstor.org/stable/26979907>
11. Banks, J. (2012). Barriers and Opportunities for Reducing Methane Emissions from Coal Mines. 22. https://cdn.catf.us/wp-content/uploads/2019/10/21093457/201209-Barriers_and_Opportunities_in_Coal_Mine_Methane_Abatement.pdf
12. BC Oil and Gas Commission. (2019, January 16). Commission Introduces New Regulations to Meet Methane Targets (IB 2019-01). <https://www.bcogc.ca/news/commission-introduces-new-regulations-to-meet-methane-targets/>

13. Bezerra, L. G., Gomes, G., & Costa, L. (2022, March 25). Brazil Launches Methane Zero National Program with a Package of Incentive Measures to Biogas and Biomethane. Eye on ESG. <https://www.eyeesg.com/2022/03/brazil-launches-methane-zero-national-program-with-a-package-of-incentive-measures-to-biogas-and-biomethane/>
14. BIC. (2019, August 29). The Business Case for Reducing Methane Emissions. BIC. <https://businessincalgary.com/month-and-year/september-2019/the-business-case-for-reducing-methane-emissions/>
15. Bittle, J. (2022, August 9). The Inflation Reduction Act Promises Thousands of New Oil Leases. Drillers Might not Want Them. Grist. <https://grist.org/energy/inflation-reduction-act-oil-gas-leases-federal-land/>
16. Bluesource. (2021). Oil and Gas Methane Reductions. Bluesource. <https://www.bluesource.com/services/oil-and-gas/>
17. Bollen, J., Guay, B., Jamet, S., & Corfee-Morlot, J. (2009). Co-Benefits of Climate Change Mitigation Policies: Literature Review and New Results. OECD. <https://doi.org/10.1787/224388684356>
18. Bonnet, C., Bouamra-Mechemache, Z., & Corre, T. (2018). An Environmental Tax Towards More Sustainable Food: Empirical Evidence of the Consumption of Animal Products in France. *Ecological Economics*, 147, 48–61. <https://doi.org/10.1016/j.ecolecon.2017.12.032>
19. Brandt, A. R., Heath, G. A., & Cooley, D. (2016). Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environmental Science & Technology*, 50(22), 12512–12520. <https://doi.org/10.1021/acs.est.6b04303>
20. Brazil Ministry of Environment. (2012, February). U.S.-Brazil Joint Initiative on Urban Sustainability. https://archive.epa.gov/international/jius/web/html/brazilian_national_solid_waste_policy.html
21. Brazil Ministry of Environment. (2021). Final Report on the Monitoring and Assessment of the National Adaptation Plan to Climate Change 2016-2020 Cycle. https://www.gov.br/mma/pt-br/assuntos/climaozoniodesertificacao/clima/arquivos/business-sector-report_en_web.pdf
22. Brazil Ministry of Mines and Energy. (2021, June 29). RenovaBio. Ministério de Minas e Energia. <https://www.gov.br/mme/pt-br/assuntos/secretarias/petroleo-gas-natural-e-biocombustiveis/renovabio-1/renovabio-ingles/renovabio-ingles>
23. Brink, S., Godfrey, H., Kang, M., Lyser, S., Majkut, J., Mignotte, S., Peng, W., Reid, M., Sengupta, M., & Singer, L. (2013, February). Methane Mitigation Opportunities in China. https://scholar.princeton.edu/sites/default/files/weipeng/files/WWS2012-2013_Methane_Workshop_Submitted.pdf
24. Brown, A. (2022, June 9). New Zealand Announces World-First Plan to Tax Cow and Sheep Burps. <https://www.npr.org/2022/06/09/1104014587/new-zealand-announces-world-first-plan-to-tax-cow-and-sheep-burps>
25. Brown, M., & Phillis, M. (2022, August). Climate Change? The Inflation Reduction Act's Surprise Winner, the US Oil and Gas Industry. <https://www.usatoday.com/story/news/nation/2022/08/18/climate-change-inflation-reduction-act-oil-gas/7837956001/>
26. Cai, B., Lou, Z., Wang, J., Geng, Y., Sarkis, J., Liu, J., & Gao, Q. (2018). CH₄ Mitigation Potentials from China Landfills and Related Environmental Co-Benefits. *Science Advances*, 4(7), 1–8. <https://doi.org/10.1126/sciadv.aar8400>
27. CCAC. (2015). The CCAC Oil & Gas Methane Partnership. <https://www.ccacoalition.org/en/activity/ccac-oil-gas-methane-partnership>
28. CCAC. (2021). Benefits and Costs of Mitigating Methane Emissions. Climate & Clean Air Coalition. <https://www.ccacoalition.org/en/content/benefits-and-costs-mitigating-methane-emissions>
29. CCAC. (2022). Methane. Climate & Clean Air Coalition. <https://www.ccacoalition.org/en/slcp/methane>



30. CCAC & UNEP. (2021a). Assessment of Environmental and Societal Benefits of Methane Reductions (web tool). Climate & Clean Air Coalition. <https://www.ccacoalition.org/en/resources/assessment-environmental-and-societal-benefits-methane-reductions-web-tool>
31. CCAC & UNEP. (2021b). Global Methane Assessment. <https://www.ccacoalition.org/en/resources/global-methane-assessment-full-report>
32. CCAPP. (2021, September). China's Carbon Neutrality and Clean Air Synergies. <https://www.efchina.org/Attachments/Report/report-cemp-20211020/%E4%B8%AD%E5%9B%BD%E7%A2%B3%E4%B8%AD%E5%92%8C%E4%B8%8E%E6%B8%85%E6%B4%81%E7%A9%BA%E6%B0%94%E5%8D%8F%E5%90%8C%E8%B7%AF%E5%BE%842021.pdf>
33. Chang, Y., & Zhang, S. (2017). Reflections on Legal Regulation on CBM in China. 19(5), 1–9. <http://www.cnki.com.cn/Article/CJFDTotal-PXSY201705002.htm>
34. Cheewaphongphan, P., Chatani, S., & Saigusa, N. (2019). Exploring Gaps between Bottom-Up and Top-Down Emission Estimates Based on Uncertainties in Multiple Emission Inventories: A Case Study on CH₄ Emissions in China. *Sustainability*, 11(7), Article 7. <https://doi.org/10.3390/su11072054>
35. Chen, D., Chen, A., Hu, X., Li, B., Li, X., Guo, L., Feng, R., Yang, Y., & Fang, X. (2022a). Substantial Methane Emissions from Abandoned Coal Mines in China (SSRN Scholarly Paper No. 4067033). <https://doi.org/10.2139/ssrn.4067033>
36. Chen, L., Frederiksen, P., Li, X., & Shu, B. (2020). Review of Biogas Models and Key Challenges in the Further Development in China. *IOP Conference Series: Earth and Environmental Science*, 446(2), 022007. <https://doi.org/10.1088/1755-1315/446/2/022007>
37. Chen, Z., Jacob, D., Nesser, H., Sulprizio, M., Lorente, A., Varon, D., Lu, X., Shen, L., Qu, Z., Penn, E., & Yu, X. (2022b). Methane Emissions from China: A High-Resolution Inversion of TROPOMI Satellite Observations [Preprint]. *Gases/Atmospheric Modelling/Troposphere/Physics (physical properties and processes)*. <https://doi.org/10.5194/acp-2022-303>
38. China Environment Chamber of Commerce. (2021, December 8). The Latest Statistical Briefing of the National Municipal Solid Waste Treatment. <http://www.zhbbw.com/huanqiusaomiao/202112/120846726.html>
39. China NCCC. (2018). The People's Republic of China Second Biennial Update Report on Climate Change. https://unfccc.int/sites/default/files/resource/China%202BUR_English.pdf
40. Clark, A., Malik, N. S., & Rathi, A. (2021, November 9). Why Methane is Climate's Low-Hanging, Invisible Fruit: QuickTake. *The Washington Post*. https://www.washingtonpost.com/business/energy/why-methane-is-climates-low-hanging-invisible-fruit-quicktake/2021/11/02/a21e2fe0-3c19-11ec-bd6f-da376f47304e_story.html
41. Clean Air Institution, EDF, PEMBINA Institute, David Suzuki Foundation, & Environmental Defence. (2019, September 19). Best Practices on Oil and Gas Methane Emissions Regulations. <https://www.edf.org/sites/default/files/content/CanadaFactSheet.pdf>
42. Climate Action Tracker. (2021, September 15). New Zealand. <https://climateactiontracker.org/countries/new-zealand/>
43. Climate Watch. (2020). Methane Emissions (kt of CO₂ Equivalent). https://data.worldbank.org/indicator/EN.ATM.METH.KT.CE?most_recent_value_desc=true
44. Collins, W., Orbach, R., Bailey, M., Biraud, S., Coddington, I., DiCarlo, D., Peischl, J., Radhakrishnan, A., & Schimel, D. (2022). Monitoring Methane Emissions from Oil and Gas Operation. *Optics Express*, 30(14), 24326. <https://doi.org/10.1364/OE.464421>
45. CSIRO & GMI. (2018, October 25). Expert Dialogue on Ventilation Air Methane (VAM). https://www.globalmethane.org/documents/res_coal_VAM_Dialogue_Report_20181025.pdf
46. Cook, R. (2022, August 11). Ranking of Countries with the Most Cattle. [//beef2live.com/story-ranking-countries-cattle-0-106905](http://beef2live.com/story-ranking-countries-cattle-0-106905)

47. Creedy, D. (2019). Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Coal Mines. UN. <https://doi.org/10.18356/cac3a157-en>
48. Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Vullo, E. L., Solazzo, E., Monforti-Ferrario, F., Olivier, J., & Vignati, E. (2021). EDGAR v6.0 Greenhouse Gas Emissions. <http://data.europa.eu/89h/97a67d67-c62e-4826-b873-9d972c4f670b>
49. CSIRO & GMI. (2018). Expert Dialogue on Ventilation Air Methane (VAM) Melbourne, Australia. https://www.globalmethane.org/documents/res_coal_VAM_Dialogue_Report_20181025.pdf
50. Daly, M. (2022, March 24). Federal Regulators Pulls Back Plan to Assess Climate Impact of Gas Pipelines. PBS NewsHour. <https://www.pbs.org/newshour/politics/federal-regulators-pulls-back-plan-to-assess-climate-impact-of-gas-pipelines>
51. Deng, Z., Ciais, P., Tzompa-Sosa, Z. A., Saunois, M., Qiu, C., Tan, C., Sun, T., Ke, P., Cui, Y., Tanaka, K., Lin, X., Thompson, R. L., Tian, H., Yao, Y., Huang, Y., Lauerwald, R., Jain, A. K., Xu, X., Bastos, A., ... Chevallier, F. (2022). Comparing National Greenhouse Gas Budgets Reported in UNFCCC Inventories Against Atmospheric Inversions. *Earth System Science Data*, 14(4), 1639–1675. <https://doi.org/10.5194/essd-14-1639-2022>
52. Denysenko, A., Evans, M., Kholod, N., Butler, N., Ltd, H.-E., & Roshchanka, V. (2019). Legal and Regulatory Status of Abandoned Mine Methane in Selected Countries: Considerations for Decision Makers. https://www.epa.gov/sites/default/files/2019-03/documents/legal-regulatory-status-amm_epa.pdf
53. Ding, Y. (2021, March 4). Approximately 5500 Coal Mines were Closed during the 13th Five-Year Plan. People's Daily. http://www.gov.cn/xinwen/2021-03/04/content_5590094.htm
54. Dobson, S., Goodday, V., & Winter, J. (2021). If It Matters, Measure It: A Review of Methane Sources and Mitigation Policy in Canada. <https://doi.org/10.2139/ssrn.3850984>
55. DOL. (2021). Mine Safety and Health Administration (MSHA) | Protecting Miners' Safety and Health Since 1978. <https://www.msha.gov/>
56. Du, M., Zhu, Q., Wang, X., Li, P., Yang, B., Chen, H., Wang, M., Zhou, X., & Peng, C. (2018). Estimates and Predictions of Methane Emissions from Wastewater in China from 2000 to 2020. *Earth's Future*, 6(2), 252–263. <https://doi.org/10.1002/2017EF000673>
57. Dunphy, R. T., & Lin, B. C. (1991). A Battle Plan for Local Landfills. *The Real Estate Appraiser*, 36–43. http://clout2008.com/yahoo_site_admin/assets/docs/__110449-www2_webpac_pdf_rea1976-1992_TREA1291PP36-431.296155939.pdf
58. Duren, R. M., Thorpe, A. K., Foster, K. T., Rafiq, T., Hopkins, F. M., Yadav, V., Bue, B. D., Thompson, D. R., Conley, S., Colombi, N. K., Frankenberg, C., McCubbin, I. B., Eastwood, M. L., Falk, M., Herner, J. D., Croes, B. E., Green, R. O., & Miller, C. E. (2019). California's Methane Super-Emitters. *Nature*, 575(7781), Article 7781. <https://doi.org/10.1038/s41586-019-1720-3>
59. EDF. (2014, October 2). Emerging U.S. Methane Mitigation Industry Stimulates Growth in Local Economies. Environmental Defense Fund. <https://www.edf.org/media/emerging-us-methane-mitigation-industry-stimulates-growth-local-economies>
60. EDF. (2021). Actions and Trends of Methane Emission Control at Home and Abroad—2021 China Methane Forum Background Report. http://www.cet.net.cn/uploads/soft/202103/1_29104647.pdf
61. EDF. (2022, July 1). How Reducing Methane Emissions Creates Jobs. Environmental Defense Fund. <https://www.edf.org/how-reducing-methane-emissions-creates-jobs>
62. EDGAR. (2018). Global Greenhouse Gas Emissions (CH₄). https://edgar.jrc.ec.europa.eu/index.php/dataset_ghg60
63. EIA. (2019). Total Energy Production from Petroleum and Other Liquids 2019. <https://www.eia.gov/international/rankings/world?pa=288&u=2&f=A&v=none&y=01%2F01%2F2019>



64. EIA. (2022a). Natural Gas. <https://www.eia.gov/international/data/world/natural-gas/>
65. EIA. (2022b, October). Total Energy. <https://www.eia.gov/totalenergy/index.php>
66. Environment and Climate Change Canada. (2020). National Inventory Report 1990 –2018: Greenhouse Gas Sources and Sinks in Canada. https://publications.gc.ca/collections/collection_2020/eccc/En81-4-2018-3-eng.pdf
67. Environment and Climate Change Canada. (2022). 2030 Emissions Reduction Plan: Canada’s Next Steps for Clean Air and a Strong Economy. https://publications.gc.ca/collections/collection_2022/eccc/En4-460-2022-eng.pdf
68. EPA. (2004). Methane Emissions from Abandoned Coal Mines in the United States: Emissions Inventory Methodology and 1990-2002 Emissions Estimates. <https://nepis.epa.gov/Exe/ZyPDF.cgi/600004JM.PDF?DockKey=600004JM.PDF>
69. EPA. (2010a, July 12). Mandatory Reporting of Greenhouse Gases From Magnesium Production, Underground Coal Mines, Industrial Wastewater Treatment, and Industrial Waste Landfills. Federal Register. <https://www.federalregister.gov/documents/2010/07/12/2010-16488/mandatory-reporting-of-greenhouse-gases-from-magnesium-production-underground-coal-mines-industrial>
70. EPA. (2010b, November 30). Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas Systems. Federal Register. <https://www.federalregister.gov/documents/2010/11/30/2010-28655/mandatory-reporting-of-greenhouse-gases-petroleum-and-natural-gas-systems>
71. EPA. (2015a, October 23). Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units. Federal Register. <https://www.federalregister.gov/documents/2015/10/23/2015-22842/carbon-pollution-emission-guidelines-for-existing-stationary-sources-electric-utility-generating>
72. EPA. (2015b, October 23). Standards of Performance for Greenhouse Gas Emissions From New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units. Federal Register. <https://www.federalregister.gov/documents/2015/10/23/2015-22837/standards-of-performance-for-greenhouse-gas-emissions-from-new-modified-and-reconstructed-stationary>
73. EPA. (2016, May 11). EPA Releases First-Ever Standards to Cut Methane Emissions from the Oil and Gas Sector. US EPA. <https://www.epa.gov/newsreleases/epa-releases-first-ever-standards-cut-methane-emissions-oil-and-gas-sector>
74. EPA. (2017). Abandoned Coal Mine Methane Opportunities Database. https://www.epa.gov/sites/default/files/2016-03/documents/amm_opportunities_database.pdf
75. EPA. (2019a). Coal Mine Methane Developments in the United States. https://www.epa.gov/sites/default/files/2018-03/documents/cmm_developments_in_the_us.pdf
76. EPA. (2019b). Global Non-CO2 Greenhouse Gas Emission Projections & Marginal Abatement Cost Analysis: Methodology Documentation. https://www.epa.gov/sites/default/files/2019-09/documents/nonco2_methodology_report.pdf
77. EPA. (2019c). Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation 2015-2050. https://www.epa.gov/sites/default/files/2019-09/documents/epa_non-co2_greenhouse_gases_rpt-epa430r19010.pdf
78. EPA. (2021a). U.S. Greenhouse Gas Emissions Trading Programs that Include Coal Mine Methane. https://www.epa.gov/sites/default/files/2021-01/documents/ghg_registries_2021.pdf
79. EPA. (2021b, June 1). Trends in Ozone Adjusted for Weather Conditions. <https://www.epa.gov/air-trends/trends-ozone-adjusted-weather-conditions>
80. EPA. (2022a). Coalbed Methane Outreach Program (CMOP). <https://www.epa.gov/cmop>
81. EPA. (2022b, February 3). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 [Reports and Assessments]. <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020>

82. EU. (2020). EU Methane Strategy. Have Your Say. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12504-EU-methane-strategy_en
83. EU. (2021a, October 31). International Methane Emissions Observatory Launched to Boost Action on Powerful Climate-warming Gas [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_5636
84. EU. (2021b, December 15). New EU Framework to Decarbonise Gas Markets [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6682
85. EU. (2022). Methane Emissions. https://energy.ec.europa.eu/topics/oil-gas-and-coal/methane-emissions_en
86. European Commission. (2019, December 11). The European Green Deal. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF
87. Evans, M., & Roshchanka, V. (2013). Energizing the Electricity Market for Methane. https://www.globalmethane.org/expo-docs/canada13/coal_11_Evans_Presentation.pdf
88. FAO. (2021). Meat Market Review. <https://www.fao.org/3/cb7886en/cb7886en.pdf>
89. FAOSTAT. (2021a). Food and Agriculture Data. <https://www.fao.org/faostat/en/#home>
90. FAOSTAT. (2021b). OECD-FAO Agricultural Outlook 2021-2030. 15. <https://www.fao.org/3/cb5332en/Meat.pdf>
91. Fellmann, T., Witzke, P., Weiss, F., Van Doorslaer, B., Drabik, D., Huck, I., Salputra, G., Jansson, T., & Leip, A. (2018). Major Challenges of Integrating Agriculture into Climate Change Mitigation Policy Frameworks. *Mitigation and Adaptation Strategies for Global Change*, 23(3), 451–468. <https://doi.org/10.1007/s11027-017-9743-2>
92. Finland Ministry of Environment. (2021). EU Climate Policy. Ministry of the Environment. <https://ym.fi/en/eu-climate-policy>
93. Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., & Zhang, H. (2021). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity (Climate Change 2021: The Physical Science Basis, pp. 923–1054). Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf
94. Foster, J. (2022, April 15). Farmers, Scientists Seek Solutions to Global Warming Caused by Cows. Environmental Defense Fund. <https://www.edf.org/article/farmers-seek-solutions-methane-emissions-cows>
95. Fuel Industry Press. (1952). Coal Mine Technical Security Trial Regulations. https://opac.muc.edu.cn/opac/item.php?marc_no=0000310873&list=1
96. GAO. (2022). Federal Actions Needed to Address Methane Emissions from Oil and Gas Development. <https://www.gao.gov/assets/gao-22-104759.pdf>
97. Gao, J., Guan, C., & Zhang, B. (2020). China's CH₄ Emissions from Coal Mining: A Review of Current Bottom-Up Inventories. *Science of the Total Environment*, 725, 138295. <https://doi.org/10.1016/j.scitotenv.2020.138295>
98. Gao, J., Guan, C., & Zhang, B. (2022). Why Are Methane Emissions from China's Oil & Natural Gas Systems Still Unclear? A Review of Current Bottom-Up Inventories. *Science of the Total Environment*, 807, 151076. <https://doi.org/10.1016/j.scitotenv.2021.151076>



99. Gao, J., Guan, C., Zhang, B., & Li, K. (2021). Decreasing Methane Emissions from China's Coal Mining with Rebounded Coal Production. *Environmental Research Letters*, 16(12), 124037. <https://doi.org/10.1088/1748-9326/ac38d8>
100. Gleason, C. B., & White, R. R. (2019). Beef Species-Ruminant Nutrition Cactus Beef Symposium: A Role for Beef Cattle in Sustainable U.S. Food Production. *Journal of Animal Science*, 97(9), 4010–4020. <https://doi.org/10.1093/jas/skz173>
101. Global Methane Pledge. (2021). Global Methane Pledge. <https://www.globalmethanepledge.org/>
102. GMI. (2011). Australian Coal Action Plan. https://www.globalmethane.org/documents/coal_cap_australia.pdf
103. GMI. (2022a). Brazil. <https://www.globalmethane.org/partners/detail.aspx?c=brazil#methane-emissions>
104. GMI. (2022b). Methane Emissions Data. <https://www.globalmethane.org/methane-emissions-data.aspx>
105. GMI. (2022c). Project Network Members. https://www.globalmethane.org/project-network/member_list.aspx
106. Gong, S., & Shi, Y. (2021). Evaluation of Comprehensive Monthly-Gridded Methane Emissions from Natural and Anthropogenic Sources in China. *Science of the Total Environment*, 784, 147116. <https://doi.org/10.1016/j.scitotenv.2021.147116>
107. Gorski, J., & Kenyon, D. (2018). Achieving Methane Reductions through Carbon Pricing in Alberta. *Environmental Science & Technology*, 51(21), 13008–13017. <https://doi.org/10.1021/acs.est.7b03525>
108. Government of Canada. (2016). Pan-Canadian Framework on Clean Growth and Climate Change. https://publications.gc.ca/collections/collection_2017/eccc/En4-294-2016-eng.pdf
109. Government of Canada. (2020, January 8). General Factsheet Regarding the Release of Methane and Certain Volatile Organic Compounds [Regulations]. <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/factsheet-general-information-regulations-reduction-methane.html>
110. Government of Canada. (2021, May 1). Consolidated Federal Laws of Canada, Canadian Environmental Protection Act, 1999. <https://laws-lois.justice.gc.ca/eng/acts/c-15.31/index.html>
111. Government of Canada. (2022a, March 25). Reducing Methane Emissions from Canada's Oil and Gas Sector: Discussion Paper [Consultations]. <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/consultation-reducing-methane-emissions-oil-gas-sector.html>
112. Government of Canada. (2022b, April 1). Emissions Reduction Fund. Natural Resources Canada. <https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-funding-opportunities/emissions-reduction-fund/22781>
113. Government of Canada. (2022c, June 8). Canada launches Greenhouse Gas Offset Credit System to Support a Clean, Green Economy [News releases]. <https://www.canada.ca/en/environment-climate-change/news/2022/06/canada-launches-greenhouse-gas-offset-credit-system-to-support-a-clean-green-economy.html>
114. Government of Saskatchewan. (2021). Oil and Gas Emissions Management. Government of Saskatchewan. <https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/oil-and-gas/environmental-protection/oil-and-gas-emissions-management>
115. Groom, N. (2021). Methane Menace: Aerial Survey Spots “Super-emitter” Landfills. <https://www.reuters.com/business/sustainable-business/methane-menace-aerial-survey-spots-super-emitter-landfills-2021-06-18/>

116. Guo, F. (2011, May 17). The “Separation of Two Rights” in Coal Mines: The Gas War Between Local and Central Enterprises. http://news.sohu.com/20110517/n307697966_1.shtml
117. Ha, M., Gutenberger, G., Ou, L., Cai, H., & Hawkins, T. (2022). Opportunities for Recovering Resources from Municipal Wastewater (ANL/ESD-21/11, 1876441, 176194). <https://doi.org/10.2172/1876441>
118. Hamel, L., Lopes, L., Munana, C., & Brodie, M. (2019, November 27). The Kaiser Family Foundation/ Washington Post Climate Change Survey—Views on the Green New Deal. KFF. <https://www.kff.org/report-section/the-kaiser-family-foundation-washington-post-climate-change-survey-green-new-deal/>
119. Hayek, M. N., & Miller, S. M. (2021). Underestimates of Methane from Intensively Raised Animals Could Undermine Goals of Sustainable Development. *Environmental Research Letters*, 16(6), 063006. <https://doi.org/10.1088/1748-9326/ac02ef>
120. Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., & Zhang, Q. (2018). Historical (1750–2014) Anthropogenic Emissions of Reactive Gases and Aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, 11(1), 369–408. <https://doi.org/10.5194/gmd-11-369-2018>
121. Høglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W. (2020). Technical Potentials and Costs for Reducing Global Anthropogenic Methane Emissions in the 2050 Timeframe—Results from the GAINS Model. *Environmental Research Communications*, 2(2), 025004. <https://doi.org/10.1088/2515-7620/ab7457>
122. Hristov, A. N., Kebreab, E., Niu, M., Oh, J., Bannink, A., Bayat, A. R., Boland, T. M., Brito, A. F., Casper, D. P., Crompton, L. A., Dijkstra, J., Eugène, M., Garnsworthy, P. C., Haque, N., Hellwing, A. L. F., Huhtanen, P., Kreuzer, M., Kuhla, B., Lund, P., ... Yu, Z. (2018). Symposium Review: Uncertainties in Enteric Methane Inventories, Measurement Techniques, and Prediction Models. *Journal of Dairy Science*, 101(7), 6655–6674. <https://doi.org/10.3168/jds.2017-13536>
123. Huang, X., Wang, S., Shi, Z., Fang, L., & Yin, C. (2022). Challenges and Strategies for Biogas Production in the Circular Agricultural Waste Utilization Model: A Case Study in Rural China. *Energy*, 241, 122889. <https://doi.org/10.1016/j.energy.2021.122889>
124. IEA. (2021a). Driving Down Methane Leaks from the Oil and Gas Industry – Analysis. <https://www.iea.org/reports/driving-down-methane-leaks-from-the-oil-and-gas-industry>
125. IEA. (2021b). Global coal production, 2018-2021. <https://www.iea.org/data-and-statistics/charts/global-coal-production-2018-2021>
126. IEA. (2022, February 22). Pan-Canadian Framework on Clean Growth and Climate Change – Policies. <https://www.iea.org/policies/6909-pan-canadian-framework-on-clean-growth-and-climate-change>
127. IIASA. (2022). Site Info—GLOBIOM Documentation. <https://iiasa.github.io/GLOBIOM/>
128. IPCC. (2021). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Retrieved October 31, 2022, from https://www.ipcc-nggip.iges.or.jp/public/gp/chinese/gpgaum_cn.html
129. Irakulis-Loitxate, I., Guanter, L., Liu, Y.-N., Varon, D. J., Maasackers, J. D., Zhang, Y., Chulakadabba, A., Wofsy, S. C., Thorpe, A. K., Duren, R. M., Frankenberg, C., Lyon, D. R., Hmiel, B., Cusworth, D. H., Zhang, Y., Segl, K., Gorroño, J., Sánchez-García, E., Sulprizio, M. P., ... Jacob, D. J. (2021). Satellite-Based Survey of Extreme Methane Emissions in the Permian Basin. *Science Advances*, 7(27), eabf4507. <https://doi.org/10.1126/sciadv.abf4507>
130. Jacob, D. J., Varon, D. J., Cusworth, D. H., Dennison, P. E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L. E., Poulter, B., Qu, Z., Thorpe, A. K., Worden, J. R., & Duren, R. M. (2022). Quantifying Methane Emissions from the Global Scale Down to Point Sources Using Satellite Observations of Atmospheric Methane. *Atmospheric Chemistry and Physics*, 22(14), 9617–9646. <https://doi.org/10.5194/acp-22-9617-2022>



131. Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S. S., Vijay, V., Kumar, V., Kumar Vijay, V., & Pant, D. (2020). Valorization of Agricultural Waste for Biogas Based Circular Economy in India: A Research Outlook. *Bioresource Technology*, 304, 123036. <https://doi.org/10.1016/j.biortech.2020.123036>
132. Karacan, C. Ö., Ruiz, F. A., Cotè, M., & Phipps, S. (2011). Coal Mine Methane: A Review of Capture and Utilization Practices with Benefits to Mining Safety and to Greenhouse Gas Reduction. *International Journal of Coal Geology*, 86(2), 121–156. <https://doi.org/10.1016/j.coal.2011.02.009>
133. Keyser, D., Warner, E., & Curley, C. (2015). Quantification of the Potential Gross Economic Impacts of Five Methane Reduction Scenarios. National Renewable Energy Lab. (NREL), Golden, CO (United States). <https://doi.org/10.2172/1215139>
134. Kholod, N., Evans, M., Pilcher, R. C., Roshchanka, V., Ruiz, F., Coté, M., & Collings, R. (2020). Global Methane Emissions from Coal Mining to Continue Growing Even with Declining Coal Production. *Journal of Cleaner Production*, 256, 120489. <https://doi.org/10.1016/j.jclepro.2020.120489>
135. Konschnik, K., & Reuland, F. (2020, February 17). Canada Steps up Its Efforts to Reduce Methane Emissions. IEA. <https://www.iea.org/commentaries/canada-steps-up-its-efforts-to-reduce-methane-emissions>
136. Lamb, B. K., Edburg, S. L., Ferrara, T. W., Howard, T., Harrison, M. R., Kolb, C. E., Townsend-Small, A., Dyck, W., Possolo, A., & Whetstone, J. R. (2015). Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States. *Environmental Science & Technology*, 49(8), 5161–5169. <https://doi.org/10.1021/es505116p>
137. Lau, H. C., Li, H., & Huang, S. (2017). Challenges and Opportunities of Coalbed Methane Development in China. *Energy & Fuels*, 31(5), 4588–4602. <https://doi.org/10.1021/acs.energyfuels.7b00656>
138. Lavoie, T. N., Shepson, P. B., Cambaliza, M. O. L., Stirm, B. H., Conley, S., Mehrotra, S., Faloona, I. C., & Lyon, D. (2017). Spatiotemporal Variability of Methane Emissions at Oil and Natural Gas Operations in the Eagle Ford Basin. *Environmental Science & Technology*, 51(14), 8001–8009. <https://doi.org/10.1021/acs.est.7b00814>
139. Li, L. (2021). It Is Time to Take Care of the Problem of Massive Emptying of Coalbed Methane: At Present, China's Annual Total Emissions of Coalbed Methane Are Large and the Utilization Efficiency Is Low, Which Significantly Increases Carbon Emissions. <https://m.bjx.com.cn/mnews/20210602/1155783.shtml>
140. Lin, J., Khanna, N., Liu, X., Wang, W., Gordon, J., & Dai, F. (2022). Opportunities to Tackle Short-Lived Climate Pollutants and Other Greenhouse Gases for China. *Science of the Total Environment*, 842, 156842. <https://doi.org/10.1016/j.scitotenv.2022.156842>
141. Lin, X., Zhang, W., Crippa, M., Peng, S., Han, P., Zeng, N., Yu, L., & Wang, G. (2021). A Comparative Study of Anthropogenic CH₄ Emissions over China Based on the Ensembles of Bottom-Up Inventories. *Earth System Science Data*, 13(3), 1073–1088. <https://doi.org/10.5194/essd-13-1073-2021>
142. Liu, G., Peng, S., Lin, X., Ciais, P., Li, X., Xi, Y., Lu, Z., Chang, J., Saunio, M., Wu, Y., Patra, P., Chandra, N., Zeng, H., & Piao, S. (2021). Recent Slowdown of Anthropogenic Methane Emissions in China Driven by Stabilized Coal Production. *Environmental Science & Technology Letters*, 8(9), 739–746. <https://doi.org/10.1021/acs.estlett.1c00463>
143. Lowe, M., & Skillern, R. L. (2021). Find Measure Fix. Datu Research. <https://www.edf.org/sites/default/files/content/FindMeasureFixReport2021.pdf>
144. Lu, P., Zhou, L., Cheng, S., Zhu, X., Yuan, T., Chen, D., & Feng, Q. (2020). Main Challenges of Closed/Abandoned Coal Mine Resource Utilization in China. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 42(22), 2822–2830. <https://doi.org/10.1080/15567036.2019.1618992>

145. Lu, X., Jacob, D. J., Zhang, Y., Maasackers, J. D., Sulprizio, M. P., Shen, L., Qu, Z., Scarpelli, T. R., Nesser, H., Yantosca, R. M., Sheng, J., Andrews, A., Parker, R. J., Boesch, H., Bloom, A. A., & Ma, S. (2021a). Global Methane Budget and Trend, 2010–2017: Complementarity of Inverse Analyses Using in Situ (Globalviewplus CH₄ Obspack) and Satellite (GOSAT) Observations. *Atmospheric Chemistry and Physics*, 21(6), 4637–4657. <https://doi.org/10.5194/acp-21-4637-2021>
146. Lu, Y., Zhang, H., Zhou, Z., Ge, Z., Chen, C., Hou, Y., & Ye, M. (2021b). Current Status and Effective Suggestions for Efficient Exploitation of Coalbed Methane in China: A Review. *Energy & Fuels*, 35(11), 9102–9123. <https://doi.org/10.1021/acs.energyfuels.1c00460>
147. Maasackers, J. D., Jacob, D. J., Sulprizio, M. P., Scarpelli, T. R., Nesser, H., Sheng, J., Zhang, Y., Lu, X., Bloom, A. A., Bowman, K. W., Worden, J. R., & Parker, R. J. (2021). 2010–2015 North American Methane Emissions, Sectoral Contributions, and Trends: A High-Resolution Inversion of GOSAT Observations of Atmospheric Methane. *Atmospheric Chemistry and Physics*, 21(6), 4339–4356. <https://doi.org/10.5194/acp-21-4339-2021>
148. MacKay, K., Lavoie, M., Bourlon, E., Atherton, E., O’Connell, E., Baillie, J., Fougère, C., & Risk, D. (2021). Methane Emissions from Ppstream Oil and Gas Production in Canada are Underestimated. *Scientific Reports*, 11(1), Article 1. <https://doi.org/10.1038/s41598-021-87610-3>
149. Mahajan, M., Ashmore, O., Orvis, R., & Gopal, A. (2022). Modeling the Inflation Reduction Act Using the Energy Policy Simulator. 8. https://energyinnovation.org/wp-content/uploads/2022/08/Modeling-the-Inflation-Reduction-Act-with-the-US-Energy-Policy-Simulator_August.pdf
150. Malley, C. S., Henze, D. K., Kuylenstierna, J. C. I., Vallack, H. W., Davila, Y., Anenberg, S. C., Turner, M. C., & Ashmore, M. R. (2017). Updated Global Estimates of Respiratory Mortality in Adults ≥30 Years of Age Attributable to Long-Term Ozone Exposure. *Environmental Health Perspectives*, 125(8), 087021. <https://doi.org/10.1289/EHP1390>
151. Mancl, K. (2020, June 11). Capturing Greenhouse Gases in China’s Countryside. *New Security Beat*. <https://www.newsecuritybeat.org/2020/06/capturing-greenhouse-gases-chinas-countryside/>
152. MARA, & NDRC. (2022, May 7). Implementation Plan on Emissions Reduction and Carbon Sequestration for Agriculture and Rural Areas. http://www.kjs.moa.gov.cn/hbny/202206/t20220629_6403713.htm
153. MEE. (2001, January 1). Discharge Standard of Pollutants for Livestock and Poultry Breeding. https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/shjbh/swrwpfbz/200301/t20030101_66550.shtml
154. MEE. (2009, February 18). Policy for Sludge Treatment and Disposal & Pollution Prevention and Control Technology in Urban Sewage Treatment Plants (Trial). https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/wrfzjzsc/200903/t20090303_134820.shtml
155. MEE. (2019, December 13). Notice on Further Strengthening the Management of Environmental Impact Assessment in the Oil and Gas Industry (2019). http://www.gov.cn/zhengce/zhengce-ku/2019-12/20/content_5462708.htm
156. MEE. (2020, December 31). Administration of National Carbon Emission Trading (Trial). https://www.mee.gov.cn/xxgk2018/xxgk/xxgk02/202101/t20210105_816131.html
157. MEE. (2022, May 26). The Ministry of Ecology and Environment Held a Regular Press Conference in May. https://www.mee.gov.cn/ywdt/zbft/202205/t20220526_983531.shtml
158. MEE, Ministry of Agriculture and Rural Affairs, Ministry of Housing and Urban-Rural Development, Ministry of Water Resources, & The National Rural Revitalization Administration. (2022, February 8). Action Plan for Agricultural and Rural Pollution Control (2021-2025) (2022). http://nrra.gov.cn/art/2022/2/8/art_46_193854.html
159. MEE, NDRC, & NEA. (2020, October). Notice on Further Strengthening the Management of Environmental Impact Assessment of Coal Resources Development. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202012/t20201202_811127.html



160. MEE, & State Administration for Market Regulation. (2020, December 8). Emission Standard of Air Pollutants for Onshore Oil and Gas Exploitation and Production Industry. https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqjhjhb/dqgdwrywrwpfbz/202012/t20201225_814811.shtml
161. MEM. (2022). Coal Mine Safety Regulations. <https://mse.xauat.edu.cn/info/1018/2456.htm>
162. Mendelevitch, R., Hauenstein, C., & Holz, F. (2019). The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide? *Climate Policy*, 19(10), 1310–1324. <https://doi.org/10.1080/14693062.2019.1641462>
163. MHURD. (2014, January 9). Guidelines for Overall Management of Urban and Rural Sewage in County (City) Regions (on Trail). <http://www.water8848.com/news/201612/21/86502.html>
164. Miller, S. M., Michalak, A. M., Detmers, R. G., Hasekamp, O. P., Bruhwiler, L. M. P., & Schwietzke, S. (2019). China's Coal Mine Methane Regulations Have Not Curbed Growing Emissions. *Nature Communications*, 10(1), 303. <https://doi.org/10.1038/s41467-018-07891-7>
165. Minamikawa, K., Takahashi, M., Makino, T., Tago, K., & Hayatsu, M. (2015). Irrigation with oxygen-nanobubble water can reduce methane emission and arsenic dissolution in a flooded rice paddy. *Environmental Research Letters*, 10(8), 084012. <https://doi.org/10.1088/1748-9326/10/8/084012>
166. MARA, & NDRC. (2022, June 29). Implementation Plan on Emissions Reduction and Carbon Sequestration for Agriculture and Rural Areas (2022). <http://www.kjs.moa.gov.cn/hbny/202206/P020220630332772898679.pdf>
167. Ministry of Construction. (2004, February 19). Technical Specification for Sanitary Landfill of Domestic Waste (CJJ17-2004). <http://www.slhwbj.com/htm/154/889.html>
168. Ministry of Environmental Protection. (2008). Coalbed Methane (Coal Mine Gas) Emission Standards. <http://www.safehoo.com/Standard/Trade/Coal/202010/5614206.shtml>
169. Ministry of Natural Resources. (2018, December 29). Announcement of the Ministry of Natural Resources on the “Three Rates” Minimum Indicator Requirements (Trial) for the Rational Development and Utilization of Mineral Resources such as Coalbed Methane, Oil Shale, Silver, Zirconium, Wollastonite, Diatomite and Salt. http://www.gov.cn/xinwen/2019-01/09/content_5356064.htm
170. MOF. (2016). Notice on Subsidy Standards for Coalbed Methane (Gas) Development and Utilization during the ‘Thirteenth Five-Year Plan’ Period. https://www.jcgov.gov.cn/dtxx/ztzl/2019nzt/zdnnng-mptbdlpz/zcjd_21348/201904/t20190426_365506.shtml
171. MOF. (2019). Supplementary Notice of the Ministry of Finance on the Interim Measures for the Administration of Special Funds for Renewable Energy Development (2019). http://www.law-lib.com/law/law_view.asp?id=646828
172. MOF, & State Taxation Administration. (2007, April 11). Notice on Tax Policies Related to Accelerating Coalbed Methane Extraction (2007). <http://www.chinatax.gov.cn/n810341/n810765/n812176/n812798/c1195054/content.html>
173. MOHURD. (2003, January 16). Notice of the Ministry of Construction on Strengthening Gas Management in Domestic Waste Landfills (2002). http://www.law-lib.com/law/law_view.asp?id=42502
174. MOHURD. (2009, September 21). Construction Standard for Sanitary Landfill Treatment Projects of Domestic Waste (2009). <https://www.cn-hw.net/news/201009/17/48951.html>
175. MOHURD, National Development and Reform Commission (NDRC), & Ministry of Environmental Protection (now is Ministry of Ecology and Environment (MEE)). (2010, April 22). Guidelines for Domestic Waste Treatment Technology (2000). https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/wrfz-jszc/201005/t20100520_189725.shtml
176. Monaco, A., Ross, K., Waskow, D., & Ge, M. (2021, September 17). How Methane Emissions Contribute to Climate Change. <https://www.wri.org/insights/methane-gas-emissions-climate-change>

194. NDRC, Ministry of Science and Technology, Ministry of Foreign Affairs, & Ministry of Finance (MOF). (2005). Measures for the Operation and Management of Clean Development Mechanism Projects. http://www.gov.cn/ziliao/flfg/2005-12/08/content_121028.htm
195. NDRC, & NEA. (2022, January 29). “14th Five-Year Plan” Modern Energy System Planning. http://zfxgk.nea.gov.cn/2022-01/29/c_1310524241.htm
196. NEA. (2007). Implementation Opinions of the Ministry of Finance on Subsidies for the Development and Utilization of Coalbed Methane (Gas). http://www.nea.gov.cn/2007-05/10/c_131109779.htm
197. NEA. (2016a, September 14). Notice of the National Energy Administration on Issuing the Shale Gas Development Plan (2016-2020). http://www.gov.cn/xinwen/2016-09/30/content_5114313.htm
198. NEA. (2016b, November). The 13th Five-Year Plan for the Development and Utilization of Coalbed Methane (Coal Mine Gas). <https://policy.asiapacificenergy.org/sites/default/files/%E7%85%A4%E5%B1%82%E6%B0%94%E5%8F%91%E5%B1%95%E2%80%9C%E5%8D%81%E4%B8%89%E4%BA%94%E2%80%9D%E8%A7%84%E5%88%92.pdf>
199. NEA. (2021, December 29). Opinions on Implementing Accelerating Rural Energy Transformation and Development to Promote Rural Revitalization. http://www.gov.cn/zhengce/zhengce-ku/2022-01/07/content_5666809.htm
200. New Zealand Ministry for the Environment. (2021, November 3). Climate Change Response Act 2002. <https://www.legislation.govt.nz/act/public/2002/0040/latest/DLM158584.html>
201. NGER. (2019, May 17). About the National Greenhouse and Energy Reporting Scheme. <https://www.cleanenergyregulator.gov.au/NGER/About-the-National-Greenhouse-and-Energy-Reporting-scheme>
202. NZAGRC. (2021, May 18). Mpengethane Research Programme. New Zealand Agricultural Greenhouse Gas Research Centre. <https://www.nzagrc.org.nz/domestic/methane-research-programme/>
203. Olivier, J. G. J., & Peters, J. A. H. (2020). Trends in Global CO₂ and Total Greenhouse Gas Emissions: 2019 Report. https://www.pbl.nl/sites/default/files/downloads/pbl-2020-trends-in-global-co2-and-total-greenhouse-gas-emissions-2019-report_4068.pdf
204. Parikh, M. (2021, November 29). The Economic Impact of Cutting Methane Emissions – Michigan Journal of Economics. Michigan Journal of Economics. <https://sites.lsa.umich.edu/mje/2021/11/29/the-economic-impact-of-cutting-methane-emissions/>
205. Peng, S., Piao, S., Bousquet, P., Ciais, P., Li, B., Lin, X., Tao, S., Wang, Z., Zhang, Y., & Zhou, F. (2016). Inventory of Anthropogenic Methane Emissions in Mainland China from 1980 to 2010. *Atmospheric Chemistry and Physics*, 16(22), 14545–14562. <https://doi.org/10.5194/acp-16-14545-2016>
206. PetroChina News. (2021). China Oil and Gas Methane Alliance was Established. <http://news.cnpc.com.cn/system/2021/05/19/030033272.shtml>
207. PHMSA. (2022, May 24). USDOT Begins Accepting Applications for President Biden’s Bipartisan Infrastructure Law Program Designed to Improve Pipeline Safety, Reduce Gas Distribution Leaks in Communities Across the Country. <https://www.phmsa.dot.gov/news/usdot-begins-accepting-applications-president-bidens-bipartisan-infrastructure-law-program>
208. Plant, G., Kort, E. A., Brandt, A. R., Chen, Y., Fordice, G., Gorchov Negron, A. M., Schwietzke, S., Smith, M., & Zavala-Araiza, D. (2022). Inefficient and Unlit Natural Gas Flares Both Emit Large Quantities of Methane. *Science (New York, N.Y.)*, 377(6614), 1566–1571. <https://doi.org/10.1126/science.abq0385>
209. Province of British Columbia. (2022). Greenhouse Gas Emission Offset Projects. Province of British Columbia. <https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/offset-projects>
210. Qiu, H., Cai, Y., Bai, J., & Sun, D. (2013). Research on the Implementation Effect of the Subsidy Policy for Rural Household Biogas in China (in Chinese). 34(02), 85-92+112. <https://doi.org/10.13246/j.cnki.iae.2013.02.001>

211. Qu, Z., Jacob, D. J., Shen, L., Lu, X., Zhang, Y., Scarpelli, T. R., Nesser, H., Sulprizio, M. P., Maasakkers, J. D., Bloom, A. A., Worden, J. R., Parker, R. J., & Delgado, A. L. (2021). Global Distribution of Methane Emissions: A Comparative Inverse Analysis of Observations from the TROPOMI and GOSAT Satellite Instruments. *Atmospheric Chemistry and Physics*, 21(18), 14159–14175. <https://doi.org/10.5194/acp-21-14159-2021>
212. Ran, Z., & Zhang, Y. (2022, June 8). Global Methane Reduction in Action: Brazil’s “National Zero Methane Plan.” Weixin Official Accounts Platform. http://mp.weixin.qq.com/s?__biz=MzAwNTE1M-jgxNA==&mid=2649868733&idx=1&sn=8c6c660e24fd5e55211af8c9a4a75fb3&chksm=832460fc-b453e9eaa9cbfb542e79dcffef80e76c7814f810c2908a6d1bb6212798b6b3f4775f#rd
213. Reid, M. C., Guan, K., Wagner, F., & Mauzerall, D. L. (2014). Global Methane Emissions from Pit Latrines. *Environmental Science & Technology*, 48(15), 8727–8734. <https://doi.org/10.1021/es501549h>
214. Reisinger, A., & Leahy, S. (2019). Scientific Aspects of New Zealand’s 2050 Emission Targets. 20. <https://www.nzagrc.org.nz/assets/Publications/NZAGRC-Report-Scientific-aspects-of-2050-methane-targets.pdf>
215. RRS. (2021, July 20). Data Corner: Digging into Landfill Methane Recovery. *Resource Recycling News*. <https://resource-recycling.com/recycling/2021/07/20/data-corner-digging-into-landfill-methane-recovery/>
216. Rutherford, J. S., Sherwin, E. D., Ravikumar, A. P., Heath, G. A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., & Brandt, A. R. (2021). Closing the Methane Gap in US Oil and Natural Gas Production Emissions Inventories. *Nature Communications*, 12(1), Article 1. <https://doi.org/10.1038/s41467-021-25017-4>
217. Sarofim, M. C., Waldhoff, S. T., & Anenberg, S. C. (2015). Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, 66(1), 45–63. <https://doi.org/10.1007/s10640-015-9937-6>
218. Schwietzke, S., Griffin, W. M., Matthews, H. S., & Bruhwiler, L. M. P. (2014). Global Bottom-Up Fossil Fuel Fugitive Methane and Ethane Emissions Inventory for Atmospheric Modeling. *ACS Sustainable Chemistry & Engineering*, 2(8), 1992–2001. <https://doi.org/10.1021/sc500163h>
219. Searchinger, T., & Waite, R. (2014). More Rice, Less Methane. <https://www.wri.org/insights/more-rice-less-methane>
220. Seiple, T. E., Skaggs, R. L., Fillmore, L., & Coleman, A. M. (2020). Municipal Wastewater Sludge as A Renewable, Cost-Effective Feedstock for Transportation Biofuels Using Hydrothermal Liquefaction. *Journal of Environmental Management*, 270, 110852. <https://doi.org/10.1016/j.jenvman.2020.110852>
221. Shaanxi Province Department of Agriculture. (2011, August 4). Research Report on Rural Household Biogas of Village Economy. <https://biogas.cn.caas.cn/cy/z/fzx/z/7dde2847a4ae4fa88c-383692fa2853d8.htm>
222. Shah, T., & Otterpohl, R. (2016). Building Resilience to Climate Change Induced Extreme Weather Events through Agriculture with a Focus on the System of Rice Intensification.
223. Sheng, J., Song, S., Zhang, Y., Prinn, R. G., & Janssens-Maenhout, G. (2019). Bottom-Up Estimates of Coal Mine Methane Emissions in China: A Gridded Inventory, Emission Factors, and Trends. *Environmental Science & Technology Letters*, 6(8), 473–478. <https://doi.org/10.1021/acs.estlett.9b00294>
224. Sheng, J., Tunnicliffe, R., Ganesan, A. L., Maasakkers, J. D., Shen, L., Prinn, R. G., Song, S., Zhang, Y., Scarpelli, T., Bloom, A. A., Rigby, M., Manning, A. J., Parker, R. J., Boesch, H., Lan, X., Zhang, B., Zhuang, M., & Lu, X. (2021). Sustained Methane Emissions from China after 2012 Despite Declining Coal Production and Rice-Cultivated Area. *Environmental Research Letters*, 16(10), 104018. <https://doi.org/10.1088/1748-9326/ac24d1>



225. Shindell, D. T., Fuglestvedt, J. S., & Collins, W. J. (2017). The Social Cost of Methane: Theory and Applications. *Faraday Discussions*, 200, 429–451. <https://doi.org/10.1039/C7FD00009J>
226. Silverstein, K. (2021, May 10). Capturing Methane from Oil and Gas Operations Is Doable and Profitable. *Forbes*. <https://www.forbes.com/sites/kensilverstein/2021/05/10/capturing-methane-from-oil-and-gas-operations-is-doable-and-profitable/>
227. Song, H., Zhuo, H., Fu, S., & Ren, L. (2020). Air Pollution Characteristics, Health Risks, and Source Analysis in Shanxi Province, China. *Environmental Geochemistry and Health*, 43(1), 391–405. <https://doi.org/10.1007/s10653-020-00723-y>
228. Spokas, K., Bogner, J., Corcoran, M., & Walker, S. (2015). From California Dreaming to California Data: Challenging Historic Models for Landfill CH₄ Emissions. *Elementa: Science of the Anthropocene*, 3, 000051. <https://doi.org/10.12952/journal.elementa.000051>
229. State Administration of Work Safety, & State Coal Mine Safety Supervision Bureau. (2016). Coal Mine Safety Regulations (2016). https://www.mem.gov.cn/gk/gwgg/agwzfl/zjl_01/201603/W020190705622814170708.pdf
230. State of Queensland. (2021). Mineral Resources Act 1989. <https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-1989-110>
231. Statista. (2022). Methane Emissions from Oil & Gas by Country 2020. Statista. <https://www.statista.com/statistics/1263959/methane-emissions-from-oil-and-gas-by-country/>
232. Stavert, A. R., Saunio, M., Canadell, J. G., Poulter, B., Jackson, R. B., Regnier, P., Lauerwald, R., Raymond, P. A., Allen, G. H., Patra, P. K., Bergamaschi, P., Bousquet, P., Chandra, N., Ciais, P., Gustafson, A., Ishizawa, M., Ito, A., Kleinen, T., Maksyutov, S., ... Zhuang, Q. (2022). Regional Trends and Drivers of the Global Methane Budget. *Global Change Biology*, 28(1), 182–200. <https://doi.org/10.1111/gcb.15901>
233. Stokes, S., La, M., & Lowe, M. (2014). The Emerging U.S. Methane Mitigation Industry. *Datu Research*. https://www.daturesearch.com/wp-content/uploads/Methane-Mitigation-Industry-Report_Final.pdf
234. Tao, S., Chen, S., & Pan, Z. (2019). Current Status, Challenges, and Policy Suggestions for Coalbed Methane Industry Development in China: A Review. *Energy Science & Engineering*, 7(4), 1059–1074. <https://doi.org/10.1002/ese3.358>
235. The State Council. (1984, August 7). A Report on the Further Development of Biogas. http://www.nea.gov.cn/2015-12/13/c_131051723.htm
236. The State Council. (1985, June 1). Opinions of the Environmental Protection Committee of the State Council on Developing Ecological Agriculture and Strengthening Agricultural Ecological Environmental Protection (1985). <https://www.66law.cn/tiaoli/148672.aspx>
237. The State Council. (1994). Rules for the Implementation of the Mineral Resources Law of the People's Republic of China. <https://www.lawinfochina.com/display.aspx?id=12169&lib=law>
238. The State Council. (2006). Opinions on Accelerating the Drainage and Utilization of Coalbed Methane (Coal Mine Gas). http://www.gov.cn/zhengce/content/2008-03/28/content_2576.htm
239. The State Council. (2011). The Twelfth Five-Year Plan for Controlling Greenhouse Gas Emissions. http://www.gov.cn/zwzkg/2012-01/13/content_2043645.htm
240. The State Council. (2012, April 19). Twelfth Five-Year Plan for the Construction of National Urban Household Waste Harmless Treatment Facilities (2012). http://www.gov.cn/zwzkg/2012-05/04/content_2129302.htm
241. The State Council. (2016). The Thirteenth Five-Year Plan for Controlling Greenhouse Gas Emissions. <http://sthj.gansu.gov.cn/sthj/c114861/201909/9f2c11a838a343159e196ec577dce861/files/91277859ddb44ae4be042c91fe9af14a.pdf>

242. The State Council. (2021a, October 24). Working Guidelines for Carbon Dioxide Peak and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy. http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm
243. The State Council. (2021b, October 26). Action Plan for Reaching Carbon Emissions Peak before 2030. http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm
244. The State Council. (2022, February 11). Main Indicators for Promoting Agricultural and Rural Modernization in the 14th Five-Year Plan(2022). http://www.gov.cn/zhengce/content/2022-02/11/content_5673082.htm
245. The World Bank. (2020, September 10). With Carbon Finance, Brazil Landfills Reduce Methane Emissions and Turn Trash into Treasure. World Bank. <https://www.worldbank.org/en/news/feature/2020/09/10/with-carbon-finance-brazil-landfills-reduce-methane-emissions-and-turn-trash-into-treasure>
246. The World Bank. (2022). The World Bank Project Database. World Bank. <https://projects.worldbank.org/en/projects-operations/projects-list>
247. Trench Rossi Watanabe. (2022, March 29). Brazil: Government Implements Zero Methane Program and Federal Strategy Encouraging the Sustainable Use of Biogas and Biomethane. Trench Rossi Watanabe. <https://www.trenchrossi.com/en/legal-alerts/brazil-government-implements-zero-methane-program-and-federal-strategy-encouraging-the-sustainable-use-of-biogas-and-biomethane/>
248. Tricarico, J. M., de Haas, Y., Hristov, A. N., Kebreab, E., Kurt, T., Mitloehner, F., & Pitta, D. (2022). Symposium Review: Development of a Funding Program to Support Research on Enteric Methane Mitigation from Ruminants. *Journal of Dairy Science*. <https://doi.org/10.3168/jds.2021-21397>
249. UNECE. (2021). Best Practice Guidance for Effective Management of Coal Mine Methane at National Level: Monitoring, Reporting, Verification and Mitigation. <https://science.house.gov/staff-reports/seeing-ch4-clearly-science-based-approaches-to-methane-monitoring-in-the-oil-and-gas-sector>
250. UNEP. (2011). Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers. <https://wedocs.unep.org/xmlui/handle/20.500.11822/8048>
251. UNFCCC. (2022). CDM: Project Activities. <https://cdm.unfccc.int/Projects/projsearch.html>
252. U.S. Congress. (2022, August 16). H.R.5376—Inflation Reduction Act of 2022 (2021/2022) [Legislation]. <http://www.congress.gov/>
253. U.S. House of Representative Committee on Science. (2022). Seeing CH4 Clearly: Science-Based Approaches to Methane Monitoring in the Oil and Gas Sector | House Committee on Science, Space and Technology. <https://science.house.gov/staff-reports/seeing-ch4-clearly-science-based-approaches-to-methane-monitoring-in-the-oil-and-gas-sector>
254. USDA. (2021, June 21). Food Consumption and Nutrient Intakes. <https://www.ers.usda.gov/Data/FoodConsumption/>
255. Vaughn, T. L., Bell, C. S., Pickering, C. K., Schwietzke, S., Heath, G. A., Pétron, G., Zimmerle, D. J., Schnell, R. C., & Nummedal, D. (2018). Temporal Variability Largely Explains Top-down/Bottom-up Difference in Methane Emission Estimates from a Natural Gas Production Region. *Proceedings of the National Academy of Sciences*, 115(46), 11712–11717. <https://doi.org/10.1073/pnas.1805687115>
256. Wang, D., Ye, W., Wu, G., Li, R., Guan, Y., Zhang, W., Wang, J., Shan, Y., & Hubacek, K. (2022a). Greenhouse Gas Emissions from Municipal Wastewater Treatment Facilities in China from 2006 to 2019. *Scientific Data*, 9(1), Article 1. <https://doi.org/10.1038/s41597-022-01439-7>
257. Wang, F., Maksyutov, S., Janardanan, R., Tsuruta, A., Ito, A., Morino, I., Yoshida, Y., Tohjima, Y., Kaiser, J. W., Janssens-Maenhout, G., Lan, X., Mammarella, I., Lavric, J. V., & Matsunaga, T. (2021). Interannual Variability on Methane Emissions in Monsoon Asia Derived from GOSAT and Surface Observations. *Environmental Research Letters*, 16(2), 024040. <https://doi.org/10.1088/1748-9326/abd352>



258. Wang, M., Wu, L., & Guo, X. (2022b). Application of Grey Model in Influencing Factors Analysis and Trend Prediction of Carbon Emission in Shanxi Province. *Environmental Monitoring and Assessment*, 194(8), 542. <https://doi.org/10.1007/s10661-022-10088-7>
259. Watson, D., & LaMair, E. (2021). Investor Guidance on Epa Proposed Standards for Oil and Natural Gas Methane Emissions. <https://business.edf.org/files/Investor-Guide-to-Commenting-on-EPA-Methane-Rule-Proposal.pdf>
260. Weller, Z. D., Hamburg, S. P., & von Fischer, J. C. (2020). A National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems. *Environmental Science & Technology*, 54(14), 8958–8967. <https://doi.org/10.1021/acs.est.0c00437>
261. West, J. J., & Fiore, A. M. (2005). Management of Tropospheric Ozone by Reducing Methane Emissions. *Environmental Science & Technology*, 39(13), 4685–4691. <https://doi.org/10.1021/es048629f>
262. WHO. (2021, September 22). New Who Global Air Quality Guidelines Aim to Save Millions of Lives from Air Pollution. <https://www.who.int/news/item/22-09-2021-new-who-global-air-quality-guidelines-aim-to-save-millions-of-lives-from-air-pollution>
263. Wolf, A. (2021, September 2). Bankruptcies Fueling Environmental Crisis at Abandoned Oil Wells. <https://news.bloomberglaw.com/bankruptcy-law/bankruptcies-fueling-environmental-crisis-at-abandoned-oil-wells>
264. Worden, J. R., Cusworth, D. H., Qu, Z., Yin, Y., Zhang, Y., Bloom, A. A., Ma, S., Byrne, B. K., Scarpelli, T., Maasackers, J. D., Crisp, D., Duren, R., & Jacob, D. J. (2022). The 2019 Methane Budget and Uncertainties at 1° Resolution and Each Country Through Bayesian Integration of Gosat Total Column Methane Data and a Priori Inventory Estimates. *Atmospheric Chemistry and Physics*, 22(10), 6811–6841. <https://doi.org/10.5194/acp-22-6811-2022>
265. Xin, F., Xiao, X., Dong, J., Zhang, G., Zhang, Y., Wu, X., Li, X., Zou, Z., Ma, J., Du, G., Doughty, R. B., Zhao, B., & Li, B. (2020). Large Increases of Paddy Rice Area, Gross Primary Production, and Grain Production in Northeast China During 2000–2017. *Science of The Total Environment*, 711, 135183. <https://doi.org/10.1016/j.scitotenv.2019.135183>
266. Xu, A., Wu, Y., Chen, Z., Wu, G., Wu, Q., Ling, F., Huang, W., & Hu, H.-Y. (2020). Towards the New Era of Wastewater Treatment of China: Development History, Current Status, and Future Directions. *Water Cycle*, 1. <https://doi.org/10.1016/j.watcyc.2020.06.004>
267. Xu, M. (2022, July 14). UPDATE 2-China's June Daily Coal Output Jumps on Peak Summer Demand. Reuters. <https://www.reuters.com/article/china-economy-output-coal-idUSL1N2YW044>
268. Xu, M., & Stanway, D. (2022, January 18). China Launches Campaign to Plug Greenhouse Gas Monitoring Gap. Reuters. <https://www.reuters.com/world/china/china-launches-campaign-plug-greenhouse-gas-monitoring-gap-2022-01-19/>
269. Xu, Q., & Wang, Z. (2017). Research on Quantitative Relationship Between Gas Drainage Volume per ton and Facility Rate per million tons. *China Coal*, 43(4), 123–127. <https://doi.org/10.19880/j.cnki.ccm.2017.04.026>
270. Yang, J., Zhou, Q., & Zhang, J. (2017). Moderate Wetting and Drying Increases Rice Yield and Reduces Water Use, Grain Arsenic Level, and Methane Emission. *The Crop Journal*, 5(2), 151–158. <https://doi.org/10.1016/j.cj.2016.06.002>
271. Yang, L., Cui, Y., & Wang, G. (2021). Analysis of Technical and Regulational Aspects Affecting China CBM Progresses. 46(8), 2400–2411. <https://doi.org/10.13225/j.cnki.jccs.2021.0760>
272. Yang, M. (2009). Climate Change and Energy Policies, Coal and Coalmine Methane in China. *Energy Policy*, 37(8), 2858–2869. <https://doi.org/10.1016/j.enpol.2009.02.048>
273. Yin, D., Liu, W., Zhai, N., Wang, Y., Ren, C., & Yang, G. (2017). Regional Differentiation of Rural Household Biogas Development and Related Driving Factors in China. *Renewable and Sustainable Energy Reviews*, 67, 1008–1018. <https://doi.org/10.1016/j.rser.2016.09.023>

274. Zavala-Araiza, D., Alvarez, R. A., Lyon, D. R., Allen, D. T., Marchese, A. J., Zimmerle, D. J., & Hamburg, S. P. (2017). Super-Emitters in Natural Gas Infrastructure Are Caused by Abnormal Process Conditions. *Nature Communications*, 8(1), Article 1. <https://doi.org/10.1038/ncomms14012>
275. Zhang, B., Chen, G. Q., Li, J. S., & Tao, L. (2014). Methane Emissions of Energy Activities in China 1980–2007. *Renewable and Sustainable Energy Reviews*, 29, 11–21. <https://doi.org/10.1016/j.rser.2013.08.060>
276. Zhang, J. (2021). Analysis of the Problems Existing in the Gas Monitoring System and the Analysis of Its Transformation and Application. *Inner Mongolia Coal Economy*, 02, 191–192. <https://doi.org/10.13487/j.cnki.imce.019321>
277. Zhang, Q., Smith, K., Zhao, X., Jin, X., Wang, S., Shen, J., & Ren, Z. J. (2021a). Greenhouse Gas Emissions Associated with Urban Water Infrastructure: What We Have Learnt from China’s Practice. *WIREs Water*, 8(4), e1529. <https://doi.org/10.1002/wat2.1529>
278. Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J. D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M. P., Varon, D. J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R. A., Lorente, A., Hamburg, S. P., Aben, I., & Jacob, D. J. (2020). Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space. *Science Advances*, 6(17), eaaz5120. <https://doi.org/10.1126/sciadv.aaz5120>
279. Zhang, Y., Jacob, D. J., Lu, X., Maasakkers, J. D., Scarpelli, T. R., Sheng, J.-X., Shen, L., Qu, Z., Sulprizio, M. P., Chang, J., Bloom, A. A., Ma, S., Worden, J., Parker, R. J., & Boesch, H. (2021b). Attribution of the Accelerating Increase in Atmospheric Methane During 2010–2018 by Inverse Analysis of GOSAT Observations. *Atmospheric Chemistry and Physics*, 21(5), 3643–3666. <https://doi.org/10.5194/acp-21-3643-2021>
280. Zhao, A., O’Keefe, K., McJeon, H., Kyle, C.-S., Cui, R., Feldmann, J., Kennedy, K., Kennedy, K., Meisel, J., Nilov, D., Rajpurohit, S., & Hultman, N. (2022). An “ALL-IN” Pathway to 2030: U.S. Methane Emissions Reduction Potential. https://cgs.umd.edu/sites/default/files/2022-08/All-In%20to%202030_Methane.pdf
281. Zhao, X., Jin, X., Guo, W., Zhang, C., Shan, Y., Du, M., Tillotson, M., Yang, H., Liao, X., & Li, Y. (2019). China’s Urban Methane Emissions from Municipal Wastewater Treatment Plant. *Earth’s Future*, 7. <https://doi.org/10.1029/2018EF001113>
282. Zhong, B., Zhang, B., Tang, X., Gao, J., & Sun, X. (2021). Methane Emission Controls and Related Scientific Issues in China’s Natural Gas Industry Under the Goal of Carbon Neutrality. *China Mining Magazine*, 30(04), 1–9. https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2021&filename=ZGKA202104002&uniplatform=NZKPT&v=iPeKQqemROMksm_fIM9CL4orvX-kHfTGPgmjAt43CVMYkX89VnCwg2XJ5x2wSsQ3m
283. Zhu, T., Bian, W., Zhang, S., Di, P., & Nie, B. (2017). An Improved Approach to Estimate Methane Emissions from Coal Mining in China. *Environmental Science & Technology*, 51(21), 12072–12080. <https://doi.org/10.1021/acs.est.7b01857>
284. Zhu, Y. (2021, January 11). The “Thirteenth Five-Year Plan” Goal has Failed Again. Why Does Coalbed Methane Repeatedly Submit Low Scores? <https://baijiahao.baidu.com/s?id=1688554866306333071&wfr=spider&for=pc>



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