Air quality, health, and climate implications of China's synthetic natural gas development

Yue Qin[a], Fabian Wagner[a,b,c], Noah Scovronick[a], Wei Peng[a,1], Junnan Yang[a], Tong Zhu[d,e], Kirk R. Smith[f,2], and Denise L. Mauzerall[a,g,2]

[a]Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544; [b]Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ 08544; [c]International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; [d]State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China; [e]Beijing Innovation Center for Engineering Science and Advanced Technology, Peking University, Beijing 100871, China; [f]School of Public Health, University of California, Berkeley, CA 94720-7360; and [g]Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544

Contributed by Kirk R. Smith, March 6, 2017 (sent for review December 7, 2016; reviewed by Valerie J. Karplus and Zheng Li)

Facing severe air pollution and growing dependence on natural gas imports, the Chinese government plans to increase coal-based synthetic natural gas (SNG) production. Although displacement of coal with SNG benefits air quality, it increases CO_2 emissions. Due to variations in air pollutant and CO_2 emission factors and energy efficiencies across sectors, coal replacement with SNG results in varying degrees of air quality benefits and climate penalties. We estimate air quality, human health, and climate impacts of SNG substitution strategies in 2020. Using all production of SNG in the residential sector results in an annual decrease of ∼32,000 (20,000 to 41,000) outdoor-air-pollution-associated premature deaths, with ranges determined by the low and high estimates of the health risks. If changes in indoor/household air pollution were also included, the decrease would be far larger. SNG deployment in the residential sector results in nearly 10 and 60 times greater reduction in premature mortality than if it is deployed in the industrial or power sectors, respectively. Due to inefficiencies in current household coal use, utilization of SNG in the residential sector results in only 20 to 30% of the carbon penalty compared with using it in the industrial or power sectors. Even if carbon capture and storage is used in SNG production with today's technology, SNG emits 22 to 40% more CO_2 than the same amount of conventional gas. Among the SNG deployment strategies we evaluate, allocating currently planned SNG to households provides the largest air quality and health benefits with the smallest carbon penalties.

coal | $PM_{2.5}$ | premature mortality | residential sector | carbon capture and storage

China's ongoing coal-based synthetic natural gas (SNG) development is largely motivated by efforts to reduce its extreme ambient air pollution and dependence on foreign natural gas. Over the past 15 y, China's total natural gas consumption has increased from 25 billion cubic meters (bcm) in 2000 to 187 bcm in 2014, an annual growth rate of 15% (1). However, domestic natural gas production failed to keep pace with the increases in demand. In 2007, China's natural gas consumption surpassed domestic production for the first time, and, by the end of 2014, dependence on foreign natural gas had increased to 30% (1). After publicity surrounding high air pollution levels in 2013 (2–4), the Chinese government aimed to further increase both the quantity and the proportion of energy obtained from natural gas (5). Until 2014, natural gas accounted for approximately ∼9% and ∼5% of China's energy consumption in the residential (including both residential and commercial cooking and heating) and industrial sectors, respectively, as well as ∼2% of national total electricity generation, suggesting large potential for further increases in natural gas use in these sectors (1).

Historically, China has been characterized as rich in coal but poor in gas and oil (6). Recently, to increase natural gas supplies, the central government has emphasized domestic unconventional gas development, including SNG. As a result, 2013 was considered a "golden year" for the SNG industry. Through 2013, a total capacity of 37.1 bcm per year of SNG production had been approved by the central government, with another 40 projects (∼200 bcm per year) proposed by the industry (7). Total planned SNG capacity is ∼1.25 times China's 2014 total natural gas consumption (1). Also, the Chinese government set targets for annual SNG production of 15 bcm to 18 bcm by 2015 and 32 bcm by 2017, with a potential production of ∼57 bcm by 2020 (8–11). Notably, government plans for SNG production are continuously changing, likely due to a mix of concerns about the coal industry, local economy, air pollution in eastern China, energy security, local water stress, and global climate change (7, 12–15).

China's coal-based SNG strategy converts low-quality dirty coal in western parts of China into SNG via coal gasification and methanation. As methanation catalysts are prone to sulfur poisoning, hydrogen sulfide is removed from the coal and converted to elemental sulfur before methanation. This process essentially eliminates emissions of sulfur compounds including SO_2. Additionally, the SNG production process emits negligible NOx, which would occur if the coal were burned in steam and power-generating boilers (16). After converting coal to SNG, it is transported to and used in eastern provinces. Compared with direct combustion of coal, gas combustion emits negligible fine particulates and SO_2, and little NOx (17–19). Thus, replacing coal with SNG substantially reduces emissions of air pollutants at the location of the end user (20). However, the SNG cycle emits more CO_2 than direct use of coal. For electricity generation, up to 60% higher lifecycle CO_2 emissions occur with SNG than with ultrasupercritical coal-fired power plants per kilowatt hour of electricity generated (12). As a result, plans for

Significance

China's coal-based synthetic natural gas (SNG) projects can reduce air pollution and associated premature mortality by substituting for direct coal use in power, industry, and households. These benefits, however, come with increased CO_2 emissions unless carbon capture and storage (CCS) is applied in SNG production. Even with CCS, SNG has higher CO_2 emissions than conventional natural gas. In the United States, increases in natural gas supplies have been primarily deployed to the power sector. In China, however, due to inefficient and uncontrolled coal combustion in households, we find that allocating currently available SNG to the residential sector provides the largest air quality and health benefits and smallest climate penalties compared with allocation to the power or industrial sectors.

Author contributions: Y.Q. and D.L.M. designed research; Y.Q. performed research; F.W., N.S., W.P., and J.Y. contributed data for model simulations and evaluation; Y.Q., F.W., N.S., W.P., J.Y., T.Z., K.R.S., and D.L.M. analyzed data; and Y.Q., F.W., K.R.S., and D.L.M. wrote the paper.

Reviewers: V.J.K., Massachusetts Institute of Technology; and Z.L., Tsinghua University.

The authors declare no conflict of interest.

[1]Present address: Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, Cambridge, MA 02138.

[2]To whom correspondence may be addressed. Email: mauzeral@princeton.edu or krksmith@berkeley.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1703167114/-/DCSupplemental.

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increasing use of SNG are projected to dramatically increase CO_2 emissions.

An integrated analysis of the impacts of China's SNG plans on national air quality and associated health benefits as well as on global carbon emissions is needed to provide guidance to the Chinese government on SNG development. Moreover, as multiple SNG projects are already in place or under construction, it is important to determine production technologies and end-use applications that will bring as large air quality and health benefits as possible while keeping carbon and energy penalties as small as possible.

This paper quantifies the air quality, human health, and CO_2 emission impacts of China's SNG strategy using an integrated assessment approach. We use the ECLIPSE_V5a_CLE scenario (evaluating the climate and air quality impacts of short-lived pollutants) for 2020 as our base case as it reflects the air pollution policies and regulations in place for China's 12th Five-Year Plan (FYP) (21–24). Approximately 85% of natural gas in China is consumed in the power, industrial, and residential sectors (25). Thus, we construct three SNG sectoral allocation scenarios (SNG_Power, SNG_Industrial, and SNG_Residential) by deploying all potentially available SNG (57 bcm) in 2020 into each key demand sector in turn. We substitute SNG for coal in each sector we analyze in proportion to the gas required to displace that quantity of coal in the subsector under the base case across provinces targeted to receive SNG (Table S1). Due to large uncertainties in actual SNG production in 2020 and practical constraints on SNG deployment, SNG allocation scenarios built in this study are effectively sensitivity analyses to identify the potential impacts of SNG use in each sector. They are not intended to be analyzed as to their actual executability in the real world. We estimate changes in air pollutant emissions resulting from SNG substitution for coal under each scenario (medium scenarios in Table S1). We then simulate the resulting changes in $PM_{2.5}$ (particulate matter with aerodynamic diameter of 2.5 µm or smaller) concentrations, associated health impacts, and resulting changes in CO_2 emissions. Fig. 1 shows the potential provincial distribution of SNG production and consumption based on government plans and gas pipeline infrastructure (7, 8, 12, 26).

Through regional atmospheric chemistry model simulations, we evaluate the monthly mean $PM_{2.5}$ surface concentrations in January, April, July, and October at a horizontal resolution of 27 × 27 km^2 for the base case and for each SNG scenario. The mean concentration for the year is assumed to be the average of these four months. We also estimate the population-weighted (P-W) annual average $PM_{2.5}$ surface concentrations at the provincial level.

Burnett et al. (27) developed disease-specific integrated exposure response (IER) functions for $PM_{2.5}$ that cover the global range of exposures, including ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) for adults (≥25 y old), and acute lower respiratory infection (ALRI) for children (<5 y old). Based on the

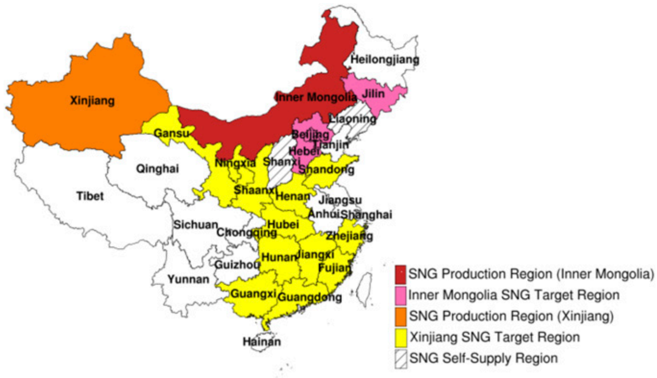

Fig. 1. Map of provinces planning to produce and consume SNG in mainland China in 2020 based on government plans and pipeline infrastructure (7, 8, 12, 26).

IER functions and P-W provincial $PM_{2.5}$ surface concentrations, we estimate the disease-specific population attributable fraction (PAF) from exposure to ambient $PM_{2.5}$ for each province and the corresponding air pollution-related premature mortality. Differences in national total premature deaths between each SNG scenario and the base case are used to estimate the avoided premature deaths under each SNG scenario. In parallel, we estimate the net changes in CO_2 emissions resulting from SNG substitution for coal under each scenario. Calculation details are described in *SI Materials and Methods*.

Results

Impacts of SNG Substitution on Pollutant and CO_2 Emissions. For all scenarios, substituting SNG for coal results in net reductions in air pollutant emissions: –40 g SO_2/m^3 to –0.7 g SO_2/m^3 SNG, –5 g NO_x/m^3 to –0.5 g NO_x/m^3 SNG, –21 g PM_{10}/m^3 to –0.7 g PM_{10}/m^3 SNG, and –19 g $PM_{2.5}$/m^3 to –0.4 g $PM_{2.5}$/m^3 SNG, varying primarily on the end-use application (Fig. 2). These reductions occur because natural gas has higher energy efficiencies and lower air pollutant emission factors (EFs) than coal per unit energy input.

Use of SNG in the residential sector results in the largest reductions in the emissions of all air pollutants considered here (Fig. 2). For instance, allocating all planned SNG to the residential sector reduces SO_2 emissions more than twice as much as allocating all SNG to the industrial sector, and 15 times more than allocating it to the power sector. SNG allocation to the power sector reduces air pollutant emissions the least; this is primarily because the power sector has the most stringent emission controls on coal combustion among the three sectors, whereas the residential sector coal emissions are generally uncontrolled. This results in the lowest average abated air pollutant EFs in the power sector (*SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes* and Fig. S1). The industrial sector also has a large fraction of low-emitting coal boilers, due to efficient control technologies, particularly for SO_2 and particulate matter. In addition, thermal efficiency improvement from a coal to gas switch is the largest in the residential sector (Table S2). Thus, proportionally substituting coal with the same amount of SNG in the residential sector leads to much larger air pollutant emission reductions than in the other two sectors. We also present the spatial distribution of monthly mean SO_2 emission reductions under each scenario as an illustration (Fig. S2), and identify substantial reductions across four seasons when all planned SNG is allocated to the residential sector, particularly in Beijing (28%), Tianjin (13%), and Hebei (18%) provinces.

Across scenarios, however, we observe energy (7 MJ/m^3 to 28 MJ/m^3 SNG) and CO_2 (0.5 kg CO_2/m^3 to 2.5 kg CO_2/m^3 SNG) penalties; this is because the higher energy content of gas over coal per carbon atom is offset by the larger quantity of coal used to produce SNG. Although energy and CO_2 penalties cannot be avoided completely, we find that SNG allocation to the residential sector, in addition to providing the largest reductions in air pollutant emissions, results in the least energy loss and the smallest increases in CO_2 emissions. These results occur because the largest thermal efficiency improvement of switching from coal to gas occurs in the residential sector (*SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes* and Table S2) (28).

Impacts of SNG Substitution on $PM_{2.5}$ Surface Concentration. We simulate China's 2020 baseline monthly mean $PM_{2.5}$ surface concentrations for January, April, July, and October (Fig. S3*A*). Model evaluation is shown in *SI Model Evaluation* (Fig. S4 and Table S3). $PM_{2.5}$ concentrations are significantly higher in January and October than in April or July; this is due to higher emissions resulting from residential heating in winter, and more stagnant meteorological conditions and less precipitation in January and October. In addition, relatively low simulated $PM_{2.5}$ concentrations occur in April partly because dust emissions are not included in our simulations. We find the Beijing–Tianjin–Hebei (BTH) region has extremely high area-wide $PM_{2.5}$ concentrations, with maximum monthly mean $PM_{2.5}$ levels reaching 170 µg/m^3 at the grid level in January. Even in April and July, the

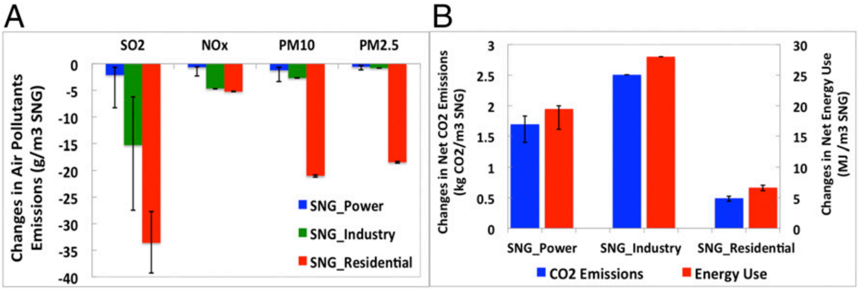

Fig. 2. (*A*) Decreases in air pollutant (SO_2, NO_x, PM_{10}, and $PM_{2.5}$) emissions and (*B*) increases in CO_2 emissions and energy consumption due to SNG substitution for coal. Vertical lines show the range of smallest to largest potential for changes in energy use and air pollutant and CO_2 emissions due to the lower bound (SNG displaces cleanest coal first) and upper bound (SNG displaces dirtiest coal first) substitution scenarios described in Table S1. The industrial sector has no error bar for CO_2 emissions and energy intensity due to the simplifying assumption in the ECLIPSE emission scenario that industrial coal boilers have the same CO_2 EF and thermal efficiency (*SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes* and Table S2).

maximum monthly mean $PM_{2.5}$ concentrations in BTH can be more than 80 μg/m^3.

Monthly mean $PM_{2.5}$ surface concentrations are reduced in all SNG scenarios, but by far the largest decrease occurs when all planned SNG is allocated to the residential sector (Fig. 3). This allocation maximizes reductions in both primary $PM_{2.5}$ emissions and the formation of secondary $PM_{2.5}$ due to reduction in emissions of major precursors (i.e., SO_2 and NO_x). Grid-level reductions are generally more than 5 μg/m^3 across all seasons in the BTH region, and can reach 60 μg/m^3 (∼30% reduction) in the dirtiest season (winter). In comparison, the $PM_{2.5}$ concentration reductions are less than 2 μg/m^3 in the BTH region year-round when all available SNG is allocated to the power sector, and less than 5 μg/m^3 when it is allocated to the industrial sector (Fig. S3 *B* and *C*).

China's base case annual average P-W $PM_{2.5}$ surface concentrations at the provincial level in 2020 are shown in Fig. 4*A*. Annual average P-W $PM_{2.5}$ concentrations are projected to be ∼70 μg/m^3 in BTH. This amount is twice China's annual average $PM_{2.5}$ national standards (35 μg/m^3) (GB3095-2012) and 7 times that of the World Health Organization (WHO) standards (10 μg/m^3) (29, 30).

Fig. 4 *B–D* shows changes in annual average P-W $PM_{2.5}$ surface concentrations across SNG sectoral scenarios. Using SNG in the residential sector to replace coal leads to the largest provincial-level P-W $PM_{2.5}$ concentration reductions. For instance, $PM_{2.5}$ concentrations are reduced by 19 μg/m^3 (26%), 12 μg/m^3 (17%), and 13 μg/m^3 (18%) in Beijing, Tianjin, and Hebei provinces, respectively. In addition to the BTH region, several other SNG producing and consuming provinces, such as Henan, Shandong, Jilin, Shanxi, and Inner Mongolia, also exhibit ∼10% $PM_{2.5}$ concentration reductions because of substantial reductions in SO_2 and $PM_{2.5}$ emissions. In contrast, provincial-level $PM_{2.5}$ concentration reductions are virtually small when all planned SNG is allocated to the industrial or power sectors [generally less than 0.6 μg/m^3 (<1.5%) and 0.2 μg/m^3 (< 0.5%), respectively].

Impacts of SNG Substitution on Premature Mortality. National total avoided premature deaths under our SNG scenarios are shown in Fig. 5, with stroke and IHD contributing roughly 60% of total reductions in premature mortality. Across scenarios, use of SNG in the residential sector results in the largest decreases in total adult premature deaths of ∼32,000 (20,000 to 40,000) and child deaths of 320 (200 to 400) annually, with the range resulting from the low and high estimates of relative risks. These reductions are roughly 10 and 60 times higher than reductions obtained by deploying SNG in the industrial and power sectors, respectively. Consistent with Liu et al. (31) findings for the BTH region, our results highlight enormous benefits for China's air quality and associated human health by switching from coal to cleaner fuels in the residential sector across the country.

Comparison of SNG Scenarios' Air Quality and Climate Impacts With and Without Utilization of Carbon Capture and Storage. Using all SNG in the residential sector clearly provides the largest air quality and human health benefits, with the smallest energy and CO_2 penalties among the scenarios we evaluate (Fig. 6). However, even under the SNG_Residential scenario, SNG substitution for coal results in an increase of 28 million tonnes of CO_2 emissions, ∼0.2% of national total projected CO_2 emissions in 2020 (24) (Fig. 6). For comparison, we replace coal with the same amount of conventional natural gas as SNG in the residential sector, and follow the same allocation strategies shown in Table S1 (medium scenarios). We find that such replacement can reduce CO_2 emissions by 214 million tonnes relative to household use of coal, or reduce CO_2 emissions by 242 million tonnes relative to SNG while providing the same amount of air quality and health benefits.

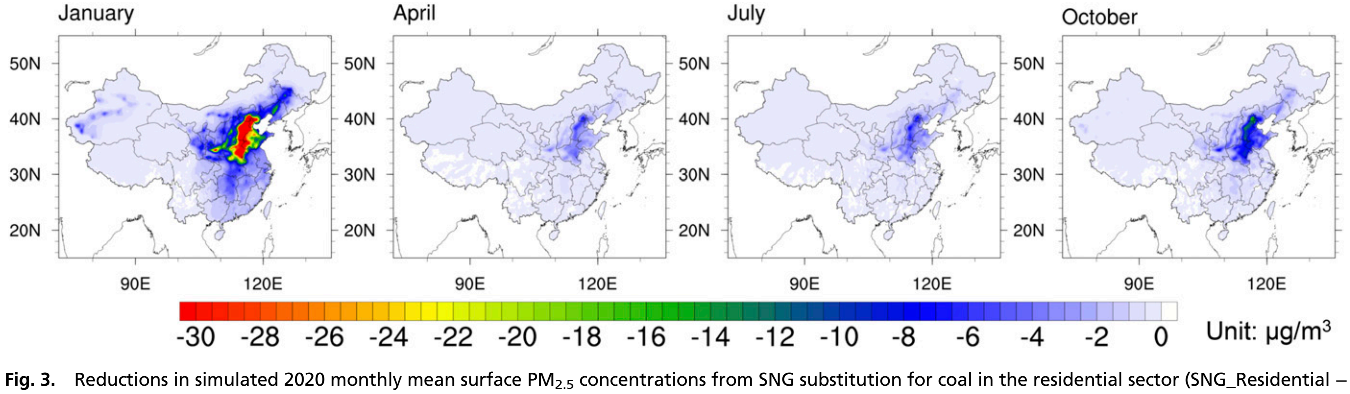

Fig. 3. Reductions in simulated 2020 monthly mean surface $PM_{2.5}$ concentrations from SNG substitution for coal in the residential sector (SNG_Residential – Base Case) (in micrograms per cubic meter).

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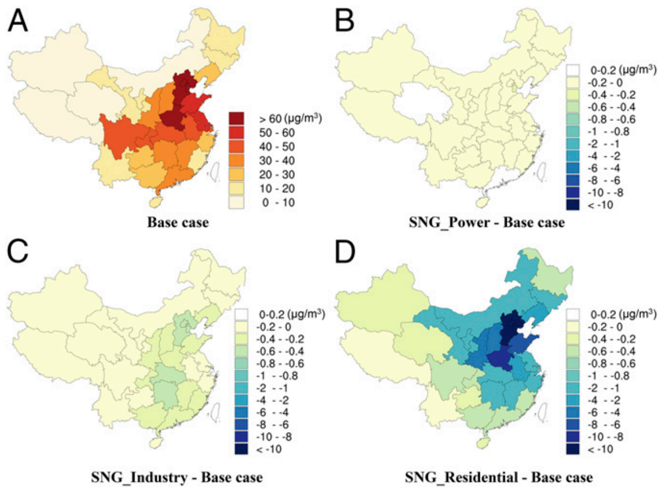

Fig. 4. (*A*) Base case annual average population-weighted $PM_{2.5}$ concentrations for each province in mainland China. (*B*–*D*) $PM_{2.5}$ concentration reductions resulting from SNG deployment under each scenario. Note the nonlinear color scale in *B*–*D*, which is used to capture regional differences at both the low and high ends of the spectrum of reductions.

As all SNG allocation strategies increase CO_2 emissions relative to coal, we explore whether carbon capture and storage (CCS), if used with SNG production, can make SNG an attractive option for both air quality and climate. China has been one of the major players working on CCS demonstration projects in recent years (32). In SNG production, CO_2 is separated from syngas before methanation regardless of conducting CCS because this optimizes the economics of the process by cost savings from higher methanation efficiency and lower volume of input syngas (16, 33). Thus, CO_2 is emitted as a by-product of SNG production, and it does not require additional energy to separate the CO_2, therefore causing a relatively low energy penalty when conducting CCS (16). We estimate the net energy penalty for conducting CCS at SNG plants to be ~9 to 15% (Table S4), with the range dependent on where the energy for conducting CCS comes from (*SI SNG Production–Energy Penalty of CCS*).

Nevertheless, even with CCS used for SNG production, net CO_2 emissions are still 22 to 40% higher than occurs with the same amount of conventional natural gas, with the range depending on end uses and the energy sources for CCS (Table S5). Substituting coal with SNG equipped with CCS requires 20 to 100% additional energy input compared with directly burning coal, varying primarily depending on end uses (Table S5). Thus, we find that SNG cannot simultaneously address the multiple objectives facing China: air quality improvement, carbon emissions mitigation, and energy intensity reduction.

Discussion

This study identifies deploying SNG to the residential sector as the allocation strategy providing the largest net environmental benefits among the substitution scenarios analyzed. We leave it to policy makers to decide how much they are willing to pay for these benefits. We did not include economic analysis of each SNG scenario. We realize that, even though deploying SNG to the residential sector results in much larger health benefits and lower climate penalties than deployment to the power and industrial sectors, it may also require higher investment on last-meter distribution pipelines, particularly for rural areas with low population density (28). However, given that only 40% of China's urban population used natural gas in 2015 (1), there may still be large opportunities to distribute SNG to urban residents using solid fuels before making large investments in reaching rural residents. Additionally, in low population-density regions, SNG can be compressed or liquefied and then transported by trucks that can be more cost-effective than pipelines (34, 35). Some provincial governments are already expanding natural gas use to rural areas by subsidizing gas pipeline construction for rural households and transporting natural gas in the form of LNG and CNG to improve the clean fuel accessibility for rural residents (36).

The absolute environmental impacts estimated in this study are subject to uncertainties in actual SNG production, how well the ECLIPSE_V5a_CLE scenario reflects the actual energy and emission status in 2020, and the representation of $PM_{2.5}$ in our atmospheric chemistry model. Our model captures the magnitude and trend of $PM_{2.5}$ concentrations fairly well, particularly in eastern regions where air quality and human health improvement predominantly occur (*SI Model Evaluation*). The actual energy use and emissions in 2020 will likely differ from the ECLIPSE_V5a_CLE scenario. Indications are that actual SNG production will be lower than the production target we use here, due, in part, to the Chinese central government's frequent downward adjustment of SNG production plans. However, our finding that substantial health benefits and relatively small climate penalties occur when available SNG is allocated to the residential sector is likely to persist as long as inefficient and uncontrolled coal use continues in the residential sector.

Our atmospheric chemistry model places all emissions into the surface layer (0 m to 32 m), and air pollutant concentrations in each grid box are instantly well mixed. The power and industrial sectors discharges much of their emissions via stacks above 32 m, whereas the residential sector primarily discharges closer to the surface than is resolved in the model. Thus, our study may have overestimated the $PM_{2.5}$-associated health benefits under the SNG_Power and SNG_Industry scenarios, and underestimated that under the SNG_Residential scenario. In addition, as household outdoor emissions are released closer to populations, they have higher intake fractions (dose or exposure effectiveness) than those from industry or power (37), which would widen the differences in benefits even further if taken into account. Finally, the significance of the residential sector would be even more striking if we included benefits to the household environment itself, i.e., health impacts from indoor and near-field air pollution (38). Nevertheless, SNG may have to be allocated to other sectors if too much future SNG production causes saturation of the residential sector or if costs of pipeline construction limit the spread of SNG to the more densely populated areas. Total 2020 SNG evaluated here (~30% of currently industry-planned SNG projects) replaces ~60% of baseline coal consumption in the residential sector. Supposing all of the ~200 bcm per year SNG projects are implemented, this will quickly use up the opportunities for coal replacement in the residential sector and lead to significantly lower marginal health benefits but larger marginal carbon penalties.

Our study does not consider the interactions between SNG and renewable energy, which can potentially increase the air

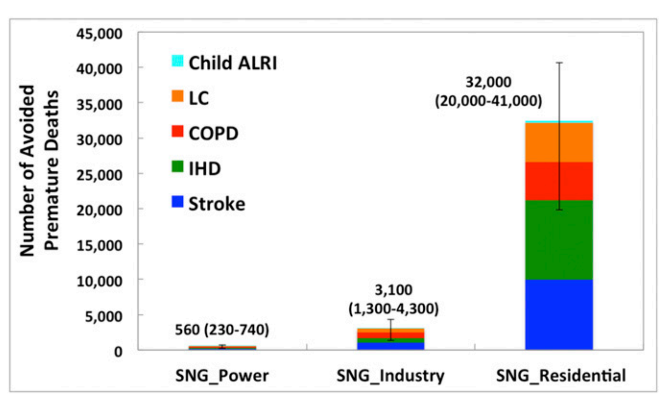

Fig. 5. National total avoided premature mortality by disease type (color) resulting from the replacement of coal with available SNG within each scenario. Child premature deaths due to ALRI are shown together with premature deaths for adults due to LC, COPD, IHD, and stroke. The first value provides the annual mean avoided premature mortality for each scenario, and the range in parentheses results from uncertainties in the relative risks for $PM_{2.5}$ exposure as reported by Burnett et al. (27).

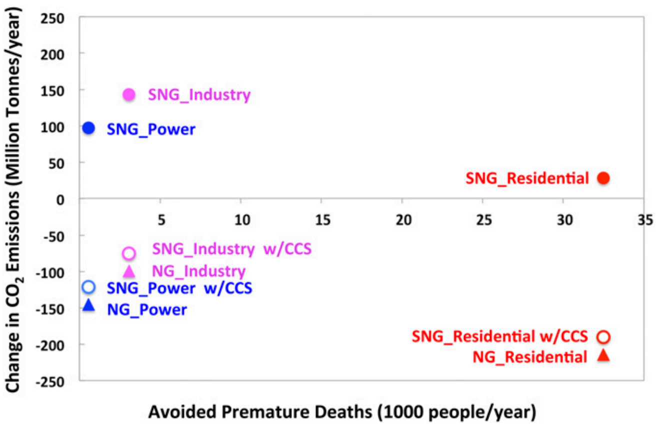

Fig. 6. Comparison of CO_2 emission changes and avoided premature mortality under various SNG allocation scenarios relative to the use of coal. Results for standard SNG scenarios all find increases in CO_2 emissions while results that include CCS and the use of conventional natural gas (NG) all result in reductions in CO_2 emissions. Solid circles represent SNG without applying CCS, and open circles represent SNG with CCS applied during SNG production. Solid triangles represent the outcome when conventional natural gas is used without CCS. We assume that electricity provided for SNG_CCS is from natural gas combined cycle (NGCC) power plants using CCS. For results with other types of power plants, refer to *SI SNG Production–Energy Penalty of CCS*.

quality and climate benefits obtained from the power sector and potentially allow electrification of the residential sector at a low-carbon intensity. However, the role that natural gas can play in facilitating wind and solar on-grid integration is likely to be limited in China in the near future given the small amount of natural gas in the power sector (even including all planned 2020 SNG). Also, the primary barriers to China's renewable integration lie elsewhere (i.e., oversupply of coal-fired electricity with fixed annual operation hours and inadequate transmission capacity) (39).

Conclusions

China's SNG development has important implications for both regional air quality and global climate. Since 2013, China's severe air pollution has drawn enormous public attention and a commitment from the government to implement measures that improve air quality (4). Switching from coal to gas is identified in the national action plan as a strategy to improve air quality (5), and efforts to increase natural gas supply, including via development of SNG production, are under way. However, wide concerns about China's SNG strategy exist as CO_2 emissions per unit of end-use energy delivered from SNG projects greatly exceed that associated with most other energy sources and will have lasting and significant impacts on climate change (7, 15).

We find that sectoral allocation makes a huge difference in the environmental performance of a limited quantity of SNG. For instance, SNG substitution for coal in the residential sector can reduce $PM_{2.5}$ concentrations in the BTH region by ~20%. These areas are among the most densely populated regions with the worst air quality in China. Additionally, deploying all SNG to the residential sector can avoid 32,000 (20,000 to 41,000) air pollution-related premature deaths nationwide in 2020. In contrast, allocating all SNG to the power or industrial sectors barely improves air quality and avoids only 560 (230 to 740) or 3,100 (1,300 to 4,300) premature deaths, respectively. Similarly, due to relative efficiencies in the use of coal and gas in the industrial and power sectors compared with the residential sector, net increases in CO_2 emissions when all planned SNG is used in the industrial or power sectors to replace coal are 2 and 4 times higher, respectively, than if it is used in the residential sector. We also compare the health impacts and net carbon emissions from two regional allocation scenarios, and find that allocating SNG to affluent provinces or proportionally to provinces based on their baseline gas needs for coal replacement leads to similar reductions in national total premature mortality and carbon emission increases (see *SI Regional SNG Allocation* for details).

Critically, energy and CO_2 penalties exist across all scenarios. Thus, without CCS used in SNG production, the air quality and human health benefits of SNG substitution for coal are achieved at the expense of CO_2 emission increases. Even with CCS, however, the climate performance of SNG remains worse than conventional gas (SNG+CCS emits 22 to 40% more CO_2 than the same amount of conventional gas), and applying CCS for SNG production results in ~9 to 15% additional energy loss compared to SNG without CCS. In China's 2015 intended nationally determined contributions, China pledged to peak its CO_2 emissions by 2030 or earlier, and to lower CO_2 emissions per unit of gross domestic product by 60 to 65% from the 2005 levels by 2030 (40). Thus, SNG development is inconsistent with China's efforts to reduce energy and carbon intensity, but it does provide substantial air quality improvement with relatively small climate cobenefits if done in conjunction with CCS. To achieve its goals, China may wish to limit the scale of SNG development and to conduct pilot projects on pairing CCS with SNG production to facilitate achievement of its international climate commitment while addressing its domestic air pollution issue.

Allocating SNG to the residential sector is likely to bring the largest air quality benefits with the smallest carbon penalties, even without CCS. Importantly, the air quality benefits brought by SNG can easily be achieved by other sources of natural gas, which have a lower carbon footprint. Given the multiple challenges facing China today, other domestic gas sources, including tight gas, coal-bed methane, and shale gas (with methane leakage well controlled) (41), as well as increased energy efficiency and an increasingly electrified energy economy driven by renewable energy, are likely to provide equal air quality benefits with lower negative climate impacts. Large challenges exist, however, in switching from coal to natural gas. Challenges include an underdeveloped pipeline infrastructure, high infrastructure costs particularly in low-population regions, and low price competitiveness of natural gas compared with cheap coal. However, the Chinese central government has demonstrated a political willingness to address these issues and has set ambitious near- and long-term natural gas use targets, and has designed and approved substantial natural gas pipeline expansion projects (i.e., Xinjiang SNG pipeline project) while reforming China's natural gas market (8, 42). Meanwhile, provincial and lower-level governments are also subsidizing local pipeline construction and natural gas consumption for rural residents (36). Nevertheless, a reasonable price on carbon would facilitate a more accurate valuation of natural gas relative to both carbon-intensive coal and carbon-free renewables.

Materials and Methods

We use an integrated assessment approach to estimate the air pollution-associated human health impacts in mainland China under each SNG scenario. The ECLIPSE_V5a_CLE scenario, developed by the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model at the International Institute for Applied Systems Analysis (IIASA, gains.iiasa.ac.at/models/), is used as our 2020 base case anthropogenic emission input. The GAINS model provides detailed information regarding energy mix and consumption, end-use technology, and EFs for major air pollutants in each subsector at the provincial level. Based on the ECLIPSE_V5a_CLE scenario, we design SNG allocation scenarios by deploying all planned production of SNG to replace coal in the power sector, industrial sector, and residential sector, in turn, in proportion to baseline gas required for coal replacement in each subsector. We estimate the provincial anthropogenic emissions under the base case and each scenario accordingly, and assume 2020 emissions within each province follow the same spatial and temporal pattern as that of the 2010 Multi-Resolution Emission Inventory for China (MEIC, www.meicmodel.org).

We use the weather research and forecasting model coupled with chemistry, version 3.6 (WRF-Chem v3.6), to simulate air pollutant concentrations for the 2020 base case and for each SNG scenario (43). The study domain covers East Asia at a horizontal resolution of 27×27 km^2 with 31 vertical levels, from the surface to 50 millibars (mb), with a 32-m-thick surface layer. The global 3D chemical transport model [Model for Ozone and Related Tracers (MOZART-4)], with a resolution of 1.9° latitude $\times$ 2.5° longitude, provides the chemical initial and boundary conditions (www.acom.ucar.edu/wrf-chem/mozart.shtml). Meteorological data for 2015 are from the National Centers for Environmental Prediction (NCEP) Global Forecast System final gridded analysis datasets at a 6-h resolution (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs). Biogenic emissions are calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (44).

To evaluate the health effects of the SNG allocation scenarios, we estimate the changes in premature mortality that are associated with long-term exposure to ambient $PM_{2.5}$ pollution for both adults and children based on the IER functions developed from the Global Burden of Disease studies (27). Detailed methods are shown in *SI Materials and Methods*.

ACKNOWLEDGMENTS. We thank Dr. Eric D. Larson for guidance on estimating the energy penalties of conducting CCS during SNG production. Funding for this study was provided by a graduate fellowship from the Woodrow Wilson School of Public and International Affairs at Princeton University (to Y.Q.), postdoctoral support from the Climate Futures Initiative at Princeton University (to N.S.), and National Natural Science Foundation Committee of China Grants 41421064 and 21190051.

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