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China's Methane Mitigation Potential:
An Assessment of Costs and Uncertainties through 2060

Nina Khanna, Jiang Lin, Xu Liu[1] and Wenjun Wang[2]
[1]Peking University
[2]University of California, Berkeley

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1. Introduction

There is increasing recognition that limiting global temperature increase to below 1.5° Celsius (C) requires going beyond reducing carbon dioxide (CO_2) emissions to also mitigate emissions of non-CO_2 greenhouse gases (GHGs) (IPCC, 2018). Emissions of methane, a short-lived climate pollutant and potent greenhouse gas, have contributed to approximately 30% of the current rise in global average temperatures (UNEP & CCAC, 2021; IEA, 2023). Reducing methane emissions is critical to slowing the adverse impacts of climate change in the near term and could help avoid nearly 0.3C of global temperature increase by the 2040s (UNEP & CCAC, 2021). Although methane has a shorter atmospheric lifetime than CO_2 (12 years vs. 100 years), its global warming impact is up to 83 times greater than CO_2 over a 20-year timeframe (GWP20), and up to 29 time greater over a 100-year timeframe (GWP100) (IPCC, 2021). By 2030, measures that reduce methane can cut warming more significantly than those targeting only CO_2 emissions, due in part to reductions of co-emitted pollutant aerosol particles from fossil fuel combustion that help cool the planet (Dreyfus et al., 2022). Additionally, because methane emissions contribute to ozone pollution and accompanying adverse effects on human health and agricultural productivity, its reduction can provide co-benefits in improved air quality, better health conditions, and increased crop yields (UNEP & CCAC, 2021).

China is the world's largest methane emitter, accounting for nearly one-fifth of total global methane emissions (UNEP & CCAC, 2021). China's national climate change policies did not focus significantly on methane until the early 2010s, although prior Clean Development Mechanism projects had included methane mitigation (Yu et al., 2022). More recently, China's focus on methane mitigation in its climate change strategy has been elevated in both the domestic and international arenas. Domestically, China's 14^{th} Five-Year Plan for national economic development, endorsed in 2021, explicitly included methane mitigation for the first time. Internationally, the U.S.-China Joint Glasgow Declaration at the 26th UNFCCC Conference of the Parties (COP26) in 2021 emphasized the urgency of reducing methane emissions in both countries. On November 7, 2023, China released its national methane emissions control action plan and later committed to include methane and other non-CO_2 GHGs in its forthcoming Nationally Determined Commitment for 2035. As this is a relatively new area in China's climate change mitigation and policy development efforts, a strong scientific and analytical basis for understanding the country's key methane emission sources and mitigation opportunities, along with their associated uncertainties, is critical to developing an effective methane mitigation roadmap.

There are generally two methods for estimating methane emissions in compiling emissions inventories: bottom-up and top-down. Bottom-up methods such as point-source measurements and facility-scale in situ aircraft measurements help improve the understanding of the process of emissions generation and development of possible mitigation strategies. Top-down methods monitor the spatial and temporal trends of emissions through the use of remote observatories, towers and satellites. The two types of methods are complementary, and top-down results help enable the rigorous comparison with bottom-up results (National Academies of Sciences, Engineering, and Medicine et al., 2018).

Regardless of method, large uncertainties exist in methane emissions inventories from various sources. For example, uncertainties from bottom-up methods may relate to emission factors (EFs) and activity-level data, whereas uncertainties from top-down methods may relate to instrumentation precision and atmospheric inverse modeling assumptions. Estimating the level of uncertainty is essential since it reveals both the accuracy and confidence level of emissions and inventory estimates.

Recent literature and analysis of China's methane emissions and mitigation potential has mostly focused on specific sectors, such as coal mining (Sheng et al. 2019, Gao et al. 2021, Chen et al. 2022, Zhu et al. 2022, IEA 2023) and agriculture (Zeng et al. 2020, Xia et al. 2023) and, less commonly, solid waste (Du et al. 2019, Zhu et al. 2023). These studies explore sector-specific data sources, challenges, and mitigation opportunities in detail but do not provide a comprehensive national view of methane emissions and opportunities, and only a few attempted to quantify areas of uncertainty. Other recent studies (EPA 2019, Lin et al. 2019, Yu et al. 2022) have included multi-sector modeling and analysis of China's methane sources and mitigation potential. EPA (2019) and Lin et al. (2019) both use a bottom-up approach to projecting China's methane emissions under different mitigation scenarios, while Yu et al. (2022) reviews results from top-down, bottom-up, and integrated assessment models.

This report builds on previous work and provides new analysis by using a bottom-up modeling approach with updated assumptions about macroeconomic and physical emissions drivers as well as abatement cost data that extends projections through 2060. Further, this work contributes to the understanding of new and emerging opportunities to reduce China's methane emissions cost-effectively in three important ways. First, we account for additional methane emission sources, such as abandoned coal mines and aquaculture, that have not yet been incorporated in multi-sectoral analyses of China. Second, we address uncertainty in methane emissions data in two ways: by using more granular, region-weighted emission factors for the coal mining sector, and by assessing uncertainties in specific rice cultivation mitigation measures. Third, we evaluate promising new mitigation opportunities, such as biochar application in rice cultivation and aquaculture, and assess possible sensitivities of including emerging measures in enteric fermentation. Ultimately, using a business-as-usual Reference Scenario and two methane mitigation scenarios (defined by abatement cost thresholds of <\$10/tCO_2e for Cost-effective Mitigation, and <\$100/tCO_2e for Deep Mitigation for considering individual mitigation measures), we comprehensively assess the mitigation potential for individual methane sources in both the near term (through 2030) and the long term (through 2060).

2. Modeling Methodology

A bottom-up spreadsheet model is used to account for all energy and non-energy sources of methane emissions in China by tracking activity drivers and unabated methane emission factors for each source and projecting changes over time under defined scenarios (Table 1).

2.1 Activity Drivers and Emission Factor Projections

Building on earlier bottom-up modeling methodology developed in Lin et al. (2019), we updated and calibrated statistics about activity drivers (e.g., population, coal production, livestock population) to the latest reported year and extended methane emission projections through 2060.

Table 1. Activity Drivers, Activity Projections, and Emission Factors for China's Methane Emission Sources

	Activity Drivers	Basis for Activity Projections	Basis for Emission Factors
Energy Sector			
Coal Mining	Coal mining production (as a function of demand), underground and surface mining	Endogenously calculated in energy system model based on demand projection and resource availability	Median EF with upper/lower bounds of uncertainty based on production-weighted provincial median EFs from Sheng et al. (2019)
Abandoned Coal Mine Methane	Abandoned coal mine capacity	4.7% annual abandonment rate (Kholod et al.) plus endogenously calculated decline in coal production capacity (if any) due to shift away from coal	Implied EF from Chen et al. (2022) Method 2 calculation
Oil and Gas Production	Oil and natural gas production output	Endogenously calculated in energy system model based on demand projection and resource availability	Tier 1 default (IPCC, 2006)
Oil and Gas Transmission & Distribution	Oil and natural gas demand for T&D	Endogenously calculated in energy system model based on demand projection and resource availability	Tier 1 default (IPCC, 2006); average values for extraction and transmission and distribution
Biomass Combustion	Rural biomass combustion for heating and cooking	Biomass demand calculated endogenously by model based on fuel shares, heating and cooking energy demand	Weighted by proportions of firewood and stalk (China 2010 GHG Inventory Guidelines)
Transport Diesel & Gasoline Vehicles	Diesel and gasoline consumption for different vehicle types and weight classes: trucks, buses, passenger vehicles	Fuel consumption by vehicle type calculated endogenously by model based on assumed fuel shares, efficiency and mobility demand	Tier 1 default (IPCC, 2006) average values
Agriculture Sector			
Rice Cultivation	Harvest area for four different growth seasons	Projected growth rates based on China Agriculture Outlook	Average EFs for each type of growth season (2010 GHG Inventory Guidelines)
Enteric Fermentation	Total livestock of cattle, buffalo, horses, donkeys, mules, camels, hogs, sheep, and goats	Varies by animal type; growth based on population, meat consumption, and linear regressions	Average EFs for type of livestock (2010 GHG Inventory Guidelines)

Manure Management	Total livestock of cattle, buffalo, horses, donkeys, mules, camels, hogs, sheep, and goats	Varies by animal type; growth based on population, meat consumption, and linear regressions	Average EFs for type of livestock (2010 GHG Inventory Guidelines)
Aquaculture	Freshwater aquaculture production	Aquaculture demand driven by population and per capita aquaculture demand	Calculated EF based on 2014-15 emissions and production data (Yuan et al., 2019)
<u>Waste and Wastewater Sector</u>			
Solid Waste	Population and waste mix	Regression of landfill waste based on population and per capita GDP	Emissions calculated using IPCC First Order Decay Model (IPCC, 2006)
Domestic Wastewater	Organics in wastewater as a function of population and urbanization	Per capita biochemical oxygen demand using Asian regional defaults	(2010 GHG Inventory Guidelines)
Industrial Wastewater	Chemical oxygen demand (COD) in wastewater	Total COD and COD removed based on regression to industrial value added	N/A

For emission factors, additional analysis was conducted to account for data gaps and uncertainties in methane emissions from coal mining and rice cultivation. For coal mine methane, the upper and lower bounds for the emission factor were derived by considering uncertainties around province-specific median emission factors reported in Gao et al. (2021). The calculation assumes constant future shares between high and low methane content production in the absence of additional information. An implied uncertainty range of +/-80% was identified based on uncertainty ranges around the median emission factor for the three largest-producing provinces of Liaoning, Inner Mongolia, and Shaanxi, which account for over 60% of current coal production (based on province-specific data from Gao et al., 2021). For rice cultivation, the baseline emission factors are determined according to the average emission factors for each type of growth season reported in China's 2010 Provincial Greenhouse Gas Inventory Guidelines (NCSC, 2010). These baseline emission factors may have incorporated some effects of the existing straw returning to the field. However, due to the lack of data, the straw return ratio in the base year and its impact on baseline emission factors are hard to quantify.

2.2 Modeling Scenarios

For future trajectories of methane emission projections, marginal abatement cost estimates are used to evaluate the potential application and scale of deployment and effectiveness of mitigation measures for each source sector from 2021 through 2060 under defined scenarios of technological and/or policy development. The scenarios evaluated include:

1. ***Reference Scenario*** of a clean energy transition and decarbonization consistent with China's energy-related targets and Zhou et al. (2022) to serve as a baseline scenario that does not consider any methane mitigation measures;
2. ***Cost-effective Mitigation Scenario*** that assumes full adoption of individual cost-effective methane mitigation measures with abatement costs below \$10/tCO_2e prior to 2050; and
3. ***Deep Mitigation Scenario*** that assumes an accelerated clean energy transition, faster adoption of cost-effective methane mitigation measures by 2025, and the application of additional, higher-cost individual mitigation measures with abatement costs below US\$100/tCO_2e.

Table 2 summarizes key differences between the two mitigation scenarios in terms of measures deployed and pace of adoption.

Table 2. Summary of Methane Mitigation Measures by Scenario

	Measures: Cost-effective Mitigation Scenario	**Additional Measures: Deep Mitigation Scenario**
Energy Sector		
Coal Mining	Ventilation air methane (VAM) oxidation for high/medium/low concentration gas; gas collection and flaring; gas collection for energy use	Accelerated full adoption of measures by 2025
Abandoned Coal Mine Methane	None (changes over time due to clean energy transition)	Earlier phasedown due to faster clean energy transition
Oil Production, Transmission & Distribution	None, due to higher costs	Practices to reduce unintended leakage; recovery and utilization of vented gas

Natural Gas Production, Transmission & Distribution	Green completion and plunger lift; leakage detection and repair; replace or retrofit high-bleed pneumatic devices or air pneumatic controllers	Accelerated full adoption of measures by 2025
Biomass Combustion	Biomass consumption is reduced from current levels due to clean energy transition	Greater reduction (64% relative to Cost-effective Mitigation scenario by 2060) in biomass consumption due to greater building electrification
Transport Diesel & Gasoline Vehicles	Diesel and gasoline consumption are reduced from current levels due to transport electrification	Greater reductions in diesel and gasoline consumption due to full transport electrification by 2050
Agriculture Sector		
Rice Cultivation	Cost-effective irrigation practices fully deployed by 2050; biochar application	Earlier (2030 vs. 2050) full deployment of changed irrigation practices
Enteric Fermentation	Improving the nutritional balance of livestock feed and feed digestibility	None*
Manure Management	Converting manure to compost	None
Aquaculture	Switching from extensive and semi-intensive to intensive systems	None
Waste and Wastewater Sector		
Solid Waste	Gas collection and flaring; gas collection for power generation	None
Domestic Wastewater	None, due to higher costs	Upgrade to anaerobic treatment with gas recovery and utilization; open sewer to aerobic wastewater treatment plant (WWTP)
Industrial Wastewater	None, due to higher costs	Upgrade to anaerobic treatment with gas recovery and utilization; open sewer to aerobic wastewater treatment plant (WWTP)

*Note: A separate sensitivity scenario was used to evaluate potential additional reductions in enteric fermentation from emerging technologies for supply-side methane reductions.

Biochar is an important mitigation strategy with significant potential to reduce methane emissions from rice cultivation, but its role in overall methane mitigation for China has received limited attention in existing multi-sector methane mitigation analyses. The current biochar utilization rate is low, but due to data availability, we made the simplifying assumption that biochar utilization is zero until 2020. There is some uncertainty surrounding biochar's methane reduction efficiency. According to the meta-analysis of 113 experimental observations in Xia et al. (2023), biochar's average methane reduction efficiency is 26.35%, with a 95% confidence interval ranging from 22.01% to 30.47%; our study adopts these findings when estimating biochar's methane mitigation potential. Our study also estimates the per unit methane reduction cost of biochar, taking into consideration uncertainties in biochar application rate, per unit cost, methane reduction efficiency, and yield improvement potential. For the biochar application rate, we assume a rate of 2.8 tons per hectare, following Nan et al. (2022). For the cost of biochar application, we use the average of cost estimates for biochar from crop straw reported by Mohammadi et al. (2017) and Clare et al. (2015), or $115 per ton. Finally, for yield improvement potential, we use the range reported by Xia et al. (2023), which incorporates 230 experimental observations from various studies. The average yield improvement potential is 11%, and the 95% confidence interval ranges from 9% to 13%. Considering uncertainties in the biochar application rate, per unit cost, methane reduction efficiency, and yield improvement potential, we estimate the per unit methane mitigation cost of biochar to be -14/tCO_2e on average, with a range from -$47/t$CO_2$e to $29/t$CO_2$e, due to the net impact of increased yield.

In addition to the two main scenarios, a sensitivity scenario was also used to evaluate emerging technologies being developed to reduce methane emissions from enteric fermentation with generally greater confidence for near to mid-term commercial availability, including methane inhibitors (e.g., 3-NOP) and methane vaccines (Reisinger et al., 2021). These measures are evaluated separately due to uncertainties surrounding the commercialization and widespread market availability, cost trajectories, and constraints around applicability, regulatory and market acceptance that differ from the more mature mitigation measures considered in the Deep Mitigation scenario. Other emerging technologies such as low emissions breeding and methane-inhibiting seaweed feed additives were not considered due to limited applicability and uncertain reduction potential and deployment timeline, respectively.

3. Results

3.1 Current Methane Emissions in China and Uncertainties

Based on updated information and analysis about the source activities that drive methane emissions ("source activity drivers"), we estimate that China's 2020 methane emissions totaled 63.8 million metric tonnes (MtCH_4), which is equal to 1,913 million metric tonnes of carbon dioxide equivalent (MtCO_2e) having a 100-year global warming potential (GWP100). Emissions sources include 41% from agriculture, 46% from energy, and 13% from waste and wastewater. Figure 1 compares our total methane emissions estimates for 2020 with others that have recently been published. Variations in estimates for the agriculture and waste sectors indicate greater uncertainty about source activity data and emission factors in both sectors.

This is particularly true for the EDGAR global emissions inventory, which is primarily based on Tier 1 global default data for emission factors with greater uncertainties from the Intergovernmental Panel on Climate Change (IPCC) (Crippa et al. 2021, 2022). In the agriculture sector, for example, enteric fermentation and manure management had an estimated uncertainty of +/-20% for activity data and +/-50% in Tier 1 emission factors, with higher uncertainty levels of -40% to +70% for the emission factor for rice cultivation (Solazzo et al. 2021). In the waste sector, similarly high uncertainty levels of -56% to +103% are seen in activity data for industrial wastewater, with 30% uncertainty in maximum methane-producing capacity and -50% to +100% uncertainty in methane correction factor, all of which are input variables that directly impact the emission factor (Solazzo et al. 2021).

Our estimate of China's methane emissions falls in the higher end of such estimates, which is likely due to the inclusion of two additional methane sources: abandoned coal mines and aquaculture. We also used regionally weighted median emission factors for coal mine methane, which enabled us to reduce some uncertainty in the energy sector. In terms of sectoral composition, our estimate of agricultural methane emissions (including 16% from aquaculture) is larger than other studies, but our estimates of the energy and waste sectors are comparable.

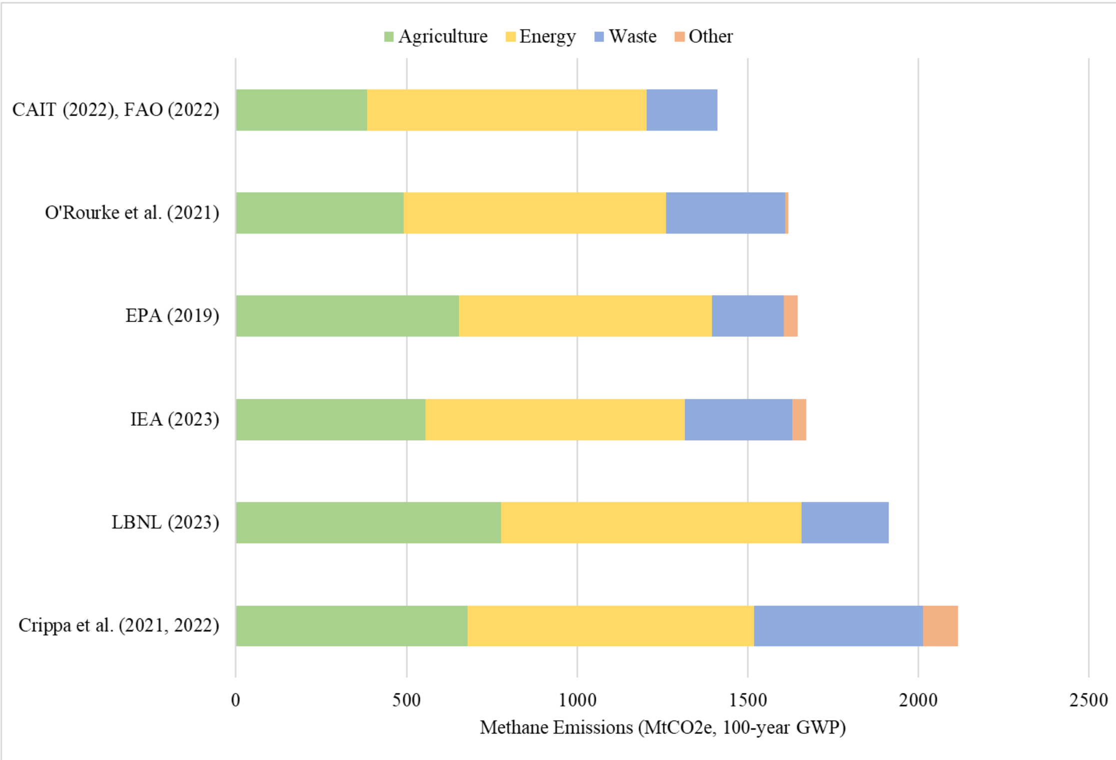

Figure 1. Estimates of China's 2020 Methane Emissions.
Sources: CAIT (2022), FAO (2022), O'Rourke et al. (2021), EPA (2019), IEA (2023), Crippa et al. (2021, 2022).
Note: Other category varies by different data sources and includes chemicals, metals and fossil fuel fires in O'Rourke et al. (2021), manufacturing, other transport, chemical and metal industries and fires in Crippa et al. (2021, 2022), stationary and mobile sources in EPA (2019), and average of other estimates from four key sources in IEA (2023).

3.2 Future Methane Trajectories, and Uncertainties

In China, key sources of uncertainty identified across bottom-up and top-down inventory estimates for 2017 include coal mining, rice cultivation, wastewater, and enteric fermentation (Yu et al. 2022). As discussed earlier, we focused on coal mining and rice cultivation as two large sources of methane emissions and conducted additional uncertainty analysis around emission factors and mitigation efficacy.

Figure 2 shows projected methane emissions and associated uncertainties from two key sources (coal mine methane and rice cultivation) under three scenarios: Reference, Cost-effective Mitigation, and Deep Mitigation. Because mitigation measures are assumed to be deployed from 2020 onwards, total methane emissions begin declining after 2020 under both the Cost-effective and Deep Mitigation scenarios, but do not decline until after 2025 under the Reference Scenario with no mitigation measures. The total emissions shown below are calculated based on median values and the error bars represent the high and low range values for the two key sources of uncertainty we analyzed, but do not account for uncertainties in other emission sources.

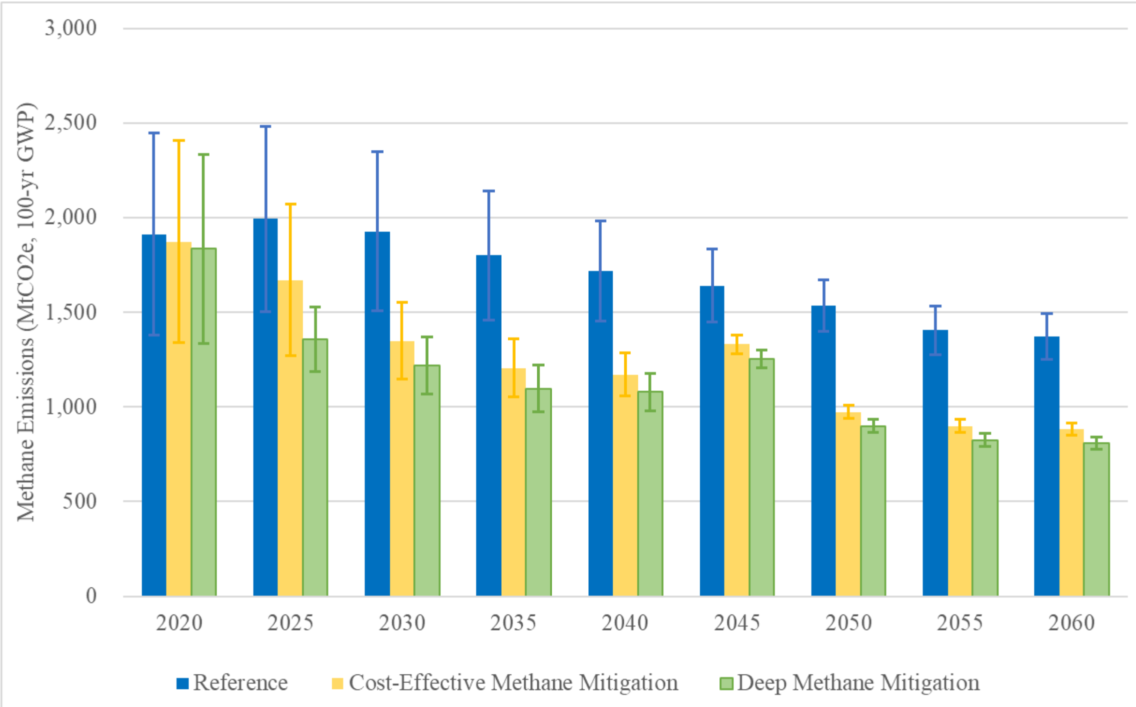

Figure 2. Total Methane Emissions with Uncertainty Ranges for Two Key Emission Sources by Scenario, 2020 – 2060

Note: error bars represent the high and low range values for uncertainties in coal mine methane and rice cultivation

The two sources of uncertainties shown in Figure 2 are from coal mine methane and rice cultivation, hence our focus on those areas. Of the two, uncertainties about the coal mine methane emission factor were significantly larger than uncertainties about the efficacy of rice cultivation methane mitigation measures. For coal mine methane, the overall uncertainty level falls over time as the economy shifts away from coal consumption and coal mining decreases until it is nearly phased out by 2060 (Figure 3).

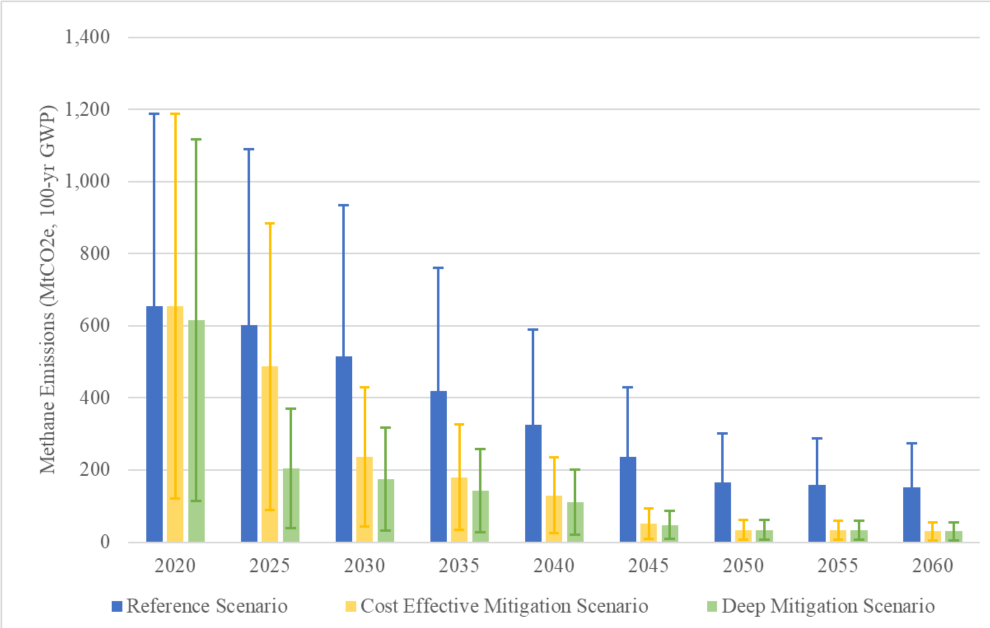

Figure 3. Coal Mine Methane Emissions and Uncertainties by Scenario, 2020 – 2060

For rice cultivation, overall uncertainty levels in both the Cost-effective and Deep Mitigation Scenarios are low but remain constant due to uncertainty about the efficacy of a mitigation measure – namely, the application of biochar (i.e., partially combusted biomass) as a soil supplement to absorb methane – which is fully deployed by 2030 (Figure 4). Despite these uncertainties, a median reduction in total rice cultivation methane emissions of 58% below the Reference Scenario is possible by 2060 under the Deep Mitigation Scenario.

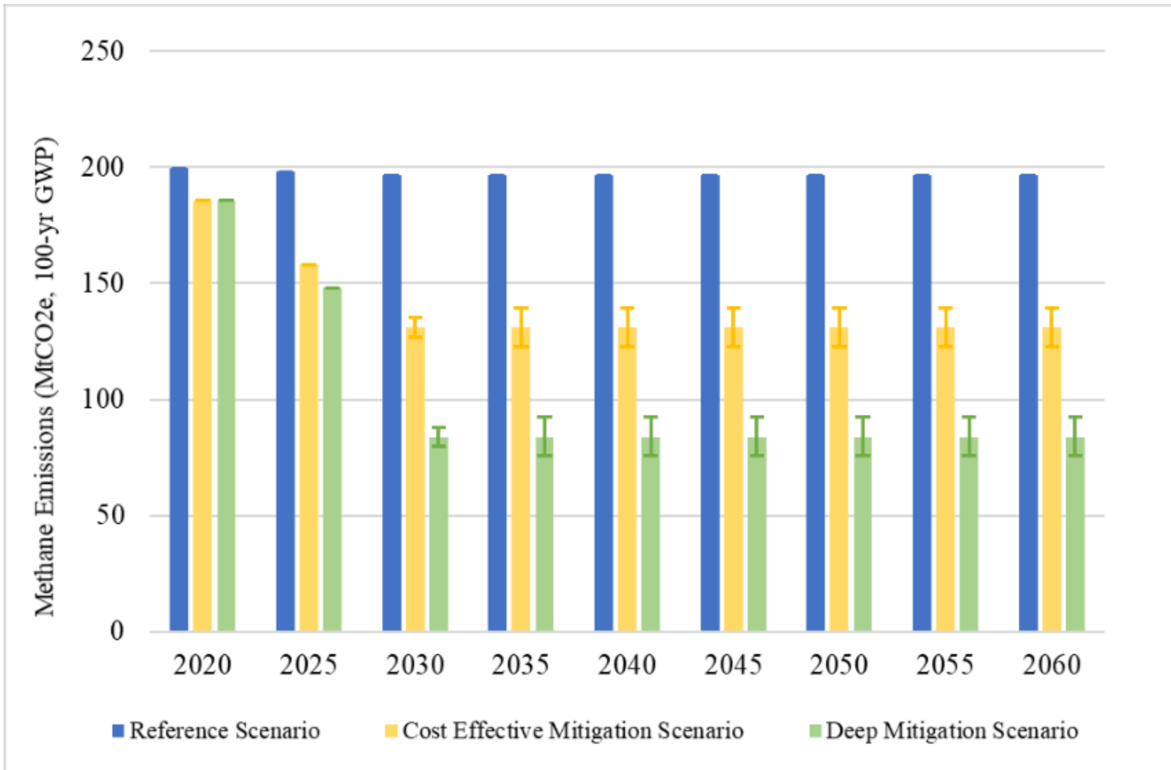

Figure 4. Rice Cultivation Methane Emissions and Uncertainties by Scenario, 2020 – 2060

For enteric fermentation, there is significant uncertainty surrounding the reduction potential, efficacy, costs, and adoption of emerging technologies for methane mitigation, particularly supply-side mitigation measures. Despite these uncertainties, it is important to consider emerging supply-side technologies in mitigation scenarios as they could achieve stronger reductions of methane emissions in some livestock systems (Reisinger et al. 2021). Due to lack of concrete costs data and highly uncertain trends in commercial development and market adoption, we added a sensitivity scenario to the Deep Mitigation Scenario to assess possible additional reductions from two supply-side measures with greater confidence for widespread commercial availability and higher reduction potential: synthetic methane inhibitor such as 3-Nitrooxypropanol (3NOP) feed additives and methane vaccines. Following reduction and market adoption projections in Reisinger et al. 2021, we found that these two novel measures could result in notable methane reductions in the near and long-term. In 2030, the adoption of synthetic methane inhibitors could reduce enteric fermentation methane emissions by 50 $MtCO_2e$ annually, or a 12.5% reduction. The adoption of commercially available methane vaccine after 2040 can provide additional methane reductions of 15% by 2050. Together, these two supply-side mitigation measures can further reduce enteric fermentation methane emissions by 94 $MtCO_2e$ by 2060, or by 2570 $MtCO_2e$ cumulatively from 2025 to 2060. With these two measures considered, China's total methane emissions could be reduced by 48% in 2060 relative to the Reference Scenario, and by 19% in 2060 relative to the Cost-Effective Mitigation Scenario.

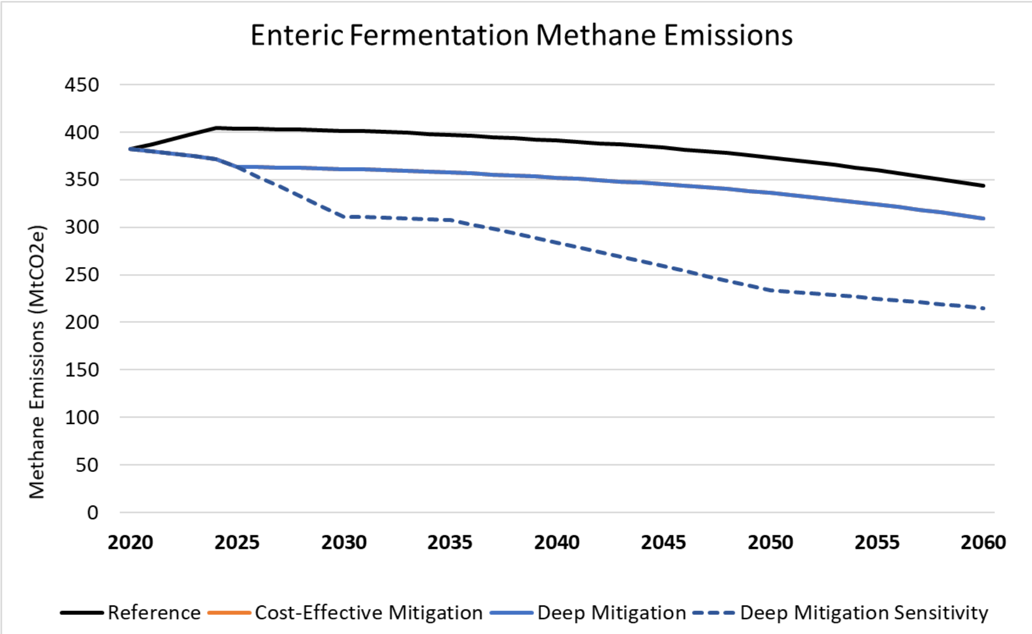

Figure 5. Enteric Fermentation Methane Emissions and Sensitivity Analysis

Note: Cost-effective and Deep Non-CO2 Mitigation have the same results for enteric fermentation, while the Deep Non-CO2 Mitigation Sensitivity considers additional adoption of methane inhibitors and vaccines.

3.3 Methane Mitigation Analysis

Figure 6 compares the annual methane reduction potential by sector over time under both the Cost-Effective and Deep Mitigation scenarios. Under both scenarios, most reduction potential will be from the energy sector – notably from coal mining in the earlier years (2020-2040) and abandoned coal mines in the later years (2025-2060) as China shifts away from coal production and fully deploys measures that destroys or utilizes ventilated air methane (VAM) released from coal mines by 2050.

Under the Deep Mitigation scenario, a slightly greater reduction potential exists on an accelerated timeframe (through 2040) due to faster deployment of VAM mitigation measures (by 2030, rather than 2050) and faster phasedown of coal consumption in an accelerated clean energy transition. In the agricultural sector, the greater methane reduction potential seen under the Deep Mitigation Scenario hinges on the deployment of additional mitigation measures in rice cultivation: in 2030, the application of changes to irrigation practices reduces methane emissions by an additional 47 $MtCO_2e$ compared to the Cost-effective Scenario. By 2060, these irrigation changes result in a total reduction potential of 317 $MtCO_2e$ under the Deep Mitigation Scenario, and 269 $MtCO_2e$ under the Cost-effective Scenario. Similarly, the implementation of higher-cost mitigation measures (e.g., anaerobic treatment with gas recovery and utilization and aerobic wastewater treatment) under the Deep Mitigation scenario results in 22 $MtCO_2e$ and 28 $MtCO_2e$ of methane reduction potential in 2030 and 2060, respectively.

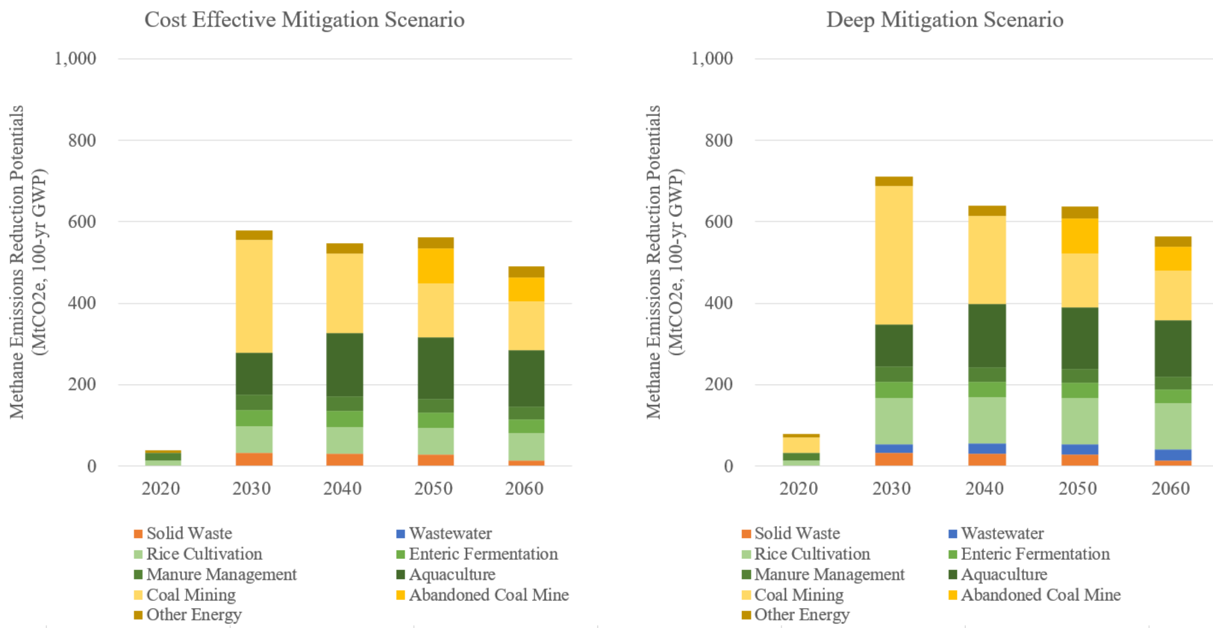

Figure 6. Methane Emission Reductions by Source, Cost-effective and Deep Methane Mitigation Scenarios.

Note: reduction potential shown are relative to Reference Scenario

In 2030, most methane mitigation potential exists in the energy sector, which accounts for 63% of total potential under the Cost-Effective Scenario and 51% under the Deep Mitigation Scenario (Figure 7). Agriculture offers a larger reduction potential under the Deep Mitigation Scenario (41% of the total) than the Cost-effective Scenario (31%), while wastewater offers a 3% total reduction under the Deep Mitigation Scenario.

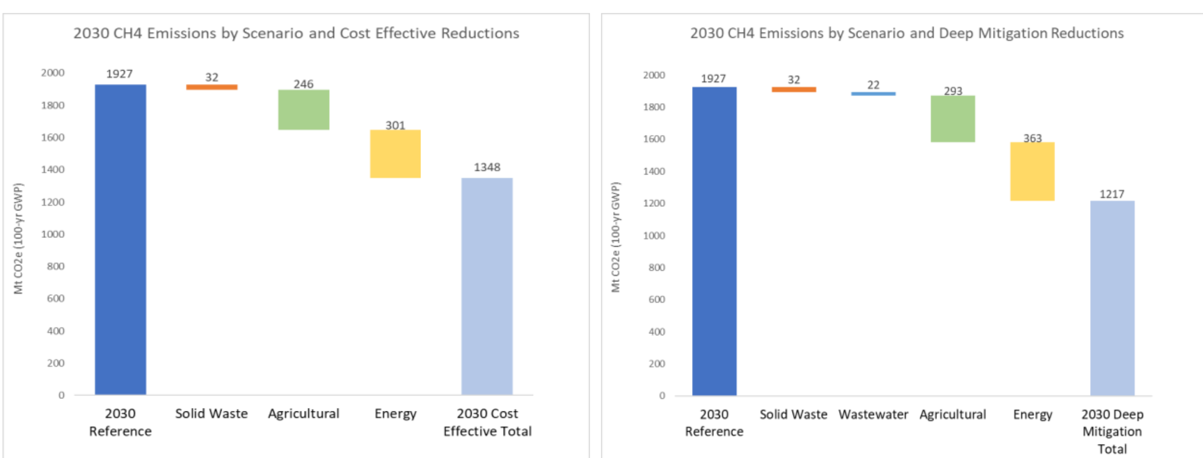

Figure 7. 2030 Methane Emissions Reductions by Sector and Scenario, in 100-yr GWP

In the near term, and taking into consideration the shorter lifetime of methane emissions by using a 20-year GWP, potential methane reductions from the energy and agriculture sectors by 2030 are shown in Figure 8.

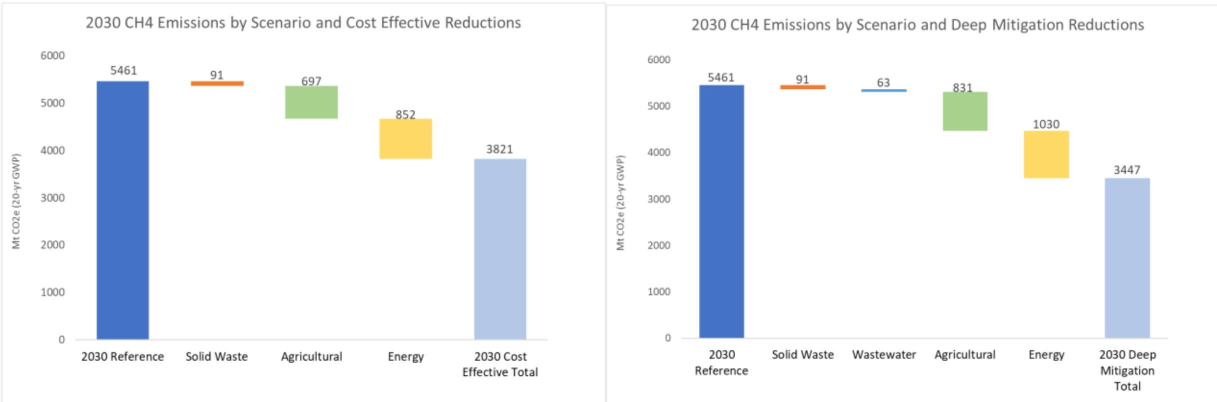

Figure 8. 2030 Methane Emissions Reductions by Sector and Scenario, in 20-yr GWP

Based on a review of several studies of non-CO_2 mitigation measures and abatement costs – i.e., EPA (2019), Höglund-Isaksson (2012), Höglund-Isaksson et al. (2020), and Yang et al. (2014) – we estimated average marginal abatement costs for each methane mitigation measure. Applicable measures for China were screened based on our scenario definitions for abatement costs, and technical methane reduction potentials were then applied to applicable subsectors in our bottom-up model. Total reduction potentials for individual measures were calculated using our sectoral models under both Cost-effective and Deep Mitigation Scenarios. By combining average cost data for applicable measures from the literature with the methane reduction potential of specific measures calculated by our model, we derived a 2030 cost curve for the Deep Mitigation Scenario (Figure 9). For all sectors (excluding manure management and biomass combustion), we find a total methane reduction potential of 660 $MtCO_2e$ in 2030 with an average cost of \$6.40/tCO_2e.

Of all mitigation measures, switching from extensive and semi-intensive systems in shallow earthen water bodies to intensive aquaculture systems that are managed and continuously aerated has a *negative* average abatement cost – that is, a net benefit of \$107/tCO_2e – to accompany its sizeable reduction potential of 104 $MtCO_2e$ in 2030. The higher stocking density of intensive aquaculture systems results in significantly higher fish production (by as much as four times that of traditional, extensive systems) and revenue that far offsets the additional costs of the system (Yuan, 2007). Biochar application and drainage in the agriculture sector, and utilizing higher-concentration coal mine methane for power generation in the energy sector, also have negative average abatement costs but a lower reduction potential. VAM in the coal mining sector has the largest reduction potential (223 $MtCO_2e$) and a relatively low average abatement cost of only \$5/tCO_2e.

Other mitigation measures with higher average abatement costs (i.e., above \$25/tCO_2e) include water and fertilizer management in rice cultivation, onsite use of lower-concentration diluted coal mine methane that would otherwise be vented, oil sector mitigation, and enteric fermentation. Collectively, these higher-cost measures provide another 164 $MtCO_2e$ of methane reduction in 2030.

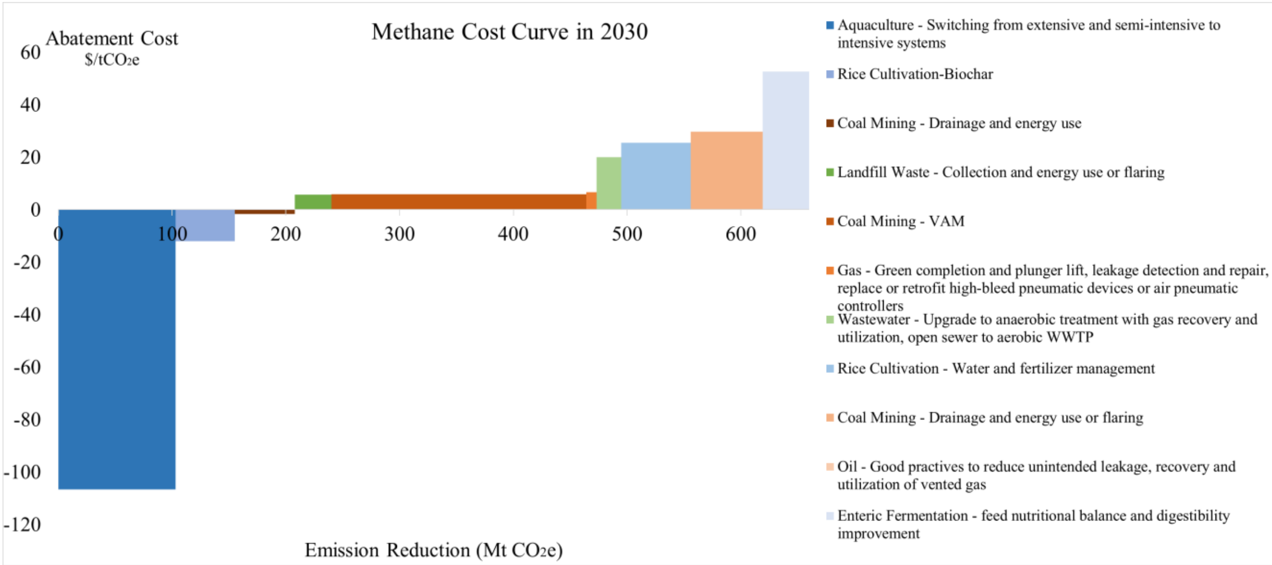

Figure 9. 2030 Methane Mitigation Cost Curve (Deep Mitigation Scenario).

Note: reductions in methane emissions from manure management and biomass combustion are not shown due to high and uncertain costs. Abatement costs shown for each subsector are the *average* costs over a mix of mitigation measures with different individual costs.

In 2060, the largest source of methane mitigation potential lies in the agriculture sector, which accounts for more than half of the total under both Cost-effective and Deep Mitigation Scenarios (Figure 10). The energy sector – which accounts for 42% and 36% of total potential 2060 methane reductions under the Cost-effective and Deep Mitigation Scenarios, respectively – represents the second-largest source of potential reductions, mainly through reductions from abandoned coal mines and coal production. By comparison, the waste sector contributes the smallest source of methane mitigation potential.

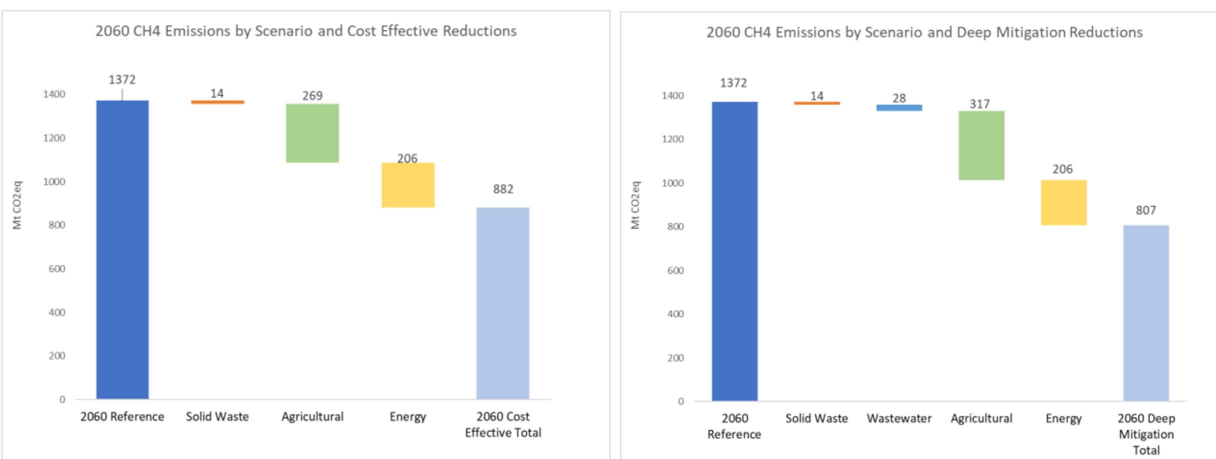

Figure 10. 2060 Methane Emissions Reduction by Sector and Scenario, in 100-yr GWP

Figure 11 compares remaining 2060 methane emissions by source under all three scenarios against a base year of 2015. Under all scenarios, there is a notable decrease in both absolute and relative methane emissions from the energy sector, primarily owing to decreased emissions from coal mining. At the same time, there is an increase in wastewater methane emissions due to growth in drivers such as industrial activity along with a relative paucity of mitigation measures for that sector having costs below

US$100/t$CO_2$e. Agricultural emissions in 2060 continue to account for half of total methane emissions, with most coming from enteric fermentation where limited mitigation measures exist. However, total 2060 methane emissions from agriculture decrease with the deployment of Deep Mitigation measures. This is particularly true when emerging mitigation technologies for enteric fermentation such as methane inhibitors such as 3NOP feed additives and methane vaccines are considered to become widely available after 2030, with the potential to further reduce 2060 methane emissions by 94 MtCO_2e. These results emphasize the need for continued focus on methane mitigation opportunities in the agriculture and wastewater sectors, which represent the majority of remaining methane emissions in 2060 – even when individual mitigation measures costing up to US$100/t$CO_2$e are fully deployed.

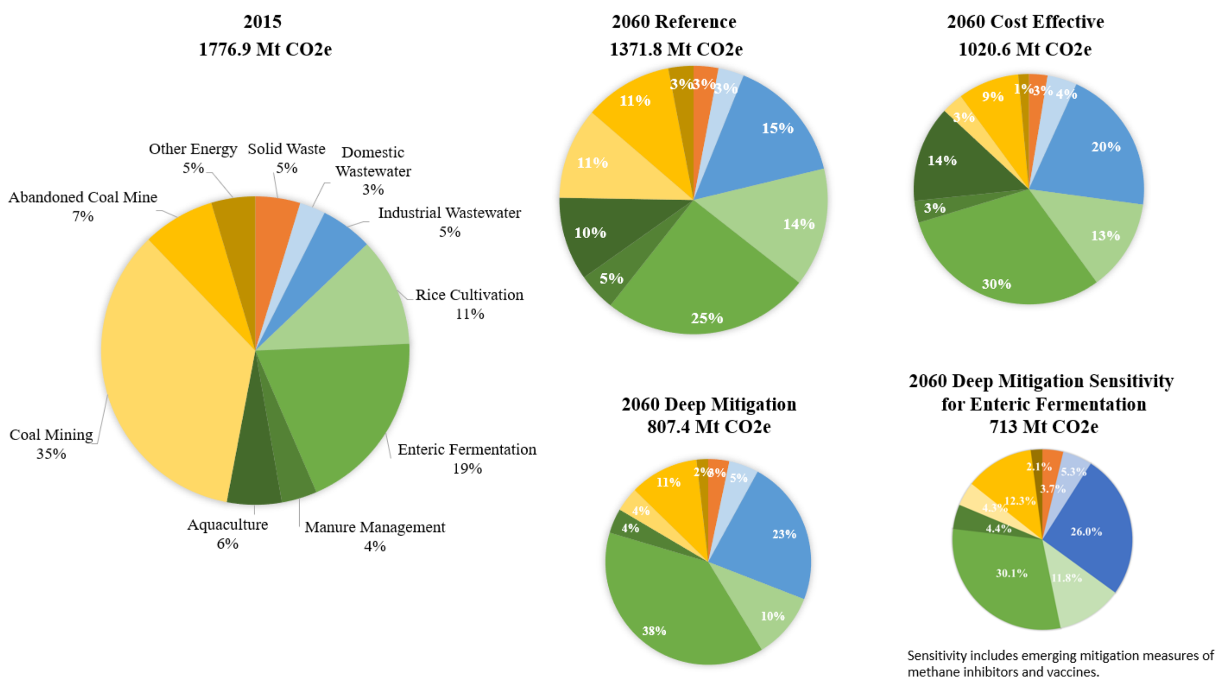

Figure 11. 2060 Remaining Methane Emissions by Subsector and Scenario, in 100-yr GWP

Note: the size of the pie charts is scaled to the magnitude of total methane emissions.

4. Conclusions and Discussion

This report uses a bottom-up modeling approach with updated activity driver projections and abatement cost analysis to account for additional methane emission sources, areas of uncertainties, and mitigation measures in the energy and agricultural sectors in China. Our modeling results for the Deep Mitigation Scenario underscore the significant potential for reducing methane emissions in China by 2030, with 660 MtCO_2e reductions (34% reduction relative to Reference scenario) possible with average abatement costs of US$6.40/t$CO_2$e and 760 Mt$CO_2$e (39% reduction) possible if more uncertain and costly manure management, biomass and emerging enteric fermentation measures are included.

Most mitigation potential in 2030 lies in the energy sector, primarily coal mining, but by 2060 this will shift to the agriculture sector following China's clean energy transition to meet its carbon neutrality goal. Despite coal's declining role in China's future energy sector, coal mining remains a key source of methane emissions and there are high uncertainties around coal mine methane emissions in the near term due to variations in emission factors linked to geographic and mine-specific conditions. Abandoned coal mine methane is another key source of emissions that has been considered in only a limited number of China studies, and possible mitigation measures are not yet well understood. In the agriculture sector, aquaculture and biochar applications in rice cultivation could reduce methane emissions at negative cost (i.e., net benefit) and should be pursued more rigorously in both research and development and implementation to enhance their mitigation efficacies. In the longer term out to 2060, the agriculture sector holds the greatest reduction potential but is also the largest source of remaining methane emissions in China, including notably enteric fermentation and rice cultivation. If emerging mitigation measure for enteric fermentation are considered to be widely deployed after 2030, enteric fermentation methane emissions could be further reduced by 94 MtCO2e, with 48% reduction possible in China's total emissions in 2060. This highlights the need to better understand and assess additional and novel mitigation measures for the agriculture sector. Additional mitigation measures must also be explored for the wastewater sector, a growing source of methane emissions where current measures are limited and costly.

This report addresses some of the largest uncertainties around projected methane emissions from coal mining and rice cultivation in China, and highlights lesser-known sources and mitigation opportunities in the energy and agriculture sectors. However, we did not consider or attempt to quantify uncertainties for other subsectors, such as waste and wastewater, whose methane emissions are expected to grow, or for enteric fermentation where novel mitigation options are being developed and commercialized. We also focused our mitigation analysis on existing and commercialized mitigation measures with abatement cost data and did not model emerging technologies for methane mitigation or broader socio-economic measures such as dietary changes. Lastly, our projections of key activity drivers could be further improved with sensitivity analysis.

5. References

Chen D., Chen A., Hu X., et al. 2022. Substantial methane emissions from abandoned coal mines in China. *Environmental Research* 214: 113944.

Clare, A., Shackley, S., Joseph, S., Hammond, J., Pan, G., & Bloom, A. (2015). Competing uses for China's straw: the economic and carbon abatement potential of biochar. *Gcb Bioenergy*, *7*(6), 1272-1282.

Climate Watch (2022), Food and Agriculture Organisation of the United Nations (2022). Climate Watch data: Climate Watch, 2022, GHG Emissions, Washington, DC: World Resources Institute. FAO 2022, FAOSTAT Emissions Database. Available at: https://www.climatewatchdata.org/ghg-emissions

Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J.G.J., Grassi, G., Rossi, S., Vignati, E. (2021), GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/173513, JRC126363; (2022) EDGAR - Emissions Database for Global Atmospheric Research (EDGAR) v7.0 Greenhouse Gas Emissions. European Commission, Joint Research Centre (JRC) [Dataset] PID: https://edgar.jrc.ec.europa.eu/dataset_ghg70

Dreyfus G., Xu Y., Shindell D., et al. 2022. "Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming." Proc. Natl. Acad. Sci. U.S.A. 119 (22): 2123536119.

Du M., Peng C., Wang X. et al. 2017. "Quantification of methane emissions from municipal solid waste landfills in China during the past decade." *Energy Reviews* 78: 272-279.

Gao J., Guan C., Zhang B., et al. 2021. "Decreasing methane emissions from China's coal mining with rebounded coal production." *Environmental Research Letters* 16: 124037.

Höglund-Isaksson, L. 2012. "Global anthropogenic methane emissions 2005–2030: Technical mitigation potentials and costs." *Atmos. Chem. Phys.* 12, 9079–9096.

Höglund-Isaksson, L., Gomez-Sanabria A., Klimont Z., et al. 2020. "Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model." *Environ. Res. Commun.* 2, 025004.

International Energy Agency (IEA). 2023. "Driving Down Coal Mine Methane Emissions." Paris: IEA. IEA, 2021, Greenhouse gas emissions from energy, https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy

Intergovernmental Panel on Climate Change (IPCC), 2018. "Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response To the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty." V.Masson-Delmotte et al., Eds. (Cambridge University Press, 2018).

IPCC, 2021. Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Lin J, Khanna N, Liu X. 2019. "China's Non-CO_2 Greenhouse Gas Emissions: Future Trajectories and Mitigation Options and Potential." *Scientific Reports* 9, 16095. https://doi:10.1038/s41598-019-52653-0

Mohammadi, A., Cowie, A. L., Cacho, O., Kristiansen, P., Mai, T. L. A., & Joseph, S. (2017). Biochar addition in rice farming systems: Economic and energy benefits. *Energy*, *140*, 415-425.

Nan, Q., Fang, C., Cheng, L., Hao, W., & Wu, W. (2022). Elevation of NO3−-N from biochar amendment facilitates mitigating paddy CH4 emission stably over seven years. *Environmental Pollution*, *295*, 118707.

National Academies of Sciences, Engineering, and Medicine; Division on Earth and Life Studies; Board on Environmental Studies and Toxicology; Board on Energy and Environmental Systems; Board on Earth Sciences and Resources; Board on Agriculture and Natural Resources; Board on Atmospheric Sciences and Climate; Committee on Anthropogenic Methane Emissions in the United States: *Improving Measurement, Monitoring, Presentation of Results, and Development of Inventories.* Washington (DC): National Academies Press (US); 2018 Mar 27.

National Center for Climate Change Strategy and International Cooperation (NCSC). *2010 Chinese Provincial Guidelines for GHG Emissions Inventory* (2011).

O'Rourke, P. R, Smith, S. J., Mott, A., Ahsan, H., McDuffie, E. E., Crippa, M., Klimont, S., McDonald, B., Z., Wang, Nicholson, M. B, Feng, L., and Hoesly, R. M. (2021, February 05). CEDS v-2021-02-05 Emission Data 1975-2019 (Version Feb-05-2021). Zenodo. https://zenodo.org/record/4741285

Sheng J., Song S., Zhang Y., et al. 2019. "Bottom-Up Estimates of Coal Mine Methane Emissions in China: A Gridded Inventory, Emission Factors, and Trends." *Environmental Science & Technology Letters*: 473–478.

United Nations Environment Programme (UNEP) and Climate and Clean Air Coalition (CCAC), 2021. "Global methane assessment: Benefits and costs of mitigating methane emissions."

U.S. EPA, 2019. *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050*.

Xia, L., Cao, L., Yang, Y., Ti, C., Liu, Y., Smith, P., ... & Yan, X. (2023). Integrated biochar solutions can achieve carbon-neutral staple crop production. *Nature Food*, *4*(3), 236-246.

Yang, L., T. Zhu, and Q. Gao. 2014. *Technologies and Policy Recommendations for Emission Reduction of Non-CO_2 Greenhouse Gas from Typical Industries in China (in Chinese)* (China Environment Press, Beijing).

Yu, S., J. Behrendt, M. Zhu, X. Cheng, W. Li, B. Liu, J. Williams, H. Zhang, R. Cui, M. Evans, N. Hultman, H. McJeon, S. Smith, Q. Chai, L. Chen, M. Chen, C. Mei, S. Fu, F. Guo, L. Höglund Isaksson, K. Jiang, N. Khanna, V. Krey, J. Lin, Y. Wu, and Z. Yang. 2022. "*Roadmap for U.S.-China Methane Collaboration: Methane Emissions, Mitigation Potential, and Policies.*" Center for Global Sustainability, University of Maryland & Energy Foundation China, 134pp.

Yuan, X. "Economics of aquaculture feeding practices: China". In M.R. Hasan (ed.). Economics of aquaculture feeding practices in selected Asian countries. FAO Fisheries Technical Paper. No. 505. Rome, FAO. 2007. pp. 65–97.

Zeng, J., Xu R., Sun R. et al. 2020. "Evaluation of methane emission flux from a typical biogas fermentation ecosystem in China." *Journal of Cleaner Production* 257: 120441.

Zhu A., Wang Q., Liu D., et al. 2022. Analysis of the Characteristics of CH4 Emissions in China's Coal Mining Industry and Research on Emission Reduction Measures. *Int. J. Environ. Res. Public Health* 2022, 19, 7408.

Zhu J., Liu Y., Luo Z. et al. 2023. "Methane mitigation strategy for food waste management: Balancing socio-economic acceptance and environmental impacts." *Sustainable Production and Consumption* 37: 389-397.