**THE WOODROW WILSON SCHOOL'S GRADUATE POLICY WORKSHOP**

# Methane Mitigation Opportunities in China

*February 2013*

**Authors:**
Shannon Brink
Harry Godfrey
Mary Kang
Shelly Lyser
Joseph Majkut
Samantha Mignotte
Wei Peng
Matthew Reid
Madhurita Sengupta
Laura Singer

**Project Advisor:**
Prof. Denise L. Mauzerall

# TABLE OF CONTENTS

**Figures and Tables**

# EXECUTIVE SUMMARY

Methane ($CH_4$) is a naturally occurring greenhouse gas that contributes approximately 20% of climate warming from anthropogenic greenhouse gases (IPCC Working Group 1 2007). Reductions in $CH_4$ emissions can slow the rate of near-term global warming and reduce global air pollution (surface ozone), thus improving human health and reducing crop-yield losses globally (United Nations Environment Programme, UNEP 2011). International cooperation in reducing $CH_4$, and other short-lived climate forcers, is essential to achieving these decreases in the rate and impact of global warming.

China is the single largest emitter of methane in the world (US Environmental Protection Agency, USEPA 2011). Global $CH_4$ emissions in 2010 totaled 7193 $MtCO_2e$, of which China produced about 925 $MtCO_2e$, surpassing both India and the United States (USEPA 2011). China's $CH_4$ emissions are a result of its large population and economic activities, including energy use and production, waste disposal and agricultural processes. Given its continued population growth and increasing rates of per capita consumption, it is likely that China's $CH_4$ emissions will continue to grow.

This report focuses on identifying methane mitigation strategies for China's municipal solid waste, manure management, wastewater and natural gas sectors. We expect emissions from these sectors to grow over the next 25 years due to demographic changes and economic development. We approach these fields to examine the potential for emissions reductions through the implementation of policies for $CH_4$ capture and recovery.

To best capitalize on opportunities for methane mitigation from these sectors we recommend the following:

For $CH_4$ Emissions Related to Organic Waste:

- Improve the quality and detail of available data about treatment processes in all waste sectors;
- Increase the capture and use of biogas and landfill gas (LFG) from waste disposal and treatment;
- Capitalize on opportunities for smart urban planning that integrates emissions reduction, capture and recovery into waste treatment and disposal.

For $CH_4$ Emissions Related to Fossil Fuel Extraction:

- Implement policies that encourage the use of cost-effective $CH_4$ leak management technologies;
- Work with institutions at all levels in the gas industry: the Big Three Chinese energy companies, other companies exploring shale gas in China and international institutions;
- Promote the inclusion of environmental considerations in unconventional gas development, such as those detailed in the *Golden Rules for Natural Gas* (IEA 2012a).

The following table shows the potential emissions reductions, co-benefits and challenges for each sector, given sector specific policy recommendations detailed in the body of the report. Associated calculations are described in the Appendices.

## Table 1. Methane Emissions Reduction Potential (2030)

| Sector | Emission Reductions Range for 2030 (% of Total Sector Emissions) | Co-Benefits | Challenges |
|---|---|---|---|
| **Municipal Solid Waste** | 47-90 $MtCO_2e$<br>(24-45%) | • Public health and sanitation<br>• Improved recycling and composting<br>• Energy Security<br>• Aesthetic value | • Capital costs<br>• Labor requirements<br>• Dispersed rural population<br>• Urban land-use |
| **Agriculture: Manure Management** | 17-36 $MtCO_2e$<br>(17-36%) | • Rural energy security<br>• Air quality and respiratory health<br>• Water quality | • Cold-weather technology development<br>• Dispersed Population<br>• Human capital constraints to maintenance |
| **Wastewater** | 20-58 $MtCO_2e$<br>(23-66%) | • Public health and sanitation<br>• Water quality and scarcity<br>• Nitrous oxide mitigation<br>• Rural energy security | • Capital costs<br>• Rapid urbanization<br>• Dispersed rural populations |
| **Natural Gas** | 31- 44 $MtCO_2e$<br>(<90%) | • Energy security<br>• Economic growth | • Technology transfer<br>• Technology advancement |

# METHODOLOGY

This report was researched and written by a group of Master in Public Affairs students at the Woodrow Wilson School, and Ph.D. candidates from the Woodrow Wilson School, the Program in Atmospheric and Oceanic Sciences and the Department of Civil and Environmental Engineering at Princeton University. Princeton University atmospheric scientist Professor Denise Mauzerall facilitated the project as part of the annual graduate policy workshop program. The goal of the workshop program is for students to contribute to addressing critical policy problems for real clients.

This particular workshop arose out of the U.S. Environmental Protection Agency (EPA) and Global Methane Initiative's (GMI) interest in better understanding methane sources and mitigation opportunities in China. Specifically, the group focused on exploring methane emissions from fossil fuel extraction as well as human and agricultural waste, which were topics of particular interest to the client. In developing the report, the group first met with the Chief of the Non-$CO_2$ Programs Branch and other experts at EPA to discuss their interests and needs. Over the following weeks, the team reviewed the latest scientific literature on methane emissions and potential mitigation strategies, interviewing relevant experts and stakeholders from government agencies, international organizations, corporations, business networks, academia and advocacy groups in the United States and China. Through careful research and deliberation, the group prepared a comprehensive analysis of methane emissions associated with fossil fuel extraction and waste treatment, before providing a suite of policy opportunities focused on reducing methane emissions and energy generation in China.

*The Woodrow Wilson School of Public and International Affairs, founded at Princeton University in 1930, provides an interdisciplinary program that prepares undergraduate and graduate students for careers in public and international affairs. The school is one of the world's premier academic and research institutions devoted to public and international affairs. The views expressed in this report are the views of the authors and do not represent the views of Princeton University, the Woodrow Wilson School, the Environmental Protection Agency, the Global Methane Initiative, or those who provided advice. Any errors of fact are the responsibility of the authors.*

# AUTHORS

**Shannon Brink** is a second-year Master in Public Affairs (MPA) candidate studying development economics with a certificate in Science, Technology, and Environmental Policy (STEP). She previously worked on economic and environmental issues for both the U.S. Agency for International Development and the U.S. Department of State. Shannon is a graduate of Princeton University, where she received an A.B. at the Woodrow Wilson School.

**Harry Godfrey** is a second-year MPA candidate studying domestic affairs and science, technology, and environmental policy. Prior to his time at the Woodrow Wilson School, Harry worked for elected officials in Washington. Harry is a graduate of the College of William & Mary, where he studied Economics and International Affairs.

**Mary Kang** is a fourth-year Ph.D. candidate in the Civil and Environmental Engineering Department and a Princeton Environmental Institute Science Technology and Environmental Policy Fellow. Her research focuses on analytical and numerical solutions within a multi-scale framework to model two-phase flow in subsurface environments. Prior to her time at Princeton, Mary received a B.A.Sc. and M.A.Sc. from the University of Waterloo in Civil and Environmental Engineering.

**Shelly Lyser** is a second-year MPA candidate studying domestic policy and science, technology, and environmental policy. Before attending the Woodrow Wilson School, she worked on natural resource issues relating to water, energy, and climate from both the scientific and policy angles. Shelly is a graduate of the University of California at Berkeley, where she received a Bachelor of Science in Environmental Sciences.

**Joseph Majkut** is a fourth-year Ph.D. candidate in the Atmospheric and Oceanic Sciences Program and a Princeton Environmental Institute Science Technology and Environmental Policy Fellow. His thesis research focuses on the global carbon cycle, ocean dynamics, climate modeling, and inverse methods for geophysical data. Prior to his time at Princeton, Joseph studied Mathematics at Harvey Mudd College in California and Applied Mathematics at the Delft University of Technology in the Netherlands.

**Samantha Mignotte** is a second-year MPA candidate focused on rural and agricultural development policy. Prior to her time at Princeton, she worked as a research and outreach associate at the Small Planet Institute in Cambridge, MA. Samantha is a graduate of Vassar College, where she received an A.B. in Political Science and Economics.

**Wei Peng** is a second-year Ph.D. candidate in the Science, Technology, and Environmental Policy Program at the Woodrow Wilson School. Her research focuses on renewable energy development in China. Prior to her time at Princeton, Wei attended Peking University, where she received a B.S. in Environmental Sciences.

**Matthew Reid** is a fifth-year Ph.D. candidate in Civil and Environmental Engineering and a Princeton Environmental Institute Science Technology and Environmental Policy Fellow. His research focuses on experimental and modeling analyses of reaction and transport dynamics of trace gases in wetlands. Matthew is a graduate of the University of Chicago, where he received an A.B. in Chemistry, after which he served as a Peace Corps Volunteer in Tanzania.

**Madhurita Sengupta** is a second-year MPA candidate studying science and technology policy and its influence on domestic and foreign policy. She previously worked at the NASA Johnson Space Center, as an

International Space Station Robotics instructor. Madhurita is a graduate of the University of Texas at Austin, where she received a B.S. in Electrical Engineering.

**Laura Singer** is a second-year MPA candidate studying international relations and science, technology, and environmental policy, with a focus on energy security. Prior to her time at Princeton, Laura worked as an economist at the New Orleans and New York Districts of the U.S. Army Corps of Engineers, examining potential large infrastructure projects, chiefly for flood risk management and environmental restoration. Laura is a graduate of Tulane University, where she received a B.A. in Economics.

*Project Advisor*
**Denise Mauzerall** is a Professor of Environmental Engineering and International Affairs in the Woodrow Wilson School and Department of Civil and Environmental Engineering. Prior to Princeton, Mauzerall worked at the USEPA implementing the Montreal Protocol. A focus of her current research is the analysis of technology and policy options that have co-benefits for air quality and climate. PhD, Atmospheric Chemistry, Harvard.

# ACKNOWLEDGEMENTS

Tom Brett, *Global Environmental Institute*
Alejandra Burchard-Levine, *Tsinghua University*
Luis Miguel Caicedo, *University of Science and Technology, Beijing*
Xiaoli Chai, *Tongji University*
Dr. Lapyan Chan, *Organic Waste Technologies*
Xihua Chen, *Global Environmental Institute*
Leon Clarke, *Joint Global Change Research Institute*
John Crittenden, *Georgia Institute of Technology*
Francisco de la Chesnaye, *Global Climate Change Resource Center, Electric Power Research Institute*
Dan Dudek, *Environmental Defense Fund*
Andrew Eil, *US Department of State, Climate and Clean Air Coalition*
Sun Fang, *Environmental Defense Fund*
Nick Feast, *Shell China Exploration and Production Co., Ltd.*
Fengting Li, *United Nations Environment Programme TONGJI Institute of Environment for Sustainable Development*
Roger Fernandez, *Environmental Protection Agency Global Methane Initiative*
Thomas Frankiewicz, *Environmental Protection Agency Global Methane Initiative*
Pamela Franklin, *U.S. Environmental Protection Agency, Chief of Non-* $CO_2$ *Programs Branch*
Phillip Hannam, *Princeton University*
Robert Harris, *Environmental Defense Fund*
Chuan He, *Peking University*
Gregory Hild, *Chevron North America, Business Development, Planning and Integration Manager*
Zhu Hongguang, *Tongji University*
Robert Howarth, *Cornell University*
Ching-Hua Huang, *Georgia Institute of Technology*
Hillary Huang, *New Tomorrow Energy Technology Co.*
Xia Huang, *Tsinghau University*
Qui Huanguang, *Center for Chinese Agricultural Policy*
Jiamen Jin, *Global Environmental Institute*
Ma Jun, Institute *of Public & Environmental Affairs*
Linghong Kong, *Global Environmental Institute*
Marcia Lacey, *Journal of the American Water Works Association*
Olivier Lefebvre, *Initiative Développement*
Junfeng Li, *National Climate Change Strategy Research and International Cooperation Center*
Zheng Li, *Tsinghua University; BP Clean Energy Research and Education Center*
Lin Li, *Chinese Academy of Science*
Alvin Lin, *Natural Resources Defense Council*
Peggy Liu, *JUCCCE*
Jian Liu, *National Development and Reform Commission*
Jun-Xin Liu, *Chinese Academy of Science*
Bryce Lloyd, *Organic Waste Technologies*
Peter Marsters, *Sichuan University*
David McCabe, *Clean Air Task Force*
Stephanie Miller, *International Finance Corporation*
Michael Oppenheimer, *Princeton University*
Gao Qingxian, *Chinese Research Academy of Environmental Science*
Bernhard Raninger, *GIZ Sino-German Biogas Project*
John Reilly, *Massachusetts Institute of Technology*
Bruce Rittman, *Arizona State University*
Deborah Seligsohn, *World Resources Institute - China*
Jun Shao, *Shanghai Environment Group Co., Ltd.*
Jingli Shi, *China National Renewable Energy Center*
Bent Svensson, *World Bank, Global Gas Flaring Reduction Partnership*

Kanghua Tao, *Shanghai Yangtze Delta Human Eco-Tech Center*
Jennifer L. Turner, *China Environment Forum, Woodrow Wilson Center*
Tao Wang, *Carnegie Endowment for International Peace*
Zhiwei Wang, *Tongji University*
Jie Wang, *New Tomorrow Energy Technology Co.*
Kaijun Wang, *Tsinghua University*
Alex Whitworth, *IHS Cambridge Energy Research Associates*
Jing Wu, *Tsinghua University*
Siqing Xia, *Tongji University*
Xuxuan Xie, *National Development and Reform Commission*
Yuefeng Xie, *Pennsylvania State University*
Haiyun Xu, *China Ministry of Housing and Urban-Rural Construction*
Guang Yang, *National Development and Reform Commission*
Ming Yang, *World Bank Global Environment Facility*
Haiying Yang, *China Ministry of Housing and Urban-Rural Construction*
Hong Yao, *Beijing Jiatong University*
Liu Yi, *Tsinghua University*
Quanhong Zang, *Beijing Chaoyang Circular Economy Industrial Park Management Center*
Nancy Zeilig, *Editor*
Shiqiu Zhang, *Peking University*
Jian Zhang, *Shandong University*
Yongming Zhang, *Shanghai Normal University*
Lixin Zhao, *Global Methane Initiative, Chinese Academy of Agriculture Engineering*
Mingxia Zheng, *Tsinghua University*
Xuefei Zhou, *Tongji University*
Tong Zhu, *Peking University*
Jiane Zuo, *Tsingua University*

# INTRODUCTION

**Methane is a naturally occurring greenhouse gas (GHG) and a precursor to air pollution that has increased in the atmosphere due to human activities.** It currently has an atmospheric concentration of 1800 ppb, which represents an increase of more than 2.5 times the preindustrial concentration of 700 ppb (Montzka, Dlugokencky et al. 2011; CDIAC and Carbon Dioxide Information Analysis Center 2013). It is an important climate forcer and contributes about 20% of warming from anthropogenic GHGs. Recent estimates indicate that methane ($CH_4$) has a positive radiative forcing of 0.48 ±0.05 $Wm^{-2}$ against a total anthropogenic forcing from GHGs of 2.6 ± 0.3 $Wm^{-2}$ and a total residual anthropogenic forcing of 1.6 ± 1 $Wm^{-2}$ (IPCC Working Group 1 2007).

**Methane is a stronger greenhouse gas than carbon dioxide, with a 100-year global warming potential 25 times greater than carbon dioxide ($CO_2$).** The average lifetime of a $CH_4$ molecule in the atmosphere is about 10 years before it is converted by chemical reactions to $CO_2$ (IPCC Working Group 1 2007). The constituent carbon atom left over from the breakdown of the $CH_4$ molecule will eventually form the basis for a $CO_2$ molecule and thereby lead to further warming (see textbox for further information).

**Immediate reductions in methane emissions would slow the rate of global warming.** Recent research shows that immediate and substantial reductions in methane emissions could now help to avert 0.28 ± 0.10°C of warming by the year 2050 (Shindell, Kuylenstierna et al. 2012), due to the short atmospheric lifetime of $CH_4$ and its powerful warming effect. However, $CH_4$ reductions would only partially offset the continuing $CO_2$ emissions for the next 30-40 years, after which the global temperature increase would continue to track $CO_2$ emissions.

**In addition to its global warming potential, methane emissions have a detrimental impact on human health, vegetation and crop yields** (Mauzerall 2011). $CH_4$ emitted to the atmosphere is oxidized by the hydroxyl radical, OH. That oxidation sets off an extensive set of nonlinear chemical reactions that results in the creation of a $CO_2$ and an ozone ($O_3$) molecule (Isaksen, Gauss et al. 2011). $O_3$ in the troposphere is both a GHG and a significant air pollutant.

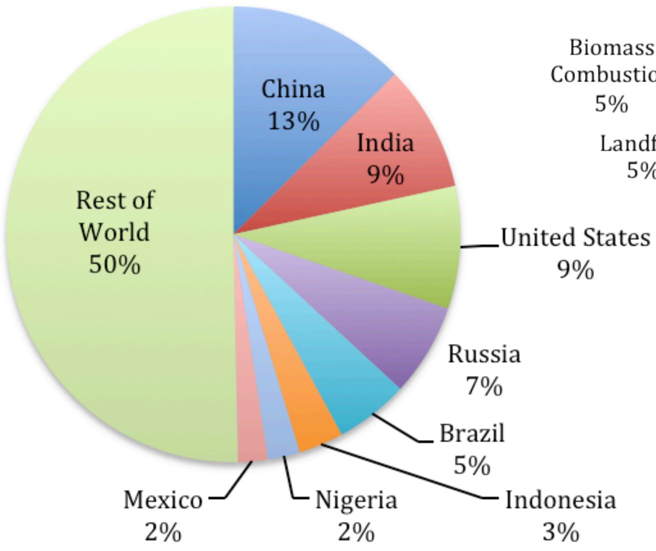
## EMISSIONS UNIT CONVERSIONS

Using a 100-year global warming potential (GWP), emissions of $CH_4$ can be converted from mass or volume into mass of $CO_2$-equivalent. The standard unit in this report is million metric tons of $CO_2$ equivalent [$MtCO_2e$]. Other units are used when appropriate for the sector, such as:

- 1 Metric Ton (MT) $CH_4$ ~ 25 MT $CO_2e$
- 1 Billion Cubic Meters (BCM) ~ 14 MT $CO_2e$

**Methane mitigation offers tangible and immediate benefits in the form of reduced greenhouse warming and air pollution.** Due to its short atmospheric lifetime, reductions in $CH_4$ emissions lead to visible climate impacts within a few short decades of policy implementation (Shindell, Kuylenstierna et al. 2012). These improvements have benefits for human health, agricultural productivity and our ability to adapt to climate change (Shindell, Kuylenstierna et al. 2012).

**Up to a third of current methane emissions can be prevented or captured at costs less than the value of the recovered methane and air quality co-benefits.** Reductions in $CH_4$ emissions have high societal benefits, ranging between 30 USD/MT $CH_4$ of improved agricultural yield and 1000 USD/MT $CH_4$ for defrayed human health costs and 2000 USD/MT $CH_4$ for decreases in the rate of climate change (Shindell, Kuylenstierna et al. 2012).



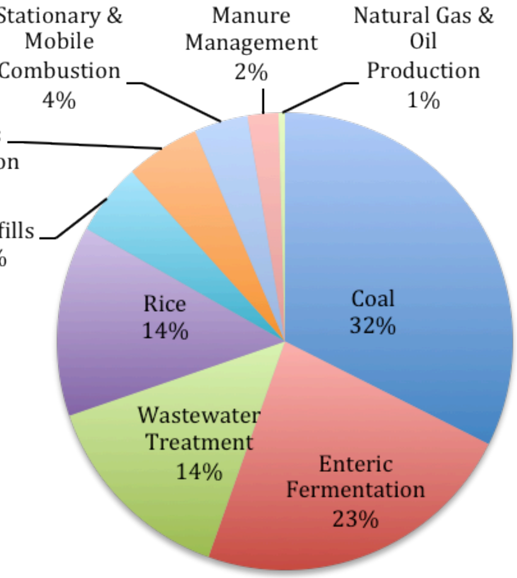


**Figure 1. Global $CH_4$ emissions, 2010. Source: (USEPA 2006)**

**Figure 2. China's $CH_4$ emissions by sector, 2010. Source: (USEPA 2011)**

**In 2010, China was the source of approximately 13% of global methane emissions making it the single largest emitter of methane in the world.** Global $CH_4$ emissions in 2010 totaled 7193 $MtCO_2e$, of which China produced about 925 $MtCO_2e$, surpassing both India and the United States (USEPA 2011). China's methane emissions are a result of its large population and general economic activities, including energy use and production, waste disposal and agricultural processes. Given its large population and increasing rates of per capita consumption, it is likely that China's $CH_4$ emissions will continue to grow if action is not taken now.

**Methane capture and recovery provides an opportunity for China to demonstrate leadership and innovation in environmental management.** Because of its sizable contribution to GHG emissions, China can use targeted policy to substantially reduce global methane emissions. Such actions can be highly cost-effective and would demonstrate the increasing governmental recognition of environmental concerns and may spur other nations to act as well.

**The role of international cooperation in reducing methane, and other short-lived climate forcers, is important.** Because the climate and air quality benefits from $CH_4$ mitigation will be experienced globally, efforts to reduce emissions in one country will benefit all (Mauzerall 2011).

**China's existing partnership with the Global Methane Initiative (GMI) can be built upon to further international cooperation.** Within the GMI, China has been active on the agriculture, municipal solid waste and coalmine methane (CMM) subcommittees. It has specifically played a leading role in CMM activities within GMI and their collaboration has led to positive gains in methane recovery. New international initiatives, such as the Climate and Clean Air Coalition (CCAC), would benefit from Chinese participation. In particular, the CCAC aims to catalyze immediate $CH_4$ emissions reductions by linking high-level financing to portfolio-level projects and by promoting the creation of national action plans to reduce emissions of methane and black carbon.

**This report focuses on identifying methane mitigation strategies for China's municipal solid waste (MSW), manure management, wastewater and natural gas sectors.** Currently, the leading sources of methane emissions in China are coal (32%), enteric fermentation (23%) and wastewater treatment (14%) (USEPA 2006). However, based on demographic changes and energy requirements, we expect emissions from other sectors to grow over the next 25 years. Based on these changes, the following sectors provide opportunity for progress in future $CH_4$ mitigation:

- *MSW:* Currently, increased per capita consumption combined with growing urbanization are causing increasing rates of MSW generation and its byproduct, landfill gas (LFG), comprised of 50% $CO_2$ and 50% $CH_4$. Bolstering the capture and use of LFG is essential to mitigating China's future $CH_4$ emissions.

- *Manure Management:* Changing meat consumption due to socioeconomic development is causing significant growth in the livestock population and thus increasing $CH_4$ emissions from this sector. Strengthening maintenance efforts can enhance its capture.

- *Wastewater:* Methane emissions from municipal and industrial wastewater sources have risen significantly in the past 20 years. Wide-scale biogas recovery from wastewater treatment provides great opportunity for methane capture, but this potential currently remains untapped.

- *Natural Gas:* There is a strong interest in moving the energy portfolio from coal to natural gas in China and a strong push for new domestic natural gas production. This creates opportunity for enhanced methane recovery and capture.

**Methane reduction activities from these sectors provide co-benefits that can enhance China's development goals.** In addition to the widespread benefits of increased crop yields and enhanced air quality that will be experienced globally as a result of decreased methane emissions, China will also experience localized positive impacts. The recovery of methane from oil and gas extraction, as well as its capture from waste management, offer opportunities to enhance domestic energy independence and rural energy access. Enhanced sanitation from waste management and the displacement of traditional rural fuels will also contribute to health improvements in both urban and rural areas.

**We assess these growing fields to examine the potential for emissions reductions by implementing technologies and policies for $CH_4$ capture and recovery.** To achieve this, we perform projections of future methane emissions through 2030 for each sector under different policy scenarios. We seek to understand how demographic and economic changes are likely to affect methane emissions trajectories and examine the potential for emissions reductions through technology substitutions. While the methodologies vary between sectors, each sector simulates three scenarios that can be broadly categorized as "High," "Medium," and "Low" emissions scenarios.[1] The assumptions underlying each scenario depend on the sector, but parallel assumptions were made where appropriate, such as in the number and functionality of household biodigesters to treat animal and human waste. Our projections attempt to define the envelope of likely future methane emissions from various sectors in China and point to opportunities to mitigate future emissions through technological change. The ranges of potential emissions reductions considered feasible in each sector are summarized in Table 1.

---

[1] See the appropriate appendix for sector-specific methodological details. In general, we employed respected methodologies that were feasible given the available data. These included IPCC National Greenhouse Gas Inventory methods and USEPA landfill gas models.

# COAL MINE METHANE (CMM): A GMI – CHINA SUCCESS STORY

Global methane emissions from coalmines were estimated in 2010 to be almost 584 $MtCO_2e$, accounting for approximately 8% of worldwide anthropogenic methane emissions. These emissions are projected to rise by 15% over the next 10 years (Global Methane Initiative, GMI 2011). China's estimated methane emissions from coal mines that same year were more than 295 $MtCO_2e$, greatly outpacing the US, who as the 2nd largest emitter of CMM, released slightly over 68 $MtCO_2e$ (Clean Air Task Force, CATF 2012).

Prior to the early 1990's, CMM in China was simply vented and released in order to enhance coalmine safety. Since then, China has become a national leader in developing and implementing methane capture technology for coalmines.

**China has greatly increased its rate of CMM gas capture and is improving its utilization rates.** In 2009, 96 $MtCO_2e$ was captured from coalmines and 25 $MtCO_2e$ was utilized (CATF 2012).

**China currently leads the world in implementation of CMM capture technologies.** In 2009, it hosted 40 of the world's 96 CMM capture projects at active coalmines (Higashi 2009). Electricity generation capacity from CMM in China is almost 1000 MW nationally and it hosts the world's largest CMM-generated electricity plant at Jincheng, with a capacity of 120 MW (GMI 2011).

**This success was supported through targeted efforts by the USEPA and UNDP-GEF to increase CMM capture and utilization in China's coalmines (Higashi 2009)**. These efforts included the provision of technical resources and financial support, as well as information exchange, technology demonstrations, capacity-building exercises and EPA-sponsored feasibility studies.

**The Chinese government has also enacted policies to encourage capture and utilization of CMM.** These include: requiring CMM to be drained prior to mining; requiring the implementation of emissions monitoring; and requiring the utilization or flaring of CMM with a concentration of 30% or higher. Tax credits and discounts are available to mining operations that implement CMM capture technologies. Priority grid access and subsidies are also available to CMM-generated electricity.

**China now sits on the CMM Subcommittee of GMI and has had success working within the organization to reduce methane emissions.** EPA has supported comprehensive feasibility studies with successful results, as well as sponsored workshops, technology demonstrations and capacity building efforts within China. EPA has also sponsored and conducted feasibility studies for large CMM projects in China.

**The Chinese have innovated in their utilization of CMM for power generation**. This innovation includes adaptation to varying methane concentrations and utilization of low concentration methane, as well as making use of automation and remote operation to run CMM power generation facilities.

**CMM capture and utilization has important co-benefits, including increased safety in mines due to reduced risk of explosion.** This was the original reason for drainage and capture of CMM. Other co-benefits of CMM capture and utilization include improved air quality, improved access to energy and a more diversified energy portfolio.

**CMM capture offers opportunities for enhanced energy security.** CMM can be used as a form of unconventional natural gas, with its uses depending on its methane concentration. In China, CMM is used for town gas, electricity generation, industrial boiler fuel feed, vehicle fuel and heating purposes. Increased capture and use of methane gas has allowed the Chinese to take advantage of a naturally occurring fuel source that was previously being wasted (Higashi 2009).

## LESSONS LEARNED

**China has taken advantage of the co-benefits of decreased emissions of coalmine methane.** These include increased safety in mines, improved air quality and enhanced opportunities for energy security from the capture and utilization of methane as unconventional natural gas.

**For other sectors, the co-benefits and profit opportunities associated with decreased methane emissions should also be highlighted.** These include lower incidences of water-borne and sanitation-related diseases, improved air quality, increased energy access, increased energy security through diversification of energy sources, as well as aforementioned profit opportunities.

## RECOMMENDATIONS

In spite of its successes in the capture and utilization of CMM, China's dramatically growing demand for and production of coal means that it is and will remain the leading emitter of CMM in the world. Given this, we recommend the following:

**Continue working to increase capacity for CMM capture in smaller coalmines.** If rates of capture in smaller coalmines cannot be increased, these mines should be consolidated or closed.

**Facilitate the sale of CMM-generated electricity to the grid.** Implementation of priority grid access for CMM-generated electricity has been slow. Owners of large coalmines with the requisite capacity feel that conversion to liquefied natural gas (LNG) may be more profitable than generation of electricity (GMI 2011).

**Increase capacity for utilization of CMM gas.** Natural gas infrastructure can be used to transport CMM gas, so the construction of infrastructure in association with the developing natural gas industry advances this goal.

**Transfer technology for CMM capture in large coalmines to other GMI partner countries.** By doing so, it can help other coal-producing countries to lower their emissions of $CH_4$.

# ORGANIC WASTE SECTORS

Methane emissions from organic waste account for approximately 20% of China's total $CH_4$ emissions. This includes $CH_4$ produced from the degradation of the organic fractions of municipal solid waste (MSW) in landfills, agricultural manure management and wastewater treatment and discharge. The magnitude of $CH_4$ emissions from China's organic waste sectors alone is greater than the total $CH_4$ emissions from Mexico or Nigeria, both of which are among the top 10 $CH_4$ emitting nations globally (USEPA 2011).

There are broad commonalities across all of the organic waste sectors. The mechanism for $CH_4$ production in all of these sectors is the biological degradation of organic matter in anaerobic environments, which include manure lagoons, landfills and pit latrines, among other waste collection systems. The generation of organic waste is a function of demographics and consumption, so $CH_4$ emissions from the organic waste sector are tightly coupled with population, urbanization and greater consumption of meat and other products. Another important crosscutting theme is the potential for recovering biogas from the degradation of organic waste in landfills or household digesters. Our analyses will show that while biogas recovery already results in significant $CH_4$ emissions reductions, only a fraction of potential biogas recovery has been tapped and additional biogas capture will significantly reduce $CH_4$ emissions as well as yield major co-benefits for energy supply and air quality.

## MUNICIPAL SOLID WASTE

China's economic growth over the past two decades has caused urban centers to swell, average wages to rise and consumption patterns to change. With these changes have come rising levels of municipal solid waste (MSW) and its byproduct: landfill gas (LFG) (Landfill Methane Outreach Program, LMOP 2010). LFG is comprised of roughly 50% $CO_2$ and 50% $CH_4$. Given methane's potency as a GHG, these emissions pose a serious climate risk. The means of abating them include: changing patterns of consumption; increasing the amount of MSW collected and diverted from landfills; and improving management practices and technologies at landfills to ensure that, of the MSW deposited, more of its LFG is collected. As changing consumption requires affecting patterns of individual behavior, our analysis here focuses on abatement opportunities from the latter two categories.

### STATUS OF MUNICIPAL SOLID WASTE IN CHINA

**Progress in urban MSW collection has coincided with declining rates of recycling and composting.** In 2010, the average urban citizen produced 517 kg MSW per year in China (Huang, Wang et al. 2006). We estimate that in 2010, urban areas produced a total of 341 million metric tons (Mt) of MSW, with approximately 67% collected by waste management personnel (Xu 2012), a classification that includes both formal collection and informal waste buyers. Due to space limitations around urban areas and increasing MSW production, incineration has grown rapidly over the past decade. Of the MSW collected, we estimate that approximately 17% would be diverted to incineration facilities in 2010 (Cheng and Hu 2010). However, concerns about localized emissions may constrain this growth in the future.

Recycling once comprised a significant portion of China's waste management process. However economic and political developments have diminished these programs (Wilson, Araba et al. 2009). Today only about 4% of MSW collected is recycled. Composting has also declined as a means of waste management due to ineffective waste sorting (which yields low-quality fertilizer), the growth in chemical fertilizer use and a shrinking agricultural labor pool. Thus, as of 2010 just 2.5% of the waste collected in urban areas was diverted to compost facilities (Xu 2012).

**The quantity and disposal of waste in rural areas differs from that of urban areas.** This is in part because rural areas have a lower per capita income than their urban counterparts and different consumption patterns. Furthermore, in rural areas, population dispersion makes collection more difficult, the municipal budget to support MSW services is often smaller (in absolute terms) and composting is a more practical option. Thus, in 2010, the average rural citizen produced only 390 kg MSW per year (Li, Bai et al. 2011). We calculate that in 2010, rural China produced a total of 266 Mt of MSW.

Based on the average rate of collection for the inland provinces (Wang, He et al. 2011), we estimate that the baseline rural collection rate is 24.5%. Of the MSW collected, we assume that about 6% is diverted to incineration, a smaller fraction than in urban areas due to capital scarcity and greater land availability for landfilling.

**While rates of composting may be higher in rural than urban areas, rates of rural recycling are believed to be lower.** In rural China, the vast majority of waste that is not collected is dumped (Ye and Qin 2008). However, due to the physical proximity of agricultural production and the availability of space to conduct composting, we infer that the utility of compost is greater in rural areas and that composting occurs prior to the collection of waste. Thus, in our projections, we assume that the baseline percentage composted is twice that of urban areas and applied to all organic waste produced, not just that collected.

For recycling, we estimate that a smaller percentage of the MSW collected in rural areas is diverted to recycling because the economies of scale that can make urban recycling viable are less likely to exist in rural areas. Thus we set the rural recycling diversion rate at just 2% in our model, half that of urban areas.

## QUANTIFYING FUTURE METHANE EMISSIONS IN CHINA[2]

In this section, we use the rates and trends described above to estimate the potential future emissions from MSW generated by China's citizens between 2010 and 2030. As significant differences exist in rates of MSW production, collection, diversion and management efficacy, we have divided the following analysis into two categories: "urban" and "rural". In our projections, we simulate three policy scenarios for both categories. The outcome of each hinges upon relative levels of political awareness and investment in MSW systems.

Scenario 1: **"Low" emissions**, increased investment in collection, diversion and LFG collection systems, as well as a concerted effort to improve MSW management and reduce LFG emissions;

Scenario 2: **"Medium" emissions**, largely status quo with declines in recycling and composting halting;

Scenario 3: **"High" emissions,** reduced investment, with continued declines in recycling and composting, as well as a halt in the growth of collection and incineration rates.

Per the changes in investment and policy highlighted above, we project that the following quantities are collected, diverted, landfilled and dumped:

---

[2] Please See Appendix 1 for detailed information on these calculations.

**Table 2. Urban Disposal Scenarios, in Mt.**

| Year | Total MSW | Collected | Diverted | Landfilled | Dumped |
|---|---|---|---|---|---|
| **2010** | 341 | 228 | 48 | 180 | 113 |
| **2030** Low | 1,020 | 923 | 782 | 141 | 98 |
| **2030** Med | 1,020 | 923 | 359 | 563 | 98 |
| **2030** High | 1,020 | 682 | 117 | 565 | 339 |

**Table 3. Rural Disposal Scenarios, in Mt.**

| Year | Total MSW | Compost | Collected | Diverted | Landfilled | Dumped |
|---|---|---|---|---|---|---|
| **2010** | 266 | 7.6 | 63 | 4.1 | 58.9 | 195 |
| **2030** Low | 351 | 67 | 222 | 113 | 108 | 62 |
| **2030** Med | 351 | 10 | 264 | 63 | 201 | 77 |
| **2030** High | 351 | N/A | 86 | 4.9 | 81.1 | 265 |

Given the collection, diversion and dumping statistics outlined above, we project the following emissions of LFG and $CH_4$ based upon differing landfill management practices and technological investments:

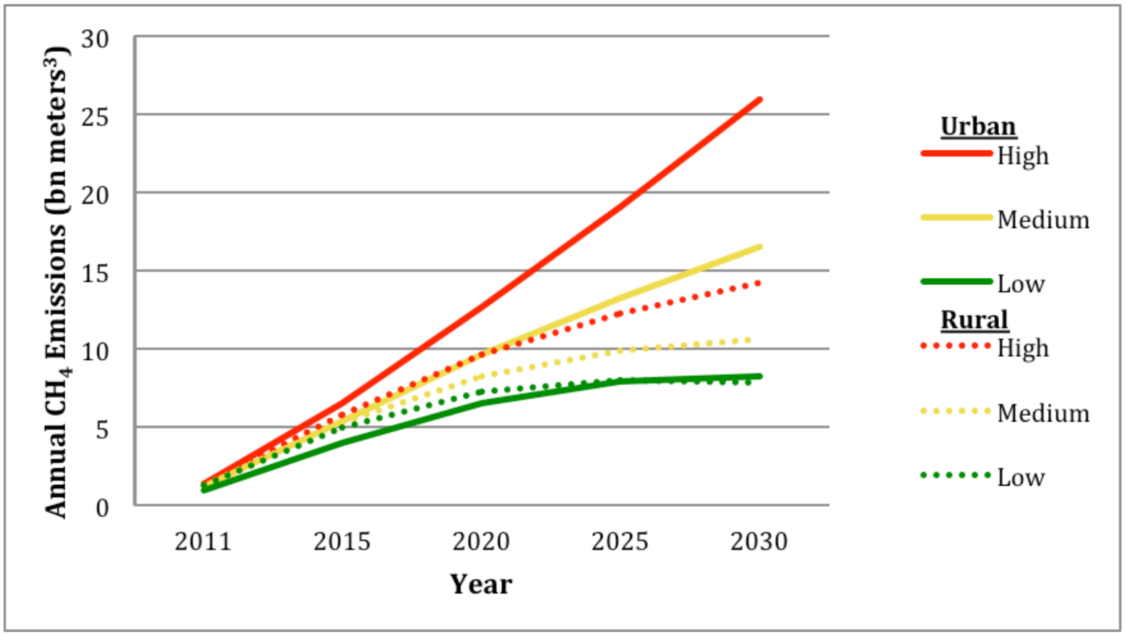


**Figure 3. Projected annual MSW $CH_4$ emissions (2011-2030).**

This graph shows the annual rates of emissions, starting in 2011 and running through 2030, for urban and rural areas in each of the three scenarios. There is a clear increasing trend in all cases for methane emissions from MSW. As the quantity of MSW grows, emissions clearly follow. But the extent to which this occurs may vary greatly depending upon location, collection and diversion rates, landfill management, etc. There is a greater range of potential emissions from urban rather than rural areas. The potential difference between the "low" and "high" scenarios in 2030 in urban areas, for instance, is much greater than that in rural areas in 2030. This has significant policy implications.

## POLICY IMPLICATIONS AND RECOMMENDATIONS

### Focus Resources on Improved Urban MSW Management

*Policies focused upon improving urban disposal and landfill management practices in urban areas would yield greater reductions in methane emissions than those focused on rural areas.* Rural areas start with lower baselines for MSW management. However the amount of MSW that winds up in open dumps and contributes to overall MSW emissions may change less with additional investment as improved collection is less effective the more dispersed the population. Moreover, even if waste reaches rural landfills, lower levels of technology and management may mean more fugitive emissions, undermining $CH_4$ abatement.

*Urban MSW Management Efforts are More Cost Effective than Rural Efforts.* In urban areas, collection sites are likely to be closely clustered, reducing MSW transportation costs. Capital to cover the upfront costs of sorting, recycling and incineration facilities is also more likely to be available. The quantities of MSW generated are also more likely to support the scale economies necessary for certain practices, like recycling, to be economically sustainable. As a result of these factors, it may be less costly on a per capita basis to increase the levels of collection, diversion and landfill management in urban than rural areas, even if you were serving a greater total population.

*Increased $CO_2$ and Black Carbon Emissions May Threaten Climate Gains from Methane Abatement.* By burning waste, rather than allowing it to decompose, incineration avoids $CH_4$ emissions. However, if the emissions of such facilities are not properly controlled, incineration can generate significant quantities of air pollutants including black carbon and $CO_2$, each with negative short- and long-term health and climate effects. On the other hand, incinerators used to produce electricity may result in reduced usage of, and thus reduced $CH_4$ emissions from, coal plants common in China as well as reduced emissions of air pollutants. Policies focused on enhancing MSW management should thus consider the tradeoffs between these various factors.

### Continue to Pursue Alternative Waste Management Methods in Rural Areas.

While conventional methods of MSW management, pioneered chiefly in urban areas, may not translate well to rural locales, alternative methods may. On-site composting, for example, avoids the $CH_4$ emissions of organic waste by eliminating the anaerobic stage in the decomposition process, reducing the amount of MSW that enters the waste stream and decreasing demand for artificial fertilizer (itself a potential climate forcer). Household level anaerobic digesters, discussed elsewhere in this report, also provide a complimentary diversion method in rural areas.

# AGRICULTURE: LIVESTOCK MANURE MANAGEMENT

As China has grown wealthier, its demand for meat and the supporting animal husbandries needed to supply it has grown significantly (Asian Development Bank, ADB 2009). Consequently, the amount of $CH_4$ emitted from the agricultural sector has increased. One method of reducing $CH_4$ emissions from livestock waste is the capture of the biogas produced during the anaerobic decomposition of manure in biogas digesters and the subsequent utilization of that gas. Biogas is produced through the anaerobic decomposition of organic materials (including human, animal and plant waste), however in China, it is primarily comprised of livestock manure (Chen, Yang et al. 2010). The resulting gas can then be used for heating, cooking and lighting. In addition to the energy benefits accrued, its displacement of traditional rural fuels (such as the direct combustion of agricultural waste, firewood or coal) can reduce indoor air pollution, contributing to health and quality of life improvements (United Nations Framework Convention on Climate Change, UNFCCC 2010; Jin 31 Oct 2012).

## THE CURRENT STATUS OF HOUSEHOLD BIOGAS DEVELOPMENT IN CHINA

**The Chinese government has invested heavily in technology development and household biogas digester installation.** Since 2001, it invested over 650 billion RMB in biogas development for the primary purpose of promoting rural energy security (Chen, Zhao et al. 2012; Feng, Guo et al. 2012). Its policies were extremely successful in rapidly increasing the number of biodigesters. From 1994 to 2000, approximately 50 thousand biodigesters were installed per year (Feng, Guo et al. 2012). By 2010, more than 38 million biodigesters had been built, with a collective annual biogas output of 13 billion $m^3$ (Chen, Zhao et al. 2012). The government has now set targets to increase the number of biodigesters to 80 million by 2020 (National Development and Reform Commission, NDRC 2007).

**Poor maintenance has diminished biodigester functionality, undermining gains in the installation of new biodigesters.** In the past, subsidies have been provided to farmers to pay for cement and biodigester installation. These subsidies did not, however, cover the costs of follow-up maintenance. A 2005 assessment found that only 60% of installed biodigesters in China actually functioned properly, with many becoming obsolete after only one to three years of operation (Zhang, Wang et al. 2012). The persistence of these functionality failures in combination with demographic change in rural areas of China resulted in the obsolescence of many biodigesters (Zhang, Wang et al. 2012). As a result, the rapid increase in digester installations over the last 30 years may overestimate actual $CH_4$ capture if it fails to account for low functionality.

**Recent policies have attempted to address maintenance failures, though capacity to do so is limited.** Policies supporting maintenance were created in accordance with the 11th Five Year Plan. A biodigester service system has recently been created that is comprised of county-level centers and rural service outlets providing maintenance and repairs in addition to biodigester installation services. By 2010, there were already 756 county-level service centers and approximately 79,000 rural service outlets. However, this system has already become overburdened due both to human capital constraints and a backlog of maintenance requests (Chen, Zhao et al. 2012).

**Current biodigester technology does not adequately address future trends in methane emissions from agriculture.** While China has been successful in promoting biogas digester installation, the country is now experiencing changes that will influence the potential for household biodigesters to reduce $CH_4$ emissions from the agriculture sector. In 1990, $CH_4$ emissions from agriculture were mainly from the southern provinces of China, but by 2006, $CH_4$ emissions from agricultural sources in the northern provinces of Jilin, Heilongjiang and Hebei had more than doubled (Fu and Yu 2010). Many of these areas never achieve ground temperature above 20°C (the temperature at which biogas production occurs efficiently), making them poorly suited for traditional household biogas production and use as an energy source (Chen, Yang et al. 2010). Because the energy security aspect of biogas production has driven China's biogas expansion, this shift may prompt a lessening in government support for production and maintenance efforts.

Another important change is the shift, starting in the 1980s, from household livestock production to large and medium-scale operations (Rae 2008). However, in 2007, despite the existence of approximately 20,000 medium and large-scale livestock farms, many with anaerobic digesters, only 3% were able to generate power (Chen, Zhao et al. 2012).

## QUANTIFYING METHANE EMISSIONS FROM MANURE MANAGEMENT & POTENTIAL CAPTURE

To determine the potential avoided emissions from the use of household biodigesters from 2010 to 2030, we simulate the following three scenarios where the number of household biodigesters remains constant at:

Scenario 1: The 2010 number of household biodigesters (38 million);

Scenario 2: 75% of the 2020 government target for biodigesters (60 million);

Scenario 3: The 2020 government target for household biodigesters (80 million).

For each scenario, we consider two different levels of biodigester functionality. In the first, 60% of installed biodigesters are fully operational and the remaining 40% are nonfunctioning (which, for the purposes of our calculations, we interpret as 100% leakage of all the $CH_4$ generated). This is consistent with the status quo efficiency levels detailed in the Zhang et al. (2005) assessment. In the second level, all installed biodigesters are assumed to be fully operational.

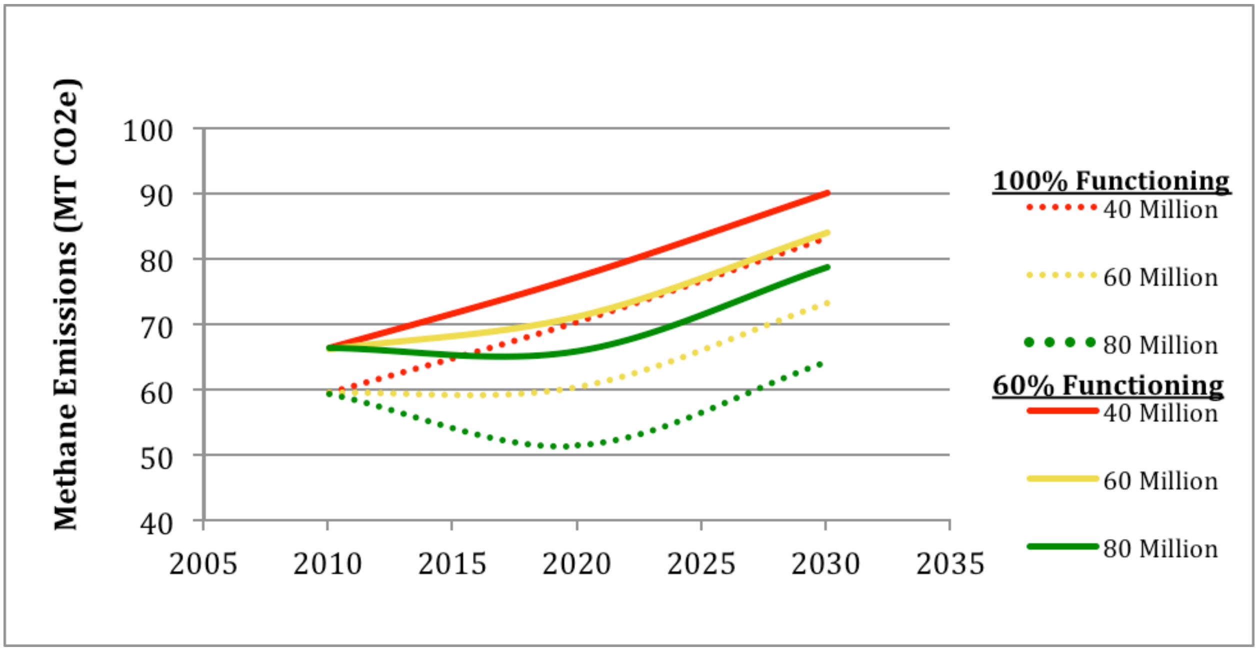


Figure 4. Projected uncaptured methane emissions from biodigester management of livestock manure (2012-2030).

We find that the initial decrease in emissions for scenarios 2 and 3 (from an increase in the number of biodigesters) disappear by 2020 because the technology interventions saturate against the growth in emissions from livestock manure. If China were to maintain its existing 40 million household biodigesters at 60% efficiency, approximately 12% of livestock manure emissions in 2020 could be captured. If instead it were to reach its 2020 goal of installing 80 million biodigesters, nearly 25% of $CH_4$ emissions from manure would be captured. To achieve this, aggressive and ongoing biodigester maintenance efforts would need to be implemented simultaneously with large increases in the number of biodigesters installed.

**Enhancing biodigester functionality with limited new installations is superior to pursuing the 2020 target number of household biodigesters.** Expanding these projections to 2030, we find, however that it would be more advantageous to install only three-quarters of the 2020 goal and pursue full efficiency levels rather than to aim only to achieve the 2020 target. If proper maintenance is implemented and full efficiency was achieved for only 60 million biodigesters, the percent of $CH_4$ emissions captured in 2030 would be more than 20% higher than if the target number of biodigesters were installed under status quo efficiency.

### RECOMMENDATIONS

**Increase funding for maintenance and if necessary, reallocate funding from the installation of new biodigesters to maintenance.** Maintenance and repair is an area currently being spearheaded by NGOs and Chinese government bodies, but is in need of greater attention and funding. By repairing digesters and bringing them back to full production capacity, $CH_4$ capture and use can be enhanced. Yet, given that the lifespan of the older biodigesters is only 20 years (Zhang, Wang et al. 2012), it may not be possible to restore all digesters to even partial functionality. Instead, funding should focus on the maintenance of newly installed digesters, in conjunction with increases in digester installations, to ensure that they do not become prematurely obsolete. This is consistent with a scenario in which only three-quarters of the 2020 goal is achieved and maintenance efforts are pursued.

**Fund research and investment in technology improvements to make biogas production more cost effective in cold climates.** Due to China's vast experience with household level biogas production, it may be more technically feasible to further explore biodigester technology than to design alternative technologies for $CH_4$ mitigation in colder climates. Moreover, since $CH_4$ emissions have not been the driving force behind biodigester development, any alternative would have to include a set of comparable co-benefits. As a result, new technologies should be aggressively pursued in order to combat the growing $CH_4$ emissions from agriculture in China's northern provinces. The cost effectiveness of implementing such technologies at the household level may, however, constrain such a strategy.

**Enhance financial support for the development of biogas infrastructure in large and medium-scale livestock operations.** Biogas production in large and medium-scale livestock operations is largely underdeveloped. Without early technological intervention, emissions from livestock manure will rise rapidly as larger livestock operations become more common. Because there may be economies of scale, larger centralized biodigesters may offer an opportunity to introduce cost-effective cold weather biogas technologies in China's northern provinces.

## WASTEWATER

China is a major contributor to global methane emissions from wastewater, but rapid changes in the country's wastewater infrastructure provide opportunity for curbing future growth in emissions. China's $CH_4$ emissions from municipal and industrial wastewater sources grew from 114 $MtCO_2e$ to 132 $MtCO_2e$ between 1990 and 2010 and now account for 29% of global wastewater emissions (USEPA 2011). Reducing emissions from China's wastewater sector—either through limiting the use of $CH_4$ generating wastewater treatment technologies or through capturing $CH_4$ for flaring or energy use—can reduce $CH_4$ emissions and yield co-benefits in terms of sanitation, health, as well as water pollution and scarcity.

### CURRENT STATUS OF WASTEWATER TREATMENT AND METHANE EMISSIONS IN CHINA

**The majority of wastewater generated in rural areas undergoes limited or no treatment.** Approximately 50% of Chinese people live in rural areas, where on-site treatment technologies, like pit latrines or direct discharge to water bodies, are the dominant wastewater disposal pathway. Pit latrines are significant sources of $CH_4$ and on a per capita basis produce more $CH_4$ than centralized municipal wastewater treatment plants (IPCC 2006). The USEPA estimates that $CH_4$ emissions from latrines account for 74% of China's domestic emissions from wastewater (USEPA 2011).[3]

---

[3] We calculate that pit latrines account for about 40% of China's domestic wastewater emissions. This discrepancy may be attributable to the EPA using emission factors other than the IPCC default values for China or to different assumptions about the share of wastewater treated by municipal wastewater versus industrial plants.

**Access to centralized wastewater treatment in urban areas has expanded significantly in the past decade,** with the number of municipal wastewater treatment plants (WWTPs) in China increasing from about 500 in 2002 to an estimated 2000-6000 in 2012 (Xu 30 Oct. 2012; Zuo 31 Oct. 2012; International Trade Administration 2005). Estimates for sewage coverage vary, but approximately 52% of Chinese are connected to wastewater treatment facilities and 64% have access to improved facilities (a broader category that includes pit latrines and off-grid technologies), up from 24% coverage in 1990 (Lieu 2009; WHO/UNICEF 2012). Access to centralized treatment closely parallels economic development, with higher rates of treatment primarily associated with the more prosperous eastern provinces (He, Lü et al. 2007).

**Anaerobic treatment of wastewater and sludge are primary sources of methane emissions.** Regardless of the type of treatment, GHGs are emitted directly during wastewater and sludge treatment. The major sources of $CH_4$ emissions are from sewers and the anaerobic treatment of wastewater and/or sludge (Guisasola, de Haas et al. 2008; Daelman, van Voorthuizen et al. 2012). Sludge has the potential to be the primary source of $CH_4$ emissions from WWTPs if it is allowed to degrade anaerobically without biogas recovery. Because of the low capital and operational costs, most of China's sludge is dried and landfilled, which has high potential for $CH_4$ emissions if there is no $CH_4$ capture from landfills (Chai 2012). Currently, relatively few landfills recover landfill gas, so most landfilled sludge contributes to $CH_4$ emissions. Additionally, anaerobic pockets can also form during aerobic treatment processes in WWTPs and can be a source of $CH_4$ emissions.

**Energy requirements for WWTPs have significant GHG emission implications.** Beyond its direct GHG emissions, sewage treatment in WWTPs requires large amounts of energy, much of which is produced by fossil fuels and is thus associated with indirect GHG emissions and higher operational costs. Lifecycle assessments of emissions from WWTPs indicate that biogas recovery from anaerobic treatment processes can replace some or all of the energy required for wastewater treatment (El-Fadel and Massoud 2001; Bani Shahabadi, Yerushalmi et al. 2010; Wang, Liu et al. 2012). A small number of WWTPs in Beijing and Shanghai currently produce about 25% of their electricity needs from biogas, but electricity generation is the exception rather than the norm (Zuo 31 Oct. 2012). Constructed wetlands, which couple high biochemical oxygen demand (BOD) removal with low lifecycle GHG emissions, may prove to be a valuable alternative to centralized WWTPs from the standpoint of energy and lifecycle emissions (Chen, Shao et al. 2011; Pan, Zhu et al. 2011; Shao, Wu et al. 2012). Constructed wetlands are best suited for suburban, peri-urban, and rural applications where land is relatively abundant. As of 2008, there were more than 200 constructed wetlands in China, with most in the eastern part of the country where greater financing was available. The western regions of China are especially suited for further expansion of constructed wetlands, due to their relatively low population (Liu, Ge et al. 2009).

### NOTABLE MUNICIPAL WASTEWATER TREATMENT PLANTS WITH BIOGAS RECOVERY

The German development agency GIZ finances the Heilongjiang Bin project in northeast China that will supply cooking gas to 35,000 households using a combined feedstock of municipal waste and animal (cattle and pig) manure. Scheduled to open in late 2012, the plant will operate in temperatures as low as -31°F and will generate nearly 12 million cubic meters of gas per year. Total investment is about $8.6 million, which includes a $2.7 million subsidy from the Chinese government (GIZ 2012).

## QUANTIFYING FUTURE METHANE EMISSIONS FOR CHINA'S WASTEWATER SECTOR

In our projections, we simulate the following three scenarios:

Scenario 1: **Existing wastewater treatment technology** with population growth and increasing urbanization through 2030. The existing technology described in the 2006 IPCC GHG inventory (Doorn, Towprayoon et al. 2006) is modified here to include 38 million household biogas digesters in rural areas;

Scenario 2: In addition to demographic changes, **moderate improvements** to urban and rural wastewater treatment technologies are assumed, including an increase in the number of household biogas digesters to 60 million; and

Scenario 3: A **maximum feasible technology** case in which China's wastewater infrastructure in 2030 is identical to that of the United States in 2010, with the exception that rural populations are equipped with pit latrines and 80 million household biogas digesters instead of the septic systems that are common in rural areas of the U.S. This scenario assumes that 95% of urban wastewater is treated in well-managed WWTPs with negligible $CH_4$ emissions.

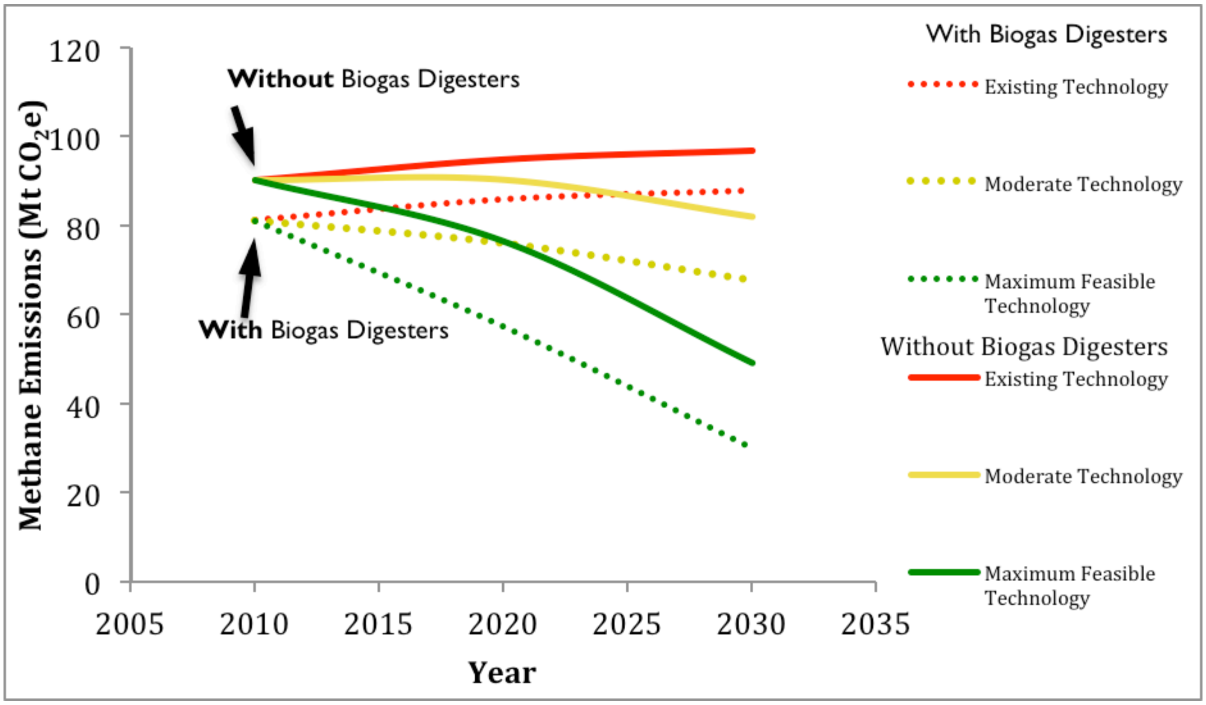


**Figure 5. Methane emissions reductions from wastewater treatment under different scenarios.**

## Table 4. Key Conclusions for China's Wastewater Sector from Future Emissions Scenarios.

| | Existing Technology | Moderate Technology Expansion | Maximum Feasible Technology |
|---|---|---|---|
| **Estimated $CH_4$ Emissions from Wastewater, 2030** | 87 $MtCO_2e$ (~7% increase relative to 2010 baseline estimate) | 62 $MtCO_2e$ (~25% reduction relative to 2010 baseline estimate) | 26 $MtCO_2e$ (~65% reduction relative to 2010 baseline estimate) |
| **Outlooks** | Household biogas digesters reduce $CH_4$ emissions by ~9 $MtCO_2e$ (~10% of total domestic wastewater $CH_4$ emissions). Increasing urbanization limits even greater increases in emissions. | Highlights potential tradeoff between improved wastewater treatment and $CH_4$ emissions in rural areas, as populations formerly without treatment are now utilizing pit latrines. | Continuing rapid expansion in the number of WWTPs and major improvements in managing WWTPs. Widespread adoption of biogas digesters to limit emissions from rural areas. |

## RECOMMENDATIONS

**Expand anaerobic treatment of municipal sewage to facilitate biogas recovery.** Recovery of biogas from municipal WWTP is currently low. Roughly one-third of WWTPs in China currently use anaerobic treatment methods that could be upgraded to recover and use biogas. Anaerobic treatment is a promising and cost-effective approach, when coupled with biogas recovery, to treat municipal sewage and also meet the energy demands of treatment plants or local populations. Sludge incineration and digestion with biogas recovery are two promising, but limited technologies that could be scaled up to facilitate $CH_4$ mitigation from this sector as well as provide a local energy source. Better management of WWTPs can also mitigate anaerobic pockets in aerobic treatment processes.

To date, there are no GMI projects in China focused on this sector and only a small fraction of wastewater treatment projects receiving CDM financing focused on municipal wastewater treatment. Therefore, despite pockets of progress, wide-scale biogas recovery remains an untapped opportunity to reduce GHG emissions while lowering energy costs. As wastewater treatment expands in China, this potential will continue to grow.

**Continue to expand biogas capture and utilization from latrines.** The connection of pit latrines to household-scale anaerobic digesters to produce biogas is a promising alternative with major benefits for both $CH_4$ emissions reductions and rural energy supply and development. While leaks from biogas digesters pose a potential problem, the waste in a pit latrine is already fully anaerobic, which represents a strong $CH_4$ source. Any capture and use of this produced $CH_4$ thus represents an improvement over a pit latrine with no $CH_4$ capture.

**Expand constructed wetlands in rural and peri-urban areas.** In addition to having a lower initial investment cost than traditional WWTPs, lifecycle analyses of constructed wetlands show that GHG emissions from these treatment systems are half those of conventional WWTPs per kilogram of BOD removed, while maintaining high performance in removal of BOD and nutrient pollution (Chen, Shao et al. 2011; Shao, Wu et al. 2012). Beyond cost savings, constructed wetlands provide beneficial ecosystem services including carbon sequestration, seasonal agriculture, reusable water supply, habitat conservation, biomass production, and educational and recreational uses (Liu, Ge et al. 2009). Constructed wetlands would be appropriate in small cities or peri-urban areas where land scarcity is not an issue, particularly for the 50% of China's rural population whose wastewater is currently discharged to lakes and rivers. For decentralized wastewater treatment, constructed wetlands could reduce China's emissions by 8-17 $MtCO_2e$ per year (Pan, Zhu et al. 2011). Given the significant share of methane emissions from pit latrines without biogas capture—10 million people produce emissions equivalent to 1.1 $MtCO_2e$—transitioning this population to constructed wetlands would be a superior option to centralized wastewater treatment from lifecycle GHG and cost perspectives. Although constructed wetlands do not have the same energy co-benefits as pit latrines with biogas capture and use, they appear especially promising for towns and villages where pit latrine users are concentrated.

**Improve the quality and detail of available data about wastewater treatment and WWTPs in China**. Scientists at the Chinese Research Academy of Environmental Sciences (CRAES) are currently developing country-specific emission factors and its Second National Communication on GHG Emissions from the Waste Sector is expected to be publicly released in 2013 (Gao 2012). It is important that future inventories include data describing treatment process type, volume of water treated, BOD and GHG emissions information, where available, in order to understand the landscape of $CH_4$ and other GHG emissions generated during wastewater treatment.

# NATURAL GAS SECTOR

Methane leaked from fossil fuel production accounts for approximately 33% of China's total methane emissions. Methane from coalmines accounts for most of that fraction. There is currently a small contribution from methane that escapes during oil and natural gas production. However, natural gas production from unconventional sources is projected to increase dramatically in China in the coming decades, making this sector especially worthy of careful examination.

Methane is the primary constituent of natural gas. Leaks of natural gas during production, transport and distribution are causes of methane emissions to the atmosphere. Likewise, small leaks of natural gas, which coexist with oil in reservoirs, escapes during oil production. Leaks in the natural gas system typically occur when a well is temporarily open for maintenance and repair, or when small bleeds from transportation pipelines and compression equipment exist. The leaks from natural gas systems are thus a function of the particular system and throughput of gas. As gas usage increases, we expect to see more leakage and higher methane emissions unless there is a change in technology and maintenance practices to seal up the system. The analysis that follows will estimate the emissions that will result from the expansion of the Chinese natural gas industry and the potential for emissions reductions using cost-effective technologies to prevent leaks.

The use of natural gas in China is growing rapidly and may approach current US rates by 2030. China is currently the world's 4th largest consumer of natural gas using 130 bcm in 2011. That consumption amounts to 4% of the Chinese energy portfolio. Projections from the International Energy Agency (IEA) indicate that the annual gas market in China may approach 500 bcm by 2030 (IEA 2012a). The Chinese government hopes much of that new gas will come from new domestic development and will include a significant contribution from unconventional gas sources including gas shales, tight sands and coalbeds (Nakanom, Pumphrey et al. 2012). We believe that the expansion of the gas industry in China provides a significant and unique opportunity for the deployment of best practices for capturing and preventing $CH_4$ emissions and bringing additional billions of cubic meters of gas into China's energy portfolio.

## NATURAL GAS MARKET OVERVIEW

**The Chinese gas market is currently oligopolistic; it is managed by 3 state owned enterprises.** The "Big Three" energy companies in China are the primary producers of domestic oil and conventional natural gas. They are: China National Petroleum Corporation (CNPC), which owned 73% of total gas output in 2010 and monopolizes pipeline construction and operations; China National Offshore Oil Corporation (CNOOC), which leads the development of three liquefied natural gas (LNG) import terminals and manages much of offshore production; and Sinopec, which operates the most promising conventional gas asset in China, the Puguang natural gas field (IEA 2012b). Guaranteed by both government policy and enormous market share, the Big Three dominate the exploration, production and import of natural gas in China as well as control the wholesale market and pipeline transmission.

**The natural gas price in China is between 2 and 5 times the US price, due to higher production and import prices.** Gas prices in most provinces in China are regulated using a cost-of-service approach where the end-user price is a sum of production costs. This sum includes the ex-plant price, a pipeline transportation tariff and city gas distribution fees. The ex-plant price is the price paid to the field operators and contributes the most to the end-user price (IEA 2012b). The end-user prices in selected cities in China in 2011 ranged from 7 to 25 USD/MBtu. As a comparison, the 2011 gas price in the Middle East and North Africa was 1-4 USD/MBtu and was 4-5 USD/MBtu in the US (IEA 2012b).

**Two recent pilot programs indicate the Chinese government's interest in a move toward market pricing.** Under the new system, a netback approach is used to link the city-gas prices (ex-plant price plus the transportation fee) in Guangdong and Guangxi provinces to the prices of specified petroleum products. It is thought that market-based pricing will spur innovation and investment into new production in the Chinese gas industry.

## POLICY FRAMEWORK

**The Chinese government has expressed a strong desire to pursue fast development of domestic gas production, mainly shale gas**. There has been a recent surge in gas use from 2000-2010, which is anticipated to continue based on China's 12th Five Year Plan. The share of natural gas in primary energy consumption is targeted to increase from 4% in 2010, to 8% in 2015 and 10% in 2020, with an annual growth rate of 18.7%. The targeted total consumption in 2015 will double the 2011 level (130 bcm) to reach 260 bcm (IEA 2012a; IEA 2012b; Nakanom, Pumphrey et al. 2012). In order to support achieving the targets, the subsidy for shale gas production from 2012 to 2015 is set at 0.4 RMB Yuan/m$^3$ (6.4 cents), which is much higher than that for coal-bed methane, which has been set at 0.2 RMB Yuan (3.2 cents) since 2007.

**In November 2009, US president Obama and Chinese president Hu announced the launch of the US-China Shale Gas Resource Initiative**, which covers (1) Resource assessment, using US experience to assess China's potential and promote environmentally sustainable development of shale gas resources, (2) Technical cooperation: joint technical studies to support China's accelerated shale gas development and (3) Investment promotion: promotion of shale gas investment in China through the U.S.-China Oil and Gas Industry Forum, study tours and workshops focused on shale gas development (US Department of Energy, DOE 2009).

**The traditional dominance of the Big Three energy companies in China has not been seen in exploratory shale gas ventures.** In order to promote investment and encourage competition in the shale gas industry, exploration licenses for shale gas are put to auctioned. Though the first auction in 2011 was exclusive to six invited publicly-owned companies, in which Sinopec and a provincial coal seam gas company won the bids for two blocks, the second tender process in 2012 was open to small companies, private investors and foreign joint ventures. The Big Three were absent from the top echelon of bidders in the second auction (Ministry of Land and Resources 2012). See Appendix 4 for further details.

**Potential environmental regulation of the methane emissions from the natural gas industry would likely be under the Department of Climate Change within the National Development and Reform Commission (NDRC).** The regulatory role of the government is relatively weak in the gas industry, with the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) providing overall supervision, the Ministry of Land and Resources issuing exploration and production licenses, the Ministry of Finance administering subsidy programs and Ministry of Foreign Affairs coordinating international cooperation of gas imports.

### NATURAL GAS PRODUCTION RESOURCES – CONVENTIONAL VS. UNCONVENTIONAL

*Conventional gas* refers to natural gas extracted from reservoirs with sufficiently high permeability such that high recovery is typically achievable with vertical wells.

*Unconventional gas* represents natural gas extracted from low-permeability reservoirs, which include coalbeds (coalbed methane or CBM), tight sandstone, and shale formations. Gas extraction from these reservoirs requires advanced technology such as hydraulic fracturing and horizontal drilling for economically viable recovery rates.

## FUTURE PRODUCTION RESOURCES

**Coal bed methane (CBM) is currently the primary source of unconventional gas in China and will continue to be the major unconventional gas source prior to 2015.** The production target for CBM in 2015 is more than 30 bcm, while the target for shale gas is 6.5 bcm. However, shale gas is potentially more important in the long run, because by the end of 2011, the remaining recoverable resource of shale gas (36tcm) exceeded CBM (9tcm) (US Energy Information Administration, EIA 2011).

**Future Chinese natural gas production levels will likely hinge on the growth of shale gas.** The geological and recoverable resource potential of shale gas is anticipated to be large: 134 and 25.8 trillion cubic meters (tcm) respectively (excluding Qinghai-Tibet area) (Nakanom, Pumphrey et al. 2012). The official goal for Chinese domestic shale gas production is 6.5 bcm in 2015 and 60-100 bcm in 2020. The development of shale gas is currently centered in Sichuan Basin because of the available infrastructure and the resource availability.

**Presently, shale gas development in China is still at the preliminary stages of assessment and exploration, with no commercial production.** Shale gas producers would need to drill thousands of new wells by 2020 to meet the development goals set out in the 12th Five Year Plan. Unofficial estimates have 2 wells being drilled each month for the past year (Schneider 2012). The targeted production boom is unlikely to occur in this decade, but the large resources available and drastic need for domestic energy sources favor the eventual development of shale gas reserves in China.

## COST-EFFECTIVE EMISSIONS REDUCTION TECHNOLOGIES

**Cost effective measures in natural gas production and distribution can reduce emissions by up to 90%.** The technical interventions that can be used to prevent $CH_4$ emissions during gas production and distribution that have been demonstrated to be profitable by the U.S. EPA Natural GasSTAR program number in the dozens. The special report, *Leaking Profits* (Natural Resources Defense Council, NRDC 2012) from the Natural Resources Defense Council, highlights 10 of those technological interventions that can produce reductions in $CH_4$ emissions by up to 90% in the U.S. oil and gas industry. Due to the higher natural gas prices in China than in the US, each of these interventions is likely to be more revenue positive for the oil and gas operators in China than in the US.

**The high price of natural gas in China makes emissions control technology highly cost-effective and profitable.** Table 5 shows a cost-benefit analysis for three highlighted emissions controls technologies used in natural gas production: Reduced Emissions Completions [REC], Instrument Air Pneumatic Systems [APS] and Plunger Lift Systems [PLS]. At US prices, the payback period for each technology is less than 1 year on a per installation basis. At Chinese prices, even conservative ones, the extremely favorable economics of reducing $CH_4$ emissions through natural gas leaks shows payback in months. These calculations are based on calculations from the Natural Gas Star databases.

## COST EFFECTIVE TECHNOLOGIES

**Reduced Emissions Completions** (REC) are otherwise known as green completions or reduced flare completions. RECs are carried out with portable equipment, owned or rented by an operator, when a natural gas well is undergoing completion or a workover. Completion occurs after a well is hydraulically fractured. It is the process that is used to remove fracturing fluids and sand from the well bore. In the United States, RECs are already required by state level regulations in Wyoming and Colorado. They will be required nationwide by 2015 through the EPA's New Source Performance Standards, which regulates volatile organic compound emissions from natural gas production and storage operations.

**Plunger Lift Systems** (PLS) are devices that carry substantial co-benefits for operators in addition to allowing increased capture of natural gas. They provide an opportunity for capturing the largest segment of emissions of natural gas from already producing wells, which are emissions during workovers, blowdowns and maintenance. Operating wells, whether conventional or unconventional, are periodically stopped to clear fluids and other debris from the well bore. During this stoppage, the gas that is in the well bore is typically released to the atmosphere or flared, as the well is open to allow the fluids to be removed. PLS are installed in the well and periodically clear the wellbore of fluids and debris by running a mechanical plunger up and down the bore hole.

**Instrument Air Pneumatic Controllers** (APC) are switches that are placed throughout the oil and gas production and distribution sector. They are pneumatic devices that regularize flow, pressure and temperature throughout the system. The valves are traditionally natural gas driven and often leak $CH_4$ when changing states or in a continuous bleed. Newer designs exist to replace the natural gas driven designs with designs driven by air.

Table 5. Economic and Environmental Benefits of Emissions Reduction Technology.

| | | Value of Gas Reclaimed | | Technology Costs | | Payback Period | |
|---|---|---|---|---|---|---|---|
| **Tech** | **Savings** (Mcm) | **US Prices** ($3/MMBTU) | **Chinese Prices** ($6.5/MMBTU) | **Purchase Cost** ($) | **Operating Cost** ($/yr) | **US** (months) | **China** (months) |
| **REC** | 7,600 | 810,000 | 1,755,000 | 500,000 | 121,250 | 5 | 2 |
| **APS** | 570 | 60,000 | 130,000 | 60,000 | | 12 | 5 |
| **PLS** | 520 | 54,750 | 118,625 | 10,363 | | 2 | 1 |

## QUANTIFYING FUTURE EMISSIONS FROM NATURAL GAS PRODUCTION

**Chinese demand for natural gas is projected to increase by 4-5 times in the next 20 years.** Our future scenarios for gas consumption and production are based on two IEA reports. We chose them to feature high and low production scenarios with some internal consistency. The high and low gas production scenarios are estimated from IEA's Golden Rules in a Golden Age of Gas (IEA 2012a). See Appendix 5 for more details on the Golden Rules. The moderate gas production scenario is based on the New Policies Scenario in the World Energy Outlook, WEO-2011, which is also the baseline/central case used in Golden Rules in Golden Age of Gas to assess and generate the Golden Rules Case and the Low Unconventional Case. Figure 6 shows the Chinese demand and domestic production in the low, moderate and high growth cases. The details of these projections are discussed in Appendix 6.

**Projections show 100 – 300 bcm of new natural gas production in China by 2030.** The rapidly growing demand for natural gas in China will be met by a combination of imports and new domestic production. The amount of new production in our projections varies in the IEA projections for 2020 and 2030. Figure 7 shows the breakdown of absolute production into conventional and unconventional gas production in the low, medium and high activity cases. Note that by 2030, conventional gas production in China is predicted to have fallen from current levels for all scenarios and growth in production comes from unconventional resources.

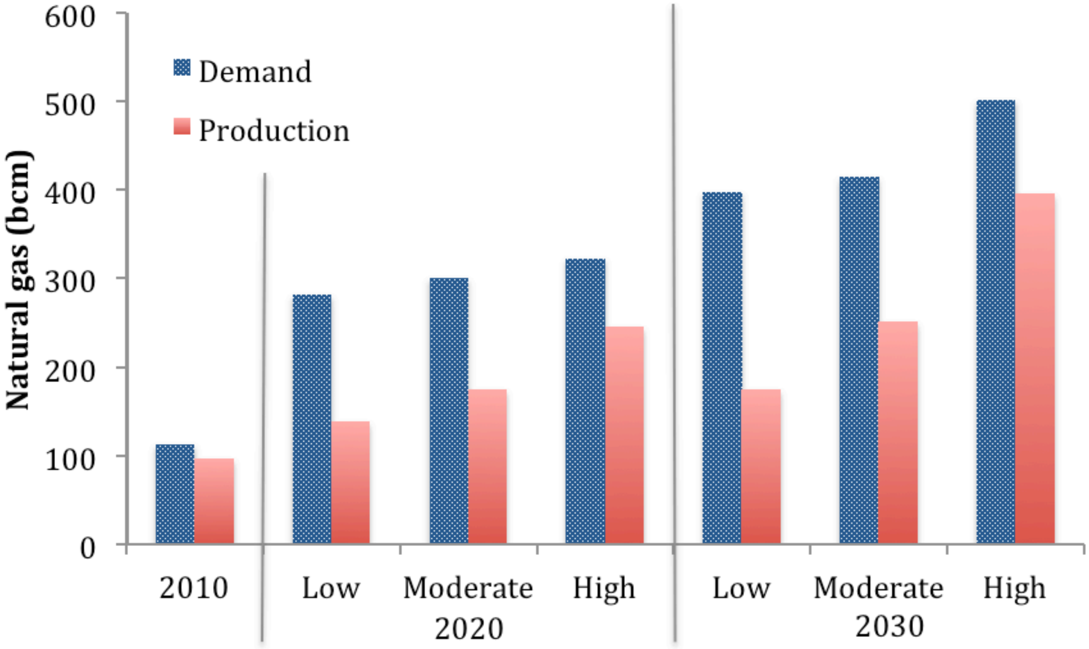


Figure 6. Future scenarios for natural gas production and demand. (IEA 2012a)

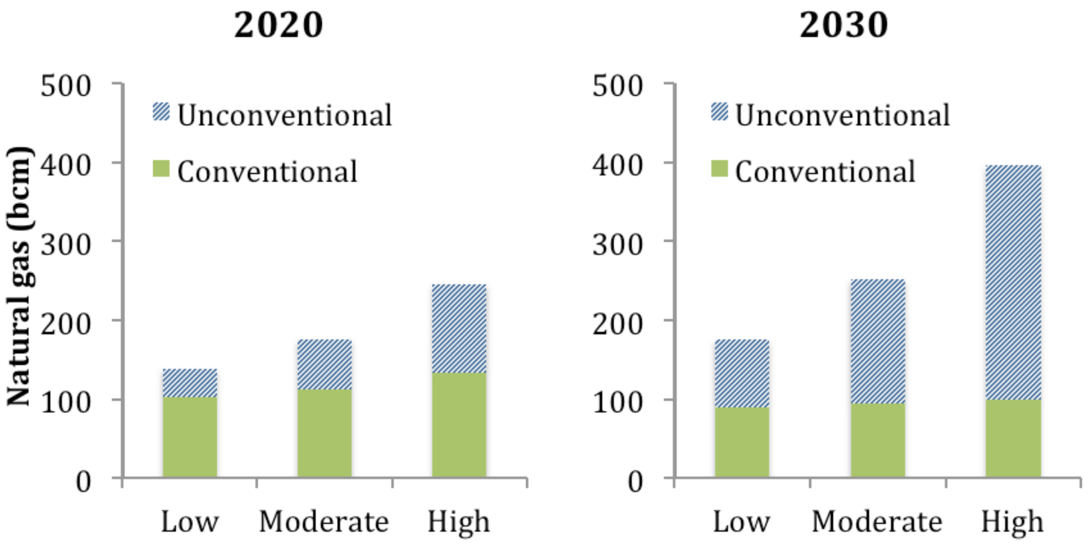


**Figure 7. Conventional vs. unconventional natural gas production. (IEA 2012a)**

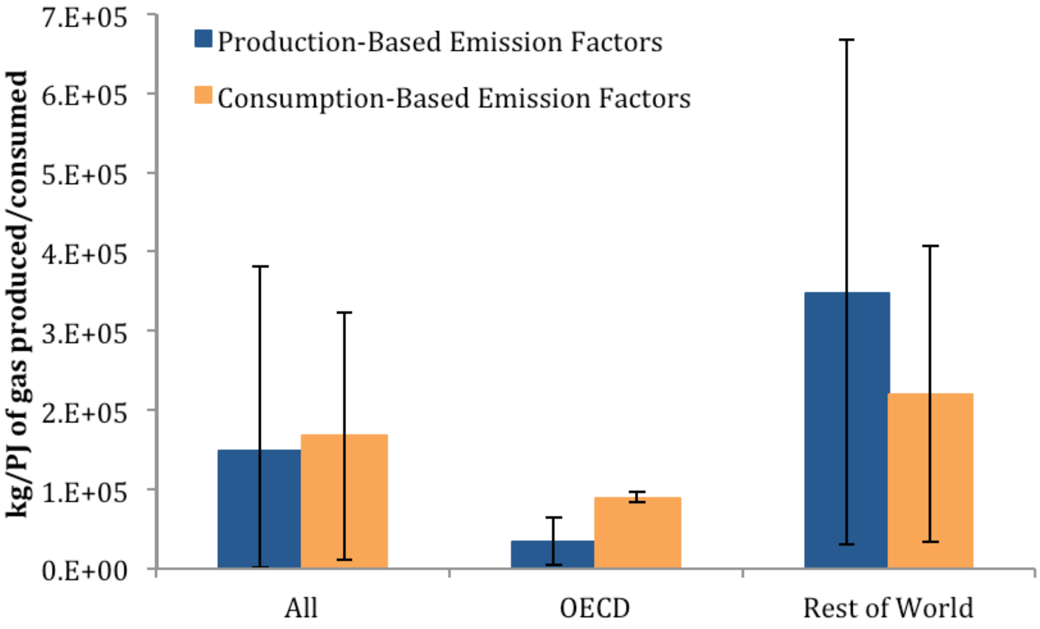


**Figure 8. Methane emission factors calculated based on the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Reference Manual (Volume 3) for natural gas and oil systems.**

**Emission factors for bulk oil and gas production are highly uncertain and limit their predictive ability (see Figure 8).** According to the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 1, Annex 1), uncertainty in $CH_4$ emission estimates associated with oil and natural gas activities are more attributed to uncertain emission factors. Using the standard deviation as a rough measure of uncertainty, Figure 8 shows that the emission factors are highly uncertain as the standard deviations of emission factors for all regions are comparable to the mean.

**Some findings claim that producing shale gas produces 2 or more times the methane emissions than conventional gas production.** The role of shale gas development in $CH_4$ emissions is an active area of research in the United States (Howarth, Santoro et al. 2011) and regulations in the U.S. are continually being proposed and amended to reflect new information and concerns. However, the increase in emissions from production due to shale gas development is not large relative to the uncertainty associated with the global emission factors. Emission factors for shale gas production outside of the U.S. are not available.

**Given the uncertainty in emission factors, we uniformly apply a bulk emission factor of $10^5$ kg/PJ to China's natural gas production activity including demand and production (both conventional and unconventional).** We use the $CH_4$ emission factors for gas produced or consumed from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. This IPCC inventory relies on outdated data from 1996; however, as shown in Figure 8, the inventory provides emission factors for select OECD countries and the rest of world. The data indicate higher emission factors are associated with ROW emissions for both production and consumption. This implies that emission factors for China are likely higher than OECD factors.

**The medium development scenarios predict approximately 40 $MtCO_2e$ $yr^{-1}$ of methane emissions from gas production and imports in 2030.** Figure 9 shows that the emissions corresponding to the total consumption, which includes all domestic production and imports, range between 39 and 49 $MtCO_2e$ $yr^{-1}$. The charts in Figure 9 show the proportional emissions between conventional, unconventional and imported gas and highlight the larger proportion of emissions associated with gas produced from unconventional sources in the moderate and high growth cases.

**Up to 36 $MtCO_2e$ $yr^{-1}$ of emissions in 2030 are preventable if best practices are implemented in the Chinese gas industry.** We calculate the scale of the possible reductions by using the 90% emissions reduction potential from the current US portfolio of $CH_4$ emissions. Thus, the emissions potential should be viewed as a best-case scenario.

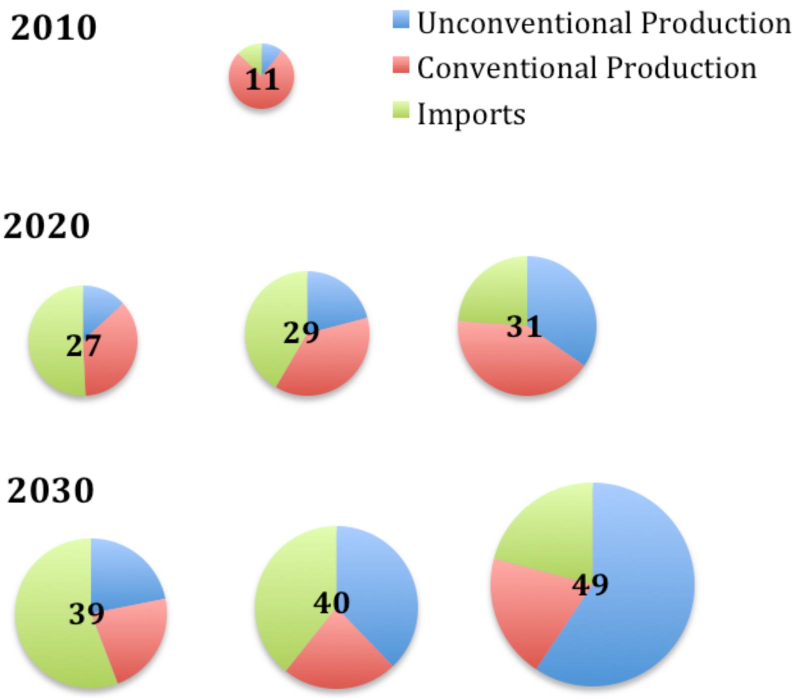


**Figure 9. Methane emissions in MT of CO2e for the low, moderate and high scenarios based on a bulk emission factor of 105 kg/PJ.**

## RECOMMENDATIONS

**Employ all feasible emissions capture technology in the growing Chinese gas industry.** We believe that the expansion of the gas industry in China provides a significant and unique opportunity for the deployment of a clean and efficient industry. Technologies to decrease fugitive emissions profitably exist with payback periods generally less than 6 months at Chinese gas prices. The development of a mature and integrated natural gas market in China is a chance to roll out best practices with respect to $CH_4$ emissions from natural gas production, distribution and consumption. The associated emissions reductions potential is in the hundreds of bcm (tens of $MtCO_2e$) per year. To facilitate this:

- Work with both the Big Three Chinese energy companies as well as the other companies exploring shale gas resources in China;
- Promote the adoption of the *Golden Rules for Natural Gas (IEA 2012a).*

**International collaborators might be able to effectively enable the implementation of capture and recovery policies as the gas market in China greatly expands.** The technologies and practices that constitute an efficient, minimal emissions necessary, natural gas sector exist internationally. The challenges to their implementation in any one place are knowledge, experience and availability.

- Leverage shale gas knowledge sharing programs to emphasize low-emissions technology and emissions monitoring and reporting.

    - U.S. – China Shale Gas Initiative;
    - Chinese Government subsidy of shale gas equipment;

- Take advantage of knowledge-sharing and financial partnerships available through international groups focused on mitigation of $CH_4$ such as the Global Methane Initiative and the Climate and Clean Air Coalition.

**Support academics, industry and government programs for emissions monitoring and reporting to improve methane emissions estimates.** Emission factors associated with natural gas production, transport and distribution are highly uncertain. The uncertainty in final emissions calculations that results from uncertainty in the international emission factors constitutes a significant fraction of the emissions reductions potential in our example. This high level of uncertainty is a limiting factor in arguing for enhanced emissions reductions.

# APPENDICES

## APPENDIX 1. QUANTIFYING FUTURE METHANE EMISSIONS FROM MSW IN CHINA

### Population Change and the Urban – Rural Divide

In order to determine China's population, we employed projections developed by the World Health Organization and United Nation's Children's Fund's (UNICEF) Joint Monitoring Program for Water Supply and Sanitation. According to their projections, in 2010 the total population of China stood at approximately 1.341 billion people. This population is projected to increase until approximately 2025, peaking at 1.395 billion before falling to 1.393 in 2030.

Of the 1.341 Chinese billion alive in 2010, nearly 50% of them lived in urban areas. According to the global urbanization projections produced by the United Nations Department of Economic and Social Affairs (UNDESA) in 2011, the percentage of the Chinese population living in urban areas will continue to grow over the next 20 years. Thus by 2030, almost 70%, or approximately 957 million people, are projected to live in urban areas, compared with 436 million in rural areas.

### Landfill Gas Emissions Model (LandGEM)

LandGEM is a first-order decay equation created by the USEPA (LMOP 2010). It is rooted in a couple of assumptions: first, that $CH_4$ generation peaks shortly (about one year) after MSW is deposited and second, that $CH_4$ generation then exponentially decreases over time once the landfill is closed. The LandGEM equation (below) can calculate the quantity (*Q*) of $CH_4$, measured in cubic meters, generated by a given amount of municipal waste ($M_1$), measured in mega grams or tons, at a set point in time (*t*), dependent upon a couple of key variables.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \left[\frac{M_i}{10}\right] e^{-k t_{ij}} \qquad (1)$$

The first is $L_0$ , the "potential methane generation capacity". This is a measure of the capacity a given amount of MSW has to produce $CH_4$ as it decays and is predominately determined by the percentage of organic matter present in the overall sample. The conventional value of this variable, as established by regulations laid out in the Clean Air Act, is 170 $m^3/Mg$ (Alexander, Burklin et al. 2005).

The second is *k*, the $CH_4$ generation rate, which captures the speed with which MSW in the landfill decays and produces $CH_4$ (LMOP 2010). This variable is a function of a number of different factors, including temperature, pH and the availability of nutrients for bacteria to breakdown. However, as many of those factors are sufficiently available in most landfills the key determinant of *k* turns out to be moisture levels, both of the landfill site and the waste contained therein. As moisture levels are often difficult to determine precisely, average precipitation is often used as a surrogate.

### Simplifying Assumptions

China's social, economic and geographic diversity make national projections a daunting task, subject to significant uncertainty. Thus, while employing the China Landfill Gas Emissions Model, we used some simplifying assumptions. For all calculations we fixed *k* to correspond with average national waste composition and assumed coal ash made up <30% of MSW, thereby establishing a constant $L_0$. To estimate emissions from open dumps, we assumed that they would behave in the same manner as shallow, unmanaged landfills. And finally, we assumed that while urban and rural MSW starts at different levels, they both grow at the same rate.

To establish a uniform *k*-value, we assumed that all waste produced is deposited in "Region Two." This area encompasses many of the population centers of China (LMOP 2009). Moreover, the associated *k*-value is based upon a typical national waste composition. Thus, the *k*-value for all calculations was 0.11.

To establish a uniform $L_0$ value, we further assumed that coal ash made up less than 30% of MSW in the period between 2010 and 2030. Coal ash is a by-product of residential furnaces and in the past has comprised a significant share of MSW. However, as home fuel use shifts from coal to natural gas, this ash has declined as a share of MSW (Cheng and Hu 2010). Thus, the $L_0$- value for all calculations was 56.

We assumed that all MSW not diverted or deposited into landfills was dumped. To model $CH_4$ emissions from these dumps, we employed the China Landfill Gas Model, but set management and collection to the lowest possible levels. This yielded a 6% abatement rate, which is roughly in line with the $CH_4$ that is oxidized as it travels through soil.

Finally, while the baseline rates of per capita MSW generation differ between the areas, we assume that both would grow at a rate of about 3.7% per year (Huang, Wang et al. 2006). MSW generation is subject to a host of factors, including income, location and family structure. However our projections are too broad to embrace such details, thus we use the national average.

### Urban Collection & Diversion – Medium Scenario

Of the waste produced in 2010, approximately 66.8% was collected by waste management personnel (Xu 2012), a classification that includes both formal garbage collectors and informal waste buyers (IWB's), who facilitate the recycling and reuse of materials. In our status quo scenario, we project that urban collection rates will continue to grow at a rate of approximately 6% per year (– 6% of that not previously collected), so collection will increase at a diminishing rate. By 2030 we estimate that roughly 90% of the MSW produced in urban areas is collected.

Of the quantity collected, we calculate that in 2010 approximately 17% will be diverted to incineration facilities (Cheng and Hu 2010). Due to space limitations around urban areas and increasing levels of MSW production, incineration has grown rapidly in China in the past decade. However, concerns about emissions and the poor quality of MSW have hindered this growth. Thus in the status quo scenario we project that incineration will continue to grow, but at a diminishing rate (about –2.1% of that not already diverted to incineration).

Recycling and reuse once comprised a significant portion of China's waste management process. However economic modernization diminished these programs (Wilson, Araba et al. 2009). Thus, today approximately 3.8% of the MSW collected is recycled. For the purposes of our projections in this scenario, we assume that this level of recycling remains constant through 2030.

Composting has also declined as a means of waste management due to a host of factors including a lack of effective sorting, which yielded low-quality fertilizer, the growth in chemical fertilizer use and a shrinking agricultural labor pool. Thus, as of 2010 just 2.5% of the waste collected in urban areas was diverted to compost facilities (Xu 2012). In this scenario, we assume that this level of composting also remains constant through 2030.

### Urban Landfill Management – Medium Scenario

In order to arrive at a collection rate of 45%, we assumed that the LFG collection system coverage was in the range of 60% to 80% (LMOP 2009). We then assumed a reasonable level of landfill management: waste was properly compacted; there was a focused tipping area; the average depth of waste was 10m or greater and a cover was applied to areas once they reached interim or final grade. Leachate seeps, the lack of weekly cover application and the absence of a sanitary liner, however, diminished overall collection efficiency to 45%.

### Urban Collection & Diversion – High Scenario

In this scenario, we project constant collection rates of 66.8% through 2030. The annual amount landfilled does continue grow, however, at the rate of MSW production growth.

As noted n the main text, for this scenario we assume that concerns surrounding the pollution generated by waste incineration, coupled with the high cost and limited efficacy of the practice, stymie efforts at facility expansion. Thus the percentage of MSW diverted to incineration remains at 17% through 2030.

While in the "medium" scenario we assumed that the rate of recycling and composting level off, here we assume both continue their decline. Recycling falls at a linear rate of roughly -0.9% per year (Wilson, Araba et al. 2009), ceasing to be a significant part of waste management by 2015. Composting, which as recently as 2001 claimed 17% of the collected waste stream (Cheng and Hu 2010) had by 2010 declined to just 2.5%, an annual decrease of 45% per year. We maintain this exponential decay path, calculating that composting ceases to be a significant MSW practice by 2020.

### Urban Landfill Management – High Scenario

In order to arrive at a collection rate of 30%, we first assumed that the LFG collection system coverage in the range of 40% to 60% (LMOP 2009). We then estimated a standard of landfill management and technology lower than that found in the "medium" scenario. Thus we added disorganized tipping practices to the list of leachate seeps, the lack of weekly cover application and the absence of a sanitary liner.

### Urban Collection & Diversion – Low Scenario

We assume a pace of growth in collection identical to that of the status quo scenario. Thus the collection rate starts at 66.8% in 2010 and follows and logarithmic growth path of roughly 6% per year, such that, by 2030 roughly 90% of the MSW produced in urban areas is collected.

In this scenario, we assume that incineration follows a linear growth path, adding approximately 2.1% per year to capacity (Cheng and Hu 2010). We likewise project growth in recycling and composting. Recycling capacity in this version of the model increases at a linear rate, adding 0.8% to capacity each year, while composting expands by 10% per year. Thus by 2030 almost 20% is diverted to recycling while roughly 17% is diverted to composting.

### Urban Landfill Management – Low Scenario

We estimate that, due to improvements in collection technology and management practices 71% of the LFG generated by the MSW over the course of the 20-year period will be captured (LMOP 2009). To arrive at this rate, we assumed that the baseline level of collection efficiency would range between 80 and 100% and that all possible means of mitigating fugitive emissions would be applied, thereby allowing the Chinese to achieve LFG collection rates comparable to the developed world.

### Rural Collection & Diversion – Medium Scenario

As is noted in the main text, local municipalities shoulder the financial burden of MSW collection (Ye and Qin 2008). Thus bucolic, inland provinces like Heilongjiang and Gansu, lacking sufficient funds, have collection rates ranging between 23 and 26 percent (Wang, He et al. 2011). For the purposes of our projections, we estimate that the baseline rural collection rate is 24.5%. In this scenario we assume that this collection rate grows, but does so at a rate lower than it's urban cousin, 3% per annum proceeding in a roughly logarithmic manner.

For the purposes of our model, we estimated that as of 2010 rural citizens composted 5% of the organic MSW, twice the rate of their urban neighbors, due to the greater utility of compost and the availability of land on which to conduct the practice. Thus, in our calculations, 5% of the 57% of overall MSW produced by rural denizens would be composted (Li, Bai et al. 2011). In our medium scenario, we also assume that this rate of composting remains constant through 2030.

Of the MSW collected, we assume that roughly 5.7% is diverted to incineration. This is third of the rate of incineration in urban areas. Our assumption is rooted in the knowledge that incineration systems are highly capital intensive (Cheng and Hu 2010). Moreover the land crunch that has prompted their growth in urban areas is less acute in rural areas. Thus we assume that incineration makes up a smaller share of the waste management pie and grows at a slower rate – roughly 1% per year in a logarithmically decreasing fashion.

The MSW that is diverted to recycling in urban areas is the result of IWB's and waste pickers – predominately rural migrants who comb urban landfills for goods they can sell for reuse and reprocessing (Li, Yang et al. 2009). Given the more dispersed nature of the population and waste, the economies of scale do not exist to the same extent in rural areas. Thus we estimate a 2% diversion rate for recycling, roughly half that of urban areas. For the purposes of our projections in this scenario, we assume that this level of recycling remains constant through 2030.

### Rural Landfill Management – Medium Scenario

Evidence and intuition would suggest that overall LFG collection efficiencies should be lower in rural landfills (Raninger 2007). Thus, in our "medium" scenario we assume an LFG collection efficiency of roughly 31%. For the purposes of our projections, we assume that LFG collection systems are able to capture between 40 and 60 percent of the gas produced (LMOP 2009). However, this collection is diminished by sub-par management practices: waste is not properly compacted, the site lacks a focused tipping area, cover material is not regularly applied and liners do not meet international standards.

### Rural Collection & Diversion – High Scenario

In this scenario we calculate that 24.5% of the MSW generated in rural areas is collected and that this percentage holds steady over the course of 20 years. Over the past decade the percentage of waste diverted to composting has declined (Cheng and Hu 2010). This is in part a symptom of poor sorting, which yields low quality compost (thus limiting its marketability) and the availability of artificial fertilizer. In this, the direst of scenarios, we assume declines going forward mirror those of the past decade. Thus we assume that the percentage that is composted decays at a rate of 45% per year.

As we have noted before, the growth in incineration has had to contend with rising environmental awareness in China. In this scenario, we assume that such awareness is not sufficient to shutter current incineration facilities, but does halt the construction of new ones. Thus the percentage of waste diverted to incineration each year remains constant at 5.7%, through 2030. Meanwhile, we assume recycling follows in the same negative linear path it has for the past decade, falling roughly 0.9% per year (Wilson, Araba et al. 2009).

### Rural Landfill Management – High Scenario

In order to arrive at an LFG collection rate of 18%, we first assumed that the LFG collection system coverage was in the range of 20% to 40% (LMOP 2009) as a result of limited investment in construction and maintenance. Furthermore, we assume that the same scarcity of capital and management would extend to the landfill as a whole: waste would not be compacted on an ongoing basis, tipping would not be focused, cover material would not routinely be applied, there would be leachate seeps and the whole of the landfill would not have an adequate lining system. All of these factors serve to increase the rate of LFG leakage.

### Rural Collection & Diversion – Low Scenario

In this scenario, composting starts at the 5% level, but we assume it grows at roughly 10% per year. This growth would be contingent upon campaigns to improve sorting practices (thereby improving quality), growing environmental awareness and government support to make compost a more competitive fertilizer. Supposing such occurs, by 2030, we project that approximately a third of organic rural MSW would be diverted to composting.

Collection rates for the remaining MSW match the 6% logarithmic growth of urban areas. Thus, while in 2010 we estimate collection to be just 24.5%, by 2030 roughly 78% is collected.

We likewise assume that the rate of growth in incineration matches that of urban areas, adding approximately 2.1% to capacity each year, starting from a baseline of 5.7% in 2010. It might be that with higher rates of collection, an expanded incineration industry on the urban outskirts also consumes some rural MSW, or that new incineration plants are constructed in rural areas. Either way, by 2030, we project that almost 47% of the waste collected would be incinerated.

Recycling too sees a steady addition of capacity in this scenario, with 0.4% added each year (half the rate of urban areas), bringing the percentage diverted to it to 10% by 2030.

### Rural Landfill Management – Low Scenario

We assume that increased rates of attention and investment would yield better management practices and technology for rural landfills. LFG collection systems at rural landfills would be upgraded to collect between 60 and 80 percent of emissions. The institution of better management practices, including trash compacting, designated tipping areas and capping, would likewise improve containment (LMOP 2009). In all, we estimated that these improvements would raise collection efficiency to 45%.

### Detailed Results Breakdown

Given the collection, diversion and dumping statistics outlined above, we project the following emissions of LFG and $CH_4$ based upon differing landfill management practices and technological investments:

### Table 6. Projected LFG and CH$_4$ Emissions from Landfill Management 2011-2030.

| | LFG Produced (bcm/y) | % LFG Abated | % LFG Emitted | Net LFG Emissions (bcm/y) | Total Emissions CH$_4$ (2011-2030) (bcm) |
|---|---|---|---|---|---|
| **Urban** | | | | | |
| **2011 Landfill *Low*** | 2.11 | 71% | 29% | 0.59 | **N/A** |
| **2011 Landfill *Med.*** | 2.11 | 45% | 55% | 1.16 | **N/A** |
| **2011 Landfill *High*** | 2.11 | 30% | 70% | 1.47 | **N/A** |
| **2011 Dump** | 1.33 | 6% | 94% | 1.26 | **N/A** |
| **2030 Landfill *Low*** | 22.2 | 71% | 29% | 6.39 | **Low: 119** |
| **2030 Dump *Low*** | 10.8 | 6% | 94% | 10.2 | |
| **2030 Landfill *Med.*** | 41.9 | 45% | 55% | 23.0 | **Med.: 193** |
| **2030 Dump *Med.*** | 10.8 | 6% | 94% | 10.2 | |
| **2030 Landfill *High*** | 41.2 | 30% | 70% | 28.7 | **High: 270** |
| **2030 Dump *High*** | 24.7 | 6% | 94% | 23.4 | |
| **Rural** | | | | | |
| **2011 Landfill *Low*** | 0.69 | 45% | 55% | 0.38 | **N/A** |
| **2011 Landfill *Med.*** | 0.69 | 31% | 69% | 0.48 | **N/A** |
| **2011 Landfill *High*** | 0.69 | 18% | 82% | 0.58 | **N/A** |
| **2011 Dump** | 2.29 | 6% | 94% | 2.16 | **N/A** |
| **2030 Landfill *Low*** | 11.3 | 45% | 55% | 6.22 | **Low: 128** |
| **2030 Dump *Low*** | 10.1 | 6% | 94% | 9.49 | |
| **2030 Landfill *Med.*** | 16.0 | 31% | 69% | 11.0 | **Med: 152** |
| **2030 Dump *Med.*** | 11.1 | 6% | 94% | 10.5 | |
| **2030 Landfill *High*** | 7.33 | 18% | 82% | 5.99 | **High: 184** |
| **2030 Dump *High*** | 24.0 | 6% | 94% | 22.6 | |

# APPENDIX 2. QUANTIFYING FUTURE METHANE EMISSIONS FROM LIVESTOCK MANURE MANAGEMENT IN CHINA

Tier 1 methodology from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) was used to calculate $CH_4$ emissions from manure management at the household level for the years 2010-2030. Emissions were projected under the three scenarios described in the main text:

Scenario 1: 2010 number of household biodigesters (38 million);
Scenario 2: 75% of the 2020 government target for biodigesters (60 million);
Scenario 3: 2020 government target for household biodigesters (80 million);

For each scenario, we considered two levels of biodigester functionality. In the first, 60% of installed biodigesters were fully operational and the remaining 40% were nonfunctioning (which, for the purposes of our calculations, we interpret as 100% leakage of all $CH_4$ generated). This is consistent with the status quo efficiency levels detailed in the 2005 Zhang et al. assessment. In the second level, all installed biodigesters are assumed to be fully operational.

The IPCC methodology computes $CH_4$ emissions from manure management using the following equation:

$$CH4, Manure = \sum_T [N(T) \cdot EF(T) \cdot 10^{-6}] \quad (2)$$

Where *N(T)* is the number of livestock head per species *T* and EF(T) is a species-specific emission factor. Ten species are included in this analysis: poultry birds, cattle and buffalos, horses, donkeys, mules, camels, sheep, goats and swine. To project the future population of poultry birds, we use livestock population data from 2000-2010 from the UN Food and Agriculture Organization (UNFAO). For all other animals, 2000-2010 data was sourced from the Chinese Statistical Yearbook 2011. For all values, we use records of livestock alive at year-end, with the exception of the swine category. The numbers used for the swine category are those provided by the Chinese Statistical Yearbook for “Slaughtered Hogs.” “Slaughtered Hogs” are used in lieu of “Year-End Hogs”. This was done because there is a large difference in the size of the population for slaughtered and year-end hogs. In order to avoid understating emissions from this species, the larger of the two categories (slaughtered hogs) was chosen.

The emission factors chosen for manure management were those listed in Chapter 10, Volume 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. For poultry, sheep, goats, camels, horses, mules and asses, emission factors for “developing countries” with an average annual temperature of 15-25°C were used. For swine, and cattle, we use Asia-specific factors based on an average annual temperature of 15-25°C. Cattle population in the Chinese Statistical Yearbook is not disaggregated between dairy and non-dairy. They are instead lumped together with data for buffalo included as well. However each category has a separate emission factor (18, 1 and 2 respectively) in the IPCC guidelines. Due to the Chinese reliance on dairy imports (partially as a result of the 2008 “Milk Scandal”) we consider dairy cattle to represent only a small role in the total cattle and buffalo population (Jia, Jikun et al. 2012). We thus chose to use the higher of the other two emission factors (equal to 2 and corresponding to buffalo).

**Table 7. Emissions Factors for Manure Management.**

| Species/ Livestock category | Emission factor for Manure Management (kg head$^{-1}$ yr$^{-1}$) |
|---|---|
| **T** | **EF$_{(T)}$** |
| Buffalo and Cattle | 2 |
| Sheep | 0.15 |
| Goats | 0.17 |
| Camels | 1.92 |
| Horses | 1.64 |
| Donkeys & Mules | 0.9 |
| Swine | 4 |
| Poultry | 0.02 |

Source: (IPCC, 2006)

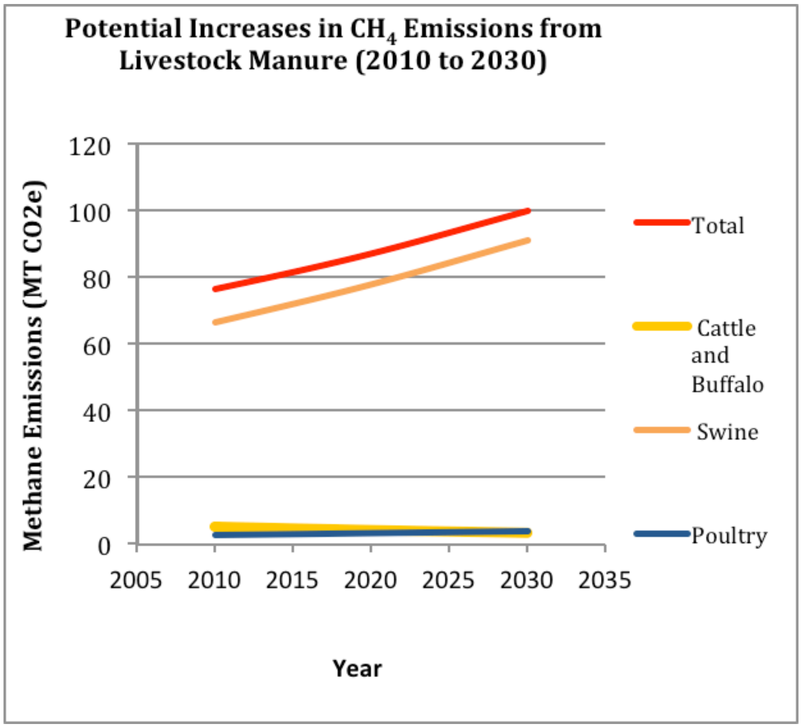


**Figure 10. Potential Emissions from Livestock Manure 2010-2030.**

In all 3 scenarios, we imagine the number of biodigesters stays constant between 2010-2030. We make the simplified assumption that on average, each household has 1 cow and 4 pigs (Lefebvre 25 Oct. 2012). For pigs, we assume all manure is disposed of via the biodigester. For the cow, we assume that some of the manure is placed in the biodigester and some is managed in drylots (and then placed in pastures). This is consistent with the practices assumed in the creation of the emission factor of 2 that we are using to calculate $CH_4$ emissions for cattle and buffalo. We also assume that each households' livestock holdings and resulting emissions from manure management stay constant over time. Instead, what changes is the country's total emissions from livestock manure because of the livestock population growth.

# APPENDIX 3. QUANTIFYING FUTURE METHANE EMISSIONS FROM WASTEWATER TREATMENT AND DISCHARGE IN CHINA

Methane emissions from domestic wastewater treatment and discharge were estimated for the years 2010–2030 using the methodology presented in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC and Intergovernmental Panel on Climate Change 2006). Emissions were projected under the three scenarios described in the main text: (a) Existing Technology, (b) Moderate Technology Expansion and (c) Maximum Feasible Technology. All of the scenarios utilized projections of China's population growth and urbanization, and scenarios (b) and (c) required assumptions about the future trajectory of China's wastewater treatment infrastructure.

The Greenhouse Gas Inventory methodology computes $CH_4$ emissions from wastewater treatment and discharge using the equation:

$$CH_4\ Emissions = \left[\sum_{i,j}\left(U_i \bullet T_{i,j} \bullet EF_j\right)\right]\left(TOW - S\right) - R \tag{3}$$

where $U_i$ is the population fraction in income group $i$, $T_{i,j}$ is the utilization of waste stream $j$ by income group $i$, $TOW$ is the total organic waste [kg BOD] across all waste streams and income groups and $EF_j$ is the emission factor [kg $CH_4$/kg BOD] for waste stream $j$. $S$ is the organic component removed as sludge and $R$ is the amount of $CH_4$ recovered [kg $CH_4$/yr]. $S$ was not considered in detail in our projections, but the effect of household biogas digesters was captured in $R$.

A default per capita BOD generation of 14.6 kg person$^{-1}$ yr$^{-1}$ was used throughout the calculations and multiplied by the national population to calculate TOW. Demographic data and projections for the years 2010-2030, which were needed to determine $U$, were acquired from the United Nations Department of Economic and Social Affairs (UNDESA 2013). Data acquired here included national population, urban population and rural population. The ratio between urban high income and urban low-income populations described in the 2006 Greenhouse Gas Inventory was assumed to remain constant through 2030, even as the urban population as a percentage of the total population increased significantly.

Scenario (a) assumed that the utilization of wastewater treatment technology $(T)$ in 2010 does not change through 2030. Default values for China from the 2006 GHG Inventory were used for $T$ in this case. The number of household biogas digesters was assumed to be 38 million (Chen, Zhao et al. 2012). In the other scenarios, $T$ in 2030 was revised to reflect the assumptions in each scenario. Scenario (b), the moderate technology expansion case, assumed that improvements in wastewater handling in centralized wastewater treatment plants in urban areas continue to occur and that in rural areas the fraction of untreated wastewater discharged to open water decreases and is largely replaced by pit latrines. The total number of household biogas digesters in rural areas was assumed to be 60 million, which is 75% of the Chinese government goal for 2020 (National Development and Reform Commission 2007). This value was chosen to reflect a partially successful expansion in the number of household biogas digesters. In scenario (c), the maximum feasible technology case, $T$ was similar to the technology utilization in the United States in 2006 (IPCC 2006). An important exception is that instead of the septic tanks common in rural areas of the U.S., it was assumed that rural populations in China use pit latrines equipped with 80 million biogas digesters. Table 1 summarizes the assumptions made for $T$ in 2030.

## Table 8. Wastewater Treatment Technology Assumptions for 2030.

| Population Group | Treatment or Discharge Pathway | Existing Technology | Moderate Technology Development | Maximum Feasible Technology |
|---|---|---|---|---|
| | | Degree of Utilization ($T_{i,j}$) | | |
| **Rural** | sewer-organized | 0 | 0 | 0.08 |
| | sewer-overloaded | 0 | 0 | 0 |
| | septic system | 0 | 0 | 0 |
| | latrine | 0.47 | 0.85 | 0.92 |
| | other - discharge | 0.5 | 0.15 | 0 |
| | open defectation | 0.03 | 0 | 0 |
| **Urban high income** | sewer-organized | 0 | 0.85 | 0.95 |
| | sewer-overloaded | 0.67 | 0 | 0 |
| | septic system | 0.18 | 0.15 | 0.05 |
| | latrine | 0.08 | 0 | 0 |
| | other - discharge | 0.07 | 0 | 0 |
| | open defecation | 0 | 0 | 0 |
| **Urban low income** | sewer-organized | 0 | 0.4 | 0.95 |
| | sewer-overloaded | 0.68 | 0.4 | 0 |
| | septic system | 0.14 | 0.15 | 0.05 |
| | latrine | 0.1 | 0.05 | 0 |
| | other - discharge | 0.03 | 0 | 0 |
| | open defecation | 0.05 | 0 | 0 |

Source: (IPCC, 2006)

Emission factors for each waste stream *j* is defined by the following equation:

$$EF_j = B_o \bullet MCF_j \qquad (4)$$

For $B_o$ we used the default maximum $CH_4$ producing capacity of domestic wastewater of 0.6 kg $CH_4$/kg BOD. Default values for *MCF,* the methane conversion factor, were used (IPCC 2006). Specific waste stream emission factors used were 0.5 for pit latrines, 0.1 for direct discharge to river, lakes and seas, 0 for well-managed centralized wastewater treatment and 0.3 for poorly-managed or overloaded centralized wastewater treatment.

Household biogas digesters were accounted for in the R term of Equation 3. Emissions reductions from household digesters were calculated using a bottom-up approach with the equation:

$$R_{biogas} = N \bullet E \bullet F \bullet BOD \bullet EF_{latrine} \tag{5}$$

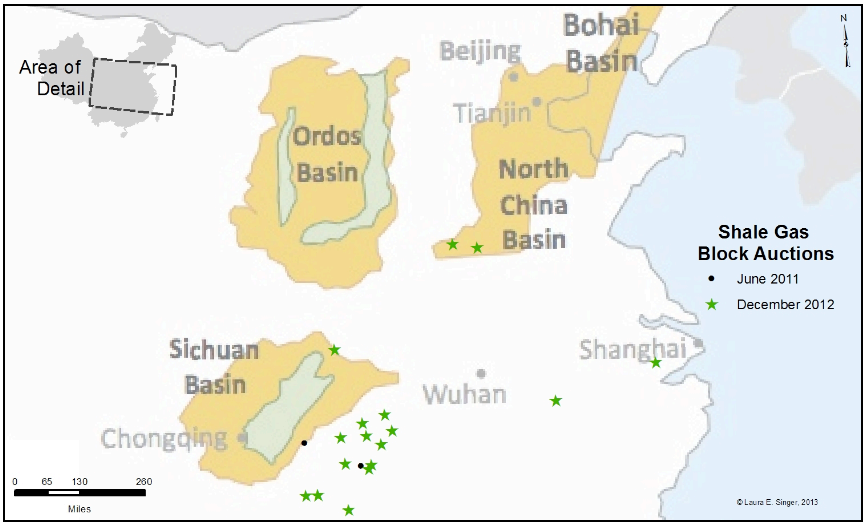
where $N$ is the total number of household biogas digesters in China, $E$ is the operational efficiency of digesters, $F$ is the average rural family size, $BOD$ is annual per-capita BOD generation and $EF_{\text{latrine}}$ is the emission factor for pit latrines. This equation assumes that each household digester is used by just one family.

$N$ was assumed to be 38 million for the baseline year 2010 and in the "Existing Technology" scenario (Chen, Zhao et al. 2012), 60 million in the moderate technology case and 80 million in the maximum feasible technology case. The operational efficiency of household biogas digesters, E, was assumed to be 60% across all scenarios (Zhang, Wang et al. 2012). $F$ was assumed to be 3.61 (China Yearbook 2004). BOD was assumed to be 14.6 kg person$^{-1}$ yr$^{-1}$ and $EF$ was 0.3, the emission factor for pit latrines. This approach essentially assumed that household biogas digesters produce $CH_4$ at the same rate as pit latrines. Note that this calculation accounted for $CH_4$ produced from human inputs to household digesters only and did not account for $CH_4$ produced from the animal waste which is typically placed in the same digesters (see the section on Manure Management).

# APPENDIX 4. SHALE GAS EXPLORATION IN CHINA

Most shale gas exploration activities in China occur in the southern region of the country. In those areas, the water resources required for hydraulic fracturing are more readily available than in other areas of the country. The following map shows the location of publicly-auctioned shale blocks. The first two rounds of public auctions took place in June 2011 (2 blocks) and Dec 2012 (19 blocks) (Ministry of Land and Resources 2012, Nakanom 2012). The yellow shaded regions illustrate the prospective shale gas basins indicated by a recent EIA assessment (EIA 2011).

## Figure 11. Shale Gas Block Auctions, 2011-2012



Source: (EIA 2011, Ministry of Land and Resources 2012)

Only 1 of the 21 blocks auctioned was won by one of the "Big Three" Chinese energy companies (Sinopec). The others were won by various types of companies, including power utilities, real estate groups, energy trading companies, coal mining companies, etc. Most of these new players are still state or province-owned (Ministry of Land and Resources 2012).

However, there are several large blocks located within Sichuan Basin whose exploration licenses were owned by the Big Three (most in the Sichuan Basin) before shale gas was discovered within. These blocks were explored earliest, and are not shown on the map.

# APPENDIX 5. THE GOLDEN RULES FOR NATURAL GAS: PROJECTION SCENARIOS BY THE INTERNATIONAL ENERGY AGENCY (IEA)

The IEA, in its report *Golden Rules for a Golden Age of Natural Gas*, (IEA 2012a) develops projections for natural gas production in China through 2035, dividing them into two different scenarios: *High Unconventional Case* and the *Low Unconventional Case*. The assumptions behind these two cases are outlined below.

*High Unconventional Case: The Golden Rules Case*
This case models "an accelerated global expansion of gas supply from unconventional resources" and is made possible by compliance with the IEA's Golden Rules of Natural Gas. Compliance with the Golden Rules for natural gas entails gaining the public's confidence in unconventional natural gas industries. To achieve this, steps must be taken by both government and industry to:

- Measure and disclose information and engage the public;
- Watch where drilling occurs for transparency;
- Isolate wells and prevent leaks;
- Treat water responsibly;
- Eliminate venting and minimize flaring, as well as other emissions;
- Be ready to "think big" (i.e., account for regional impacts, through regulation if necessary to insure investment); and
- Ensure a consistently high level of environmental performance.

Based on the U.S experience developing unconventional gas resources, additional conditions must be met to assure full resource development: access to resources, a favorable fiscal and regulatory framework, available expertise and technology, well developed infrastructure (e.g. available pipelines), favorable markets and pricing, and water availability.

*Low Unconventional Case*
This case models the outcomes for a natural gas industry where the Golden Rules are not followed. This could occur if a lack of public acceptance of new natural gas industries significantly narrows the share of unconventional resources that are accessed. This leads to lower availability and higher natural gas prices, making natural gas less competitive in the global fuel mix, behind coal.

Additional conditions that could lead to low unconventional gas development are that:
1) The resource base could be lower than currently estimated;
2) Recovery factors or production rates could be lower than thought;
3) Development of shale gas reservoirs in China could prove uneconomical;
4) Water availability is low; and
5) Government support for gas subsidies declines.

For both the High and the Low Cases, the baseline policy assumptions used to create the projections are drawn from the *New Policies Scenario* from the World Energy Outlook 2011.

The natural gas projections in years 2020 and 2030 (baseline year 2010) for the High Unconventional and Low Unconventional Cases are shown below. We interpolated between years 2020 and 2035 to calculate production estimates for 2030. Moderate represents the average between the High and Low Cases.

### Table 9. Projections from the IEA's Golden Rules Report (in billion cubic meters).

| | 2020 | | | 2030 | | |
|---|---|---|---|---|---|---|
| | High | Moderate | Low | High | Moderate | Low |
| **Demand** | 323 | 303 | 282 | 502 | 450 | 398 |
| **Production** | 246 | 193 | 139 | 397 | 287 | 176 |
| *Unconventional* | 112 | 75 | 37 | 298 | 193 | 87 |
| *Conventional* | 134 | 118 | 102 | 99 | 94 | 89 |
| **Imports** | 77 | 110 | 143 | 105 | 164 | 222 |

Sources: (IEA 2011; IEA 2012a)

# APPENDIX 6. QUANTIFYING FUTURE METHANE EMISSIONS IN CHINA FROM THE NATURAL GAS INDUSTRY

Methane emissions associated with the natural gas industry are estimated following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). Methane emissions, *E*, is estimated by

$$E = EF_i \cdot A_i \tag{6}$$

where $EF_i$ is the methane emission factor for source, *i*, and $A_i$ is the activity of source, *i*. Emissions reduction is not considered in this formulation. The activity is defined as the production and consumption projections by the IEA described in Appendix 4. Emission Factors are determined based on data available in the IPCC Emission Factor Database (EFDB). It is important to note that Equation 6 is not the only way to determine emissions.

To determine a methane emission factor specific to China, country-level methane emission factors for gas produced and consumed available in the IPCC EFDB for the natural gas production are analyzed. Although the data set does not specifically include China, the emission factor for different regions provides insight on the difference between OECD and ROW emission factors (see Figure 12). Considering all countries/regions, there are 15 production-based and 34 consumption-based emission factors respectively. Six production-based and eight consumption-based EFs are for countries in the OECD. The emission factor for $CH_4$ for natural gas production in the IPCC EFDB is data from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Countries/regions represented in the OECD category are Western Europe, the U.S., Germany and Canada. Rest of world (ROW) includes emission factors for groups of non-OECD countries. The low and high values in Figure 12 correspond to the 95% confidence level, when a range is provided. In cases where a range is not provided, the value is taken to be the same for low and high emission factors.

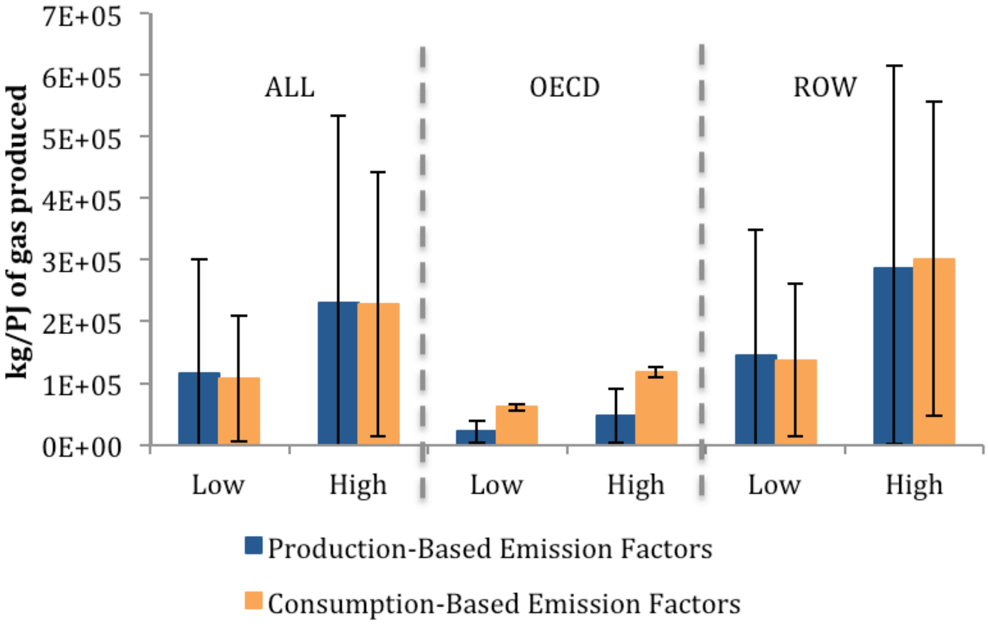


Figure 12. Emission factors from the IPCC EFDB for methane from the natural gas industry

Figure 12 shows that higher emission factors are associated with ROW values relative to OECD values for both production and consumption-based activities. This is likely to be because emission reduction measures are more prevalent in OECD countries. If we assume that China's emissions follow ROW trends, emission factors for China should be higher than OECD factors. Considering ROW only, production-based emission factors are greater than consumption-based emission factors. For OECD, consumption-based emission factors are greater than production-based emission factors. However, uncertainties associated with these values are significant such that the difference between production and consumption are difficult to establish.

The data in Figure 12 fall under the following two 2006 IPCC Source/Sink categories:

> 1B2
> *Oil and Natural Gas*
> Comprises fugitive emissions from all oil and natural gas activities. The primary sources of these emissions may include fugitive equipment leaks, evaporation losses, venting, flaring and accidental releases.
>
> 1B2b
> *Natural Gas*
> Comprises emissions from venting, flaring and all other fugitive sources associated with the exploration, production, processing, transmission, storage and distribution of natural gas (including both associated and non-associated gas).

Methane emissions from oil and gas are less associated with combustion, although $CH_4$ can be emitted during incomplete combustion and leaks. The main source of $CH_4$ emissions from this sector is from venting and equipment leaks. The reported data had to meet standards set by the IPCC/OECD/IEA program for comparability of reporting (IPCC 1996). However, there may still be some differences due to the selection of sources and segments subject to monitoring and approaches to aggregating sources and segments.

Using the standard deviations as a rough measure of uncertainty, Figure 12 shows that the emission factors are highly uncertain. This is especially true for ROW emission factors, which have standard deviations in the same order of magnitude as the mean. Given the uncertainty in emission factors, a bulk emission factor $10^5$ kg/PJ is uniformly applied to China's natural gas production and consumption activity. Therefore the emissions determined based on this emission factor should be taken as order of magnitude estimates.

In general, emission factors for the oil and gas sector are determined from various studies and sources. In the US, the 1996 EPA/GRI study provided a basis for most emission factors and is still employed for conventional production. With the growth of shale gas production, emission factors in the US have been updated to reflect the new technology. However, a doubling of the emission factor associated with unconventional production falls within the range of emission factor values presented here. Currently, emission factors for unconventional production outside of the U.S. are not available and the quantification of U.S. emissions from unconventional production remains an active area of research in the U.S. (see Appendix 6).

Methane emissions for China are estimated and illustrated in Figure 9 of the main report. The emissions are based on the bulk emission factor of $10^5$ kg/PJ and the activity defined as natural gas demand and production given in Appendix 4 of this report. The conversion of natural gas volumes to energy content used is 39 PJ/bcm. The $CH_4$ emission estimates determined here compare well with values found in literature for China, such as (Hoeglund-Isaksson 2012).

# APPENDIX 7. TECHNICAL AND POLICY UNCERTAINTY IN METHANE EMISSION AND SHALE GAS DEVELOPMENT

Recently, hydraulic fracturing (HF) or "fracking" for shale gas has received media attention due to its widespread and growing deployment in the U.S. and the great potential for similar development in China, Europe and around the world. Its potential to cause environmental damage has prevented shale gas development in some European countries, such as France, and has led to new regulations in the U.S., where shale gas development is most active. Much of the concern arises from water contamination risk from leakage of HF fluids (USEPA 2011) and GHG emissions, especially $CH_4$ (Howarth, Ingraffea et al. 2011).

Academic research into the environmental implications of HF is currently at a nascent stage. Howarth et al. (Howarth, Santoro et al. 2011) claim that $CH_4$ leakage makes shale gas less climate friendly than coal due to the high GWP of $CH_4$. Meanwhile, Jiang et al. (2011) argue that the opposite is true when considering a life-cycle analysis and lower combustion emissions. However, there is a lack of data that can strongly support either of these claims and the need for monitoring programs has been identified (e.g. (Howarth, Santoro et al. 2011; Alvarez, Pacala et al. 2012)). In addition, many direct measurement programs have been launched recently in the U.S. and these include efforts by the Environmental Defense Fund (EDF), the National Oceanic and Atmospheric Administration (NOAA) (Petron, Frost et al. 2012) and many independent researchers (e.g. Mark Zondlo at Princeton University, Sergey Paltsev at MIT). In China, limited data on $CH_4$ leakage from unconventional gas production, which includes shale gas, exist; and research activity and monitoring programs to address this need are minimal to non-existent.

In the U.S., regulations are continually being proposed and amended to reflect new information and concerns. For example, the emissions estimates for the oil and gas production sector for 2006 have recently doubled in 2010 (USEPA 2010) and an amendment to the USEPA's GHG reporting program was made as recently as August 24, 2012 (USEPA 2012). There is currently a lack of information on China's position on $CH_4$ emissions from shale gas development.

REFERENCES

ADB: Asian Development Bank (2009). "Technical Assistance Consultant's Report Project Number 40682." Final Report: Preparing the Integrated Renewable Biomass Energy Development Project.

Alexander, A., C. Burklin, et al. (2005). "Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide." EPA, Washington. D.C. : 1-48.

Alvarez, R. A., S. W. Pacala, et al. (2012). "Greater focus needed on methane leakage from natural gas infrastructure." Proceedings of the National Academy of Sciences of the United States of America **109**(17): 6435-6440.

Bani Shahabadi, M., L. Yerushalmi, et al. (2010). "Estimation of greenhouse gas generation in wastewater treatment plants – Model development and application." Chemosphere **78**(9): 1085-1092.

CATF: Clean Air Task Force (2012). "Barriers and Opportunities for Reducing Methane Emissions from Coal Mines." http://www.catf.us/resources/whitepapers/files/201209-Barriers_and_Opportunities_in_Coal_Mine_Methane_Abatement.pdf.

CDIAC: Carbon Dioxide Information Analysis Center (2013). "Advanced Global Atmospheric Gases Experiment (AGAGE) Data. ."

Chai, X. (2012). "Personal Interview: Sludge treatment technology in China."

Chen, G. Q., L. Shao, et al. (2011). "Low-carbon assessment for ecological wastewater treatment by a constructed wetland in Beijing." Ecological Engineering **37**(4): 622-628.

Chen, L., L. Zhao, et al. (2012). "The Progress and Prospects of Rural Biogas Production in China." Energy Policy **51**(58): 63.

Chen, Y., G. Yang, et al. (2010). "An assessment of the availability of household biogas resources in rural China." 1 **5**: 783-792.

Cheng, H. and Y. Hu (2010). "Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China." Bioresource Technology **101**(11): 3816-3824.

China Yearbook (2004). http://english.gov.cn/2005-08/08/content_27315.htm.

Daelman, M. R. J., E. M. van Voorthuizen, et al. (2012). "Methane emission during municipal wastewater treatment." Water Research **46**(11): 3657-3670.

DOE: US Department of Energy (2009). "DOE Fact Sheet: U.S.-China Shale Gas Resources Initiative." http://www.chinafaqs.org/library/doe-fact-sheet-us-china-shale-gas-resources-inititiative.

Doorn, M. R. J., S. Towprayoon, et al. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Intergovernmental Panel on Climate Change.

EIA: US Energy Information Administration (2011). "World shale gas resources: An Initial assessment of 14 regions outside the United States."

El-Fadel, M. and M. Massoud (2001). "Methane emissions from wastewater management." Environ Pollution **114**(2): 177-185.

Feng, Y., Y. Guo, et al. (2012). "Household biogas development in rural China: On policy support and other macro sustainable conditions." Renewable & Sustainable Energy Reviews **16**(8): 5617-5624.

Fu, C. and G. Yu (2010). "Estimation and Spatiotemporal Analysis of Methane Emissions from Agriculture in China." Environmental Management **46**(4): 618-632.

Gao, Q. (2012). Personal Interview: China's Second National Communication on Greenhouse Gases. Beijing, China: Chinese Research Academy of Environmental Sciences.

GIZ. (2012). "Sino-German Project for Optimization of Biomass Utilization - Biogas." Retrieved 25 Oct, 2012, from http://www.biogas-china.org/.

GMI and Global Methane Initiative (2011). "The U.S. government's global methane initiative accomplishments." http://www.epa.gov/globalmethane/pdf/.../usg_report_2011_full.pdf.

Guisasola, A., D. de Haas, et al. (2008). "Methane formation in sewer systems." Water Research **42**(6-7): 1421-1430.

He, P. J., F. Lü, et al. (2007). "Sewage Sludge in China: Challenges Toward a Sustainable Future." Water Practice & Technology **2**(4).

Higashi, N. (2009). "Natural gas in China: Market evolution and strategy." IEA.

Hoeglund-Isaksson, L. (2012). "Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs." Atmospheric Chemistry and Physics **12**(19): 9079-9096.

Howarth, R. W., A. Ingraffea, et al. (2011). "Natural gas: Should fracking stop?" Nature **477**: 271-275.

Howarth, R. W., R. Santoro, et al. (2011). "Methane and the greenhouse-gas footprint of natural gas from shale formations." Climatic Change **106**(4): 679-690.

Huang, Q., Q. Wang, et al. (2006). "The Current Situation of Solid Waste Management in China." Journal of Material Cycles and Waste Management **8**: 63-69.

IEA: International Energy Agency (2011). "World Energy Outlook 2011."

IEA: International Energy Agency (2012a). "Golden rules for a golden age of gas."

IEA: International Energy Agency (2012b). "Gas Pricing and Regulation-China's Challenges and IEA Experiences."

International Trade Administration (2005). Water Supply and Wastewater Treatment Market in China. Washington, D.C., U.S. Department of Commerce.

IPCC: Intergovernmental Panel on Climate Change (2006). "2006 IPCC guidelines for national greenhouse gas inventories." **2**.

IPCC Working Group 1 (2007). "Summary for Policymakers, in Climate Change 2007: The Physical Science Basis, Contribution of Working Group 1 to the Fourth Assessment Repot of the Intergovernmental Panel on Climate Change " Cambridge University Press.

IPCC, Intergovernmental Panel on Climate Change (1996). "Database on greenhouse gas emission factors ".

Isaksen, I. S. A., M. Gauss, et al. (2011). "Strong atmospheric chemistry feedback to climate warming from Arctic methane emissions." Global Biogeochemical Cycles **25**.

Jia, X., H. Jikun, et al. (2012). "China's Milk Scandal, government policy and production decisions of dairy farmers: The case of Greater Beijing." Food Policy **37**.

Jin, J. ( 31 Oct 2012). "Personal Interview."

Lefebvre, O. (25 Oct. 2012). "Telephone interview."

Li, Y., J. Bai, et al. (2011). "Waste Disposal and Its Relationship with Economic Development in Rural China." Center for Chinese Agricultural Policy & Chinese Academy of Sciences.

Li, Z.-s., L. Yang, et al. (2009). "Municipal solid waste management in Beijing City." Waste management (New York, N.Y.) **29**(9): 2596-2599.

Lieu, J. (2009). China's Power in Wastewater. China Environmental Health Project. Washington, D.C., Wilson Center.

Liu, D., Y. Ge, et al. (2009). "Constructed wetlands in China: recent developments and future challenges." Frontiers in Ecology and the Environment **7**(5): 261-268.

LMOP: Landfill Methane Outreach Program (2009). "User's Manual China Landfill Gas Model."

LMOP: Landfill Methane Outreach Program (2010). "Project Development Handbook." http://www.epa.gov/lmop/publications-tools/handbook.html.

Mauzerall, D. (2011). "Methane mitigation – Benefits for air quality, health, crop yields and climate." IGAC Newsletter: 17-18.

Ministry of Land and Resources (2012). "Announcement." http://www.mlr.gov.cn/zwgk/zytz/201212/t20121206_1163196.htm.

Montzka, S. A., E. J. Dlugokencky, et al. (2011). " Non-CO2 greenhouse gases and climate change Nature " Nature **476**: 43-50.

Nakanom, J., D. Pumphrey, et al. (2012). "Prospects for shale gas development in Asia- Examining potentials and challenges in China and India." Center for Strategic and International Studies

NDRC: National Development and Reform Commission (2007). "Medium and Long-Term Development Plan for Renewable Energy in China (Abbreviated Version, English Draft)."

NRDC: Natural Resources Defense Council (2012). "Leaking Profits."

Pan, T., X.-D. Zhu, et al. (2011). "Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: A case study in China." Ecological Engineering **37**(2): 248-254.

Petron, G., G. Frost, et al. (2012). "Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study." Journal of Geophysical Research-Atmospheres **117**.

Rae, A. (2008). "China's agriculture, smallholders and trade: driven by the livestock revolution? ." Australian Journal of Agricultural and Resouce Economics **52**(3).

Raninger, B. (2007). "Biogas from Biodegradable Municipal Waste: Potential & Business Opportunities in China." http://www.frankhaugwitz.info/doks/bio/2007_06_14_China_Biogas_from_Biodegradable_Municipal_Waste_Bernhard_Raninger.pdf.

Schneider, K. (2012). "China's Water Reserves and World's Warming Atmosphere Wait For Natural Gas Breakthrough " Circle of Blue.

Shao, L., Z. Wu, et al. (2012). "Embodied energy assessment for ecological wastewater treatment by a constructed wetland." Ecological Modelling **in press**: 9.

Shindell, D., J. C. I. Kuylenstierna, et al. (2012). "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security." Science **335**(6065): 183-189.

UNEP: United Nations Environment Programme. (2011). "Near-term climate protection and clean air benefits: Actions for controlling short- lived climate forcers."

UNFCCC: United Nations Framework Convention on Climate Change (2010). "Project Co-Benefits in Hubei Province, China: Biogas digesters enhance the welfare of low-income rural communities."

UNDESA: United Nations Department of Economic and Social Affairs (2013). " Population Division, Population Estimates and Projections Section." http://esa.un.org/unpd/wup/Country-Profiles/country-profiles_1.htm.

USEPA: US Environmental Protection Agency (2010). "Background technical support document: Greenhouse gas emissions reporting from the petroleum and natural gas industry."

USEPA: US Environmental Protection Agency (2011). DRAFT: Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 - 2030. Washington, D.C., USEPA.

USEPA: US Environmental Protection Agency (2012). "2012 Technical Corrections, Clarifying and other Amendments to the Greenhouse Gas Reporting Rule, and Confidentiality Determinations for Certain Data Elements of the Fluorinated Gas Source Category." Federal registar **77**(165).

USEPA: US Environmental Protection Agency. (2006). "Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 – 2020."

Wang, H., J. He, et al. (2011). "Municipal Solid Waste Management in Small Towns: An Economic Conducted in Yunnan, China." Development Research Group: Environment and Energy Team.

Wang, X., J. Liu, et al. (2012). "Environmental profile of typical anaerobic/anoxic/oxic wastewater treatment systems meeting increasingly stringent treatment standards from a life cycle perspective." Bioresource Technology **126**(0): 31-40.

WHO/UNICEF (2012). Estimates for the use of Improved Sanitation Facilities. Geneva, WHO / UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation.

Wilson, D., A. Araba, et al. (2009). "Building recycling rates through the informal sector." Waste management (New York, N.Y.) **29**: 629-635.

Xu, H. (2012). "The development of MSW LFG in China. China Urban Construction & Design Research Institute." http://www.globalmethane.org/partners/china.aspx.

Xu, Y. (30 Oct. 2012). Personal Interview: Analyses of GHG Emissions from Full-Scale WWTP with Different Processes. Beijing, China, Chinese Academy of Science—Center for Ecology and Environment.

Ye, C. and P. Qin (2008). "Provision of residential solid waste management service in rural China." China & World Economy **16**(5): 118-128.

Zhang, L. X., C. B. Wang, et al. (2012). "Carbon emission reduction potential of a typical household biogas system in rural China." Journal of Cleaner Production

Zuo, J. (31 Oct. 2012). Personal Interview. Beijing, China, Tsinghua University.