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.

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

SUSTAINABILITY SCIENCES

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.

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

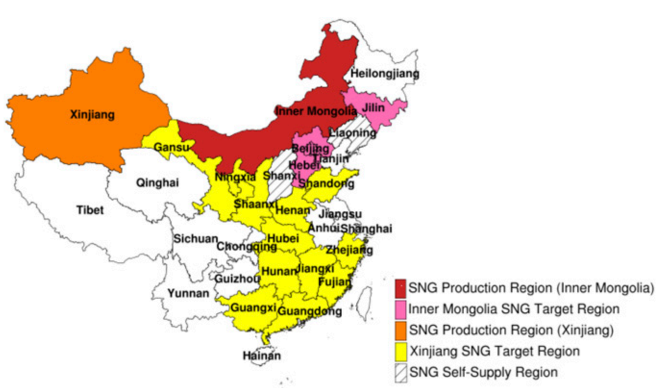

Fig. 1. Map of provinces planning to produce and consume SNG in mainland China in 2020 based on government plans and pipeline infrastructure (7, 8, 12, 26).

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

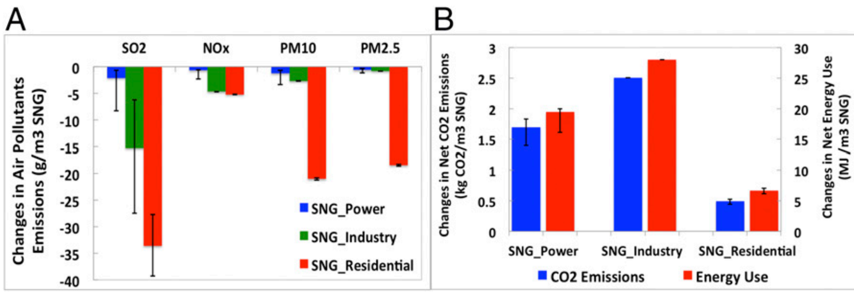

Fig. 2. (*A*) Decreases in air pollutant (SO_2, NO_x, PM_{10}, and $PM_{2.5}$) emissions and (*B*) increases in CO_2 emissions and energy consumption due to SNG substitution for coal. Vertical lines show the range of smallest to largest potential for changes in energy use and air pollutant and CO_2 emissions 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.

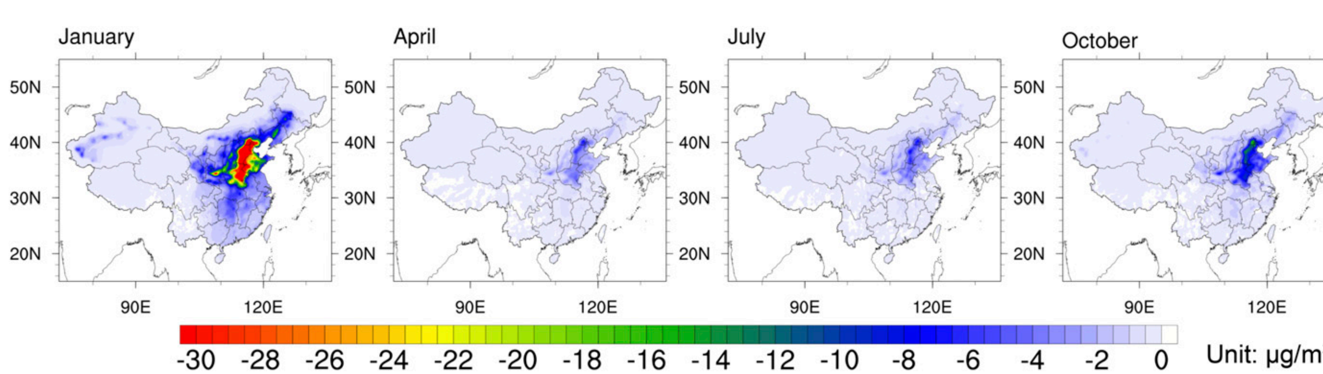

Fig. 3. Reductions in simulated 2020 monthly mean surface $PM_{2.5}$ concentrations from SNG substitution for coal in the residential sector (SNG_Residential − Base Case) (in micrograms per cubic meter).

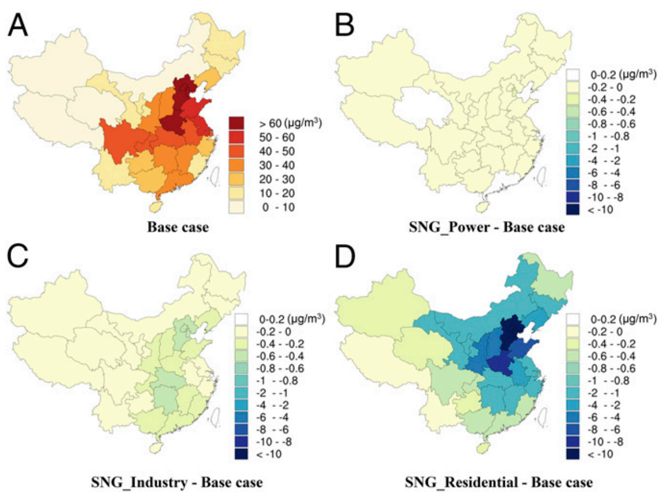

Fig. 4. (*A*) Base case annual average population-weighted $PM_{2.5}$ concentrations for each province in mainland China. (*B–D*) $PM_{2.5}$ concentration reductions resulting from SNG deployment under each scenario. Note the nonlinear color scale in *B–D*, which is used to capture regional differences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

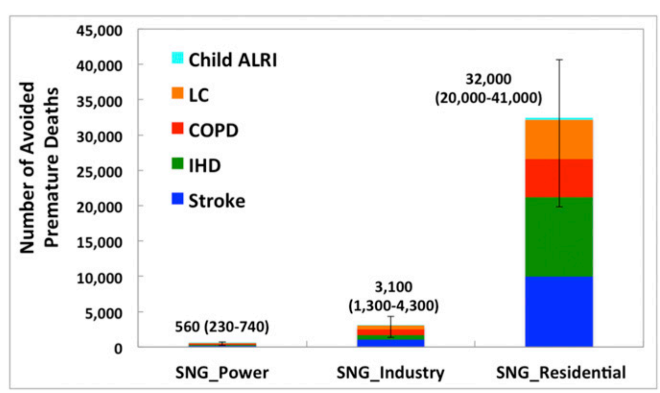

Fig. 5. National total avoided premature mortality by disease type (color) resulting from the replacement of coal with available SNG within each scenario. Child premature deaths due to ALRI are shown together with premature deaths for adults due to LC, COPD, IHD, and stroke. The first value provides 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).

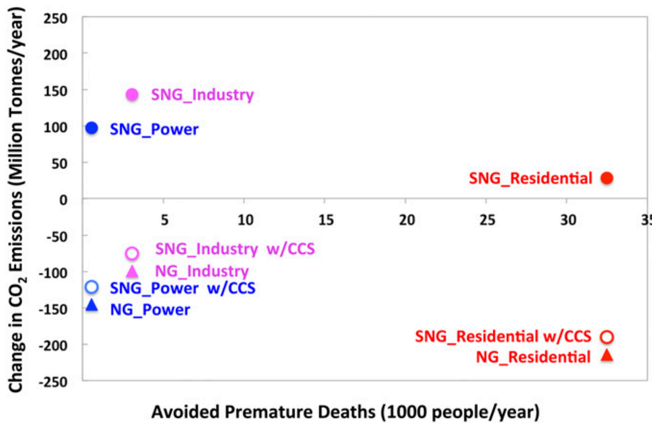

Fig. 6. Comparison of CO_2 emission changes and avoided premature mortality under various SNG allocation scenarios relative to the use of coal. Results for standard SNG scenarios all find increases in CO_2 emissions while results that include CCS and the use of conventional natural gas (NG) all result 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 × 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.

1. National Bureau of Statistics of China (2016) National Statistic Data. Available at data.stats.gov.cn/easyquery.htm?cn=C01. Accessed March 1, 2017.
2. Wang LT, et al. (2014) The 2013 severe haze over southern Hebei, China: Model evaluation, source apportionment, and policy implications. *Atmos Chem Phys* 14:3151–3173.
3. Lin A, et al. (2016) China's partial emission control. *Science* 351:674–675.
4. Sheehan P, Cheng EJ, English A, Sun FH (2014) China's response to the air pollution shock. *Nat Clim Change* 4:306–309.
5. National Energy Administration (2014) Energy industry to strengthen air pollution control work plan. Available at www.nea.gov.cn/2014-05/16/c_133339262.htm. Accessed October 5, 2016.
6. Wang JL, Feng LY, Tverberg GE (2013) An analysis of China's coal supply and its impact on China's future economic growth. *Energy Policy* 57:542–551.
7. Yang CJ, Jackson RB (2013) Commentary: China's synthetic natural gas revolution. *Nat Clim Change* 3:852–854.
8. National Development and Reform Commission (2012) *Twelfth Five Year Plan for China's Natural Gas Development* (Natl Dev Reform Comm, Beijing).
9. State Council (2014) Action plan on energy development strategy (2014–2020). Available at www.gov.cn/zhengce/content/2014-11/19/content_9222.htm. Accessed October 5, 2016.
10. National Energy Administration (2014) Strengthen the work plan for prevention and control of atmospheric pollution in energy industry. Available at www.nea.gov.cn/133338463_14002098575931n.pdf. Accessed October 7, 2016.
11. National Energy Administration (2014) *Pathways to Substantially Increase the Proportion of Natural Gas in China's Primary Energy Consumption During the 13th Five Year Plan* (Natl Energy Admin, Beijing).
12. Ding YJ, Han WJ, Chai QH, Yang SH, Shen W (2013) Coal-based synthetic natural gas (SNG): A solution to China's energy security and CO_2 reduction? *Energy Policy* 55:445–453.
13. Li HC, Yang SY, Zhang J, Kraslawski A, Qian Y (2014) Analysis of rationality of coal-based synthetic natural gas (SNG) production in China. *Energy Policy* 71:180–188.
14. Huo JW, Yang DG, Xia FQ, Tang H, Zhang WB (2013) Feasibility analysis and policy recommendations for the development of the coal based SNG industry in Xinjiang. *Energy Policy* 61:3–11.
15. Yang CJ (2015) China's precarious synthetic natural gas demonstration. *Energy Policy* 76:158–160.
16. National Energy Technology Laboratory (2011) *Coal to Synthetic Natural Gas and Ammonia*, Cost and Performance Baseline for Fossil Energy Plants (Natl Energy Technol Lab, Pittsburgh), Vol 2.
17. Huang C, et al. (2011) Emission inventory of anthropogenic air pollutants and VOC species in the Yangtze River Delta region, China. *Atmos Chem Phys* 11:4105–4120.
18. Lei Y, Zhang Q, He KB, Streets DG (2011) Primary anthropogenic aerosol emission trends for China, 1990-2005. *Atmos Chem Phys* 11:931–954.
19. Wang SW, et al. (2012) Growth in NOx emissions from power plants in China: Bottom-up estimates and satellite observations. *Atmos Chem Phys* 12:4429–4447.
20. Pacsi AP, Alhajeri NS, Zavala-Araiza D, Webster MD, Allen DT (2013) Regional air quality impacts of increased natural gas production and use in Texas. *Environ Sci Technol* 47:3521–3527.
21. Internal Energy Agency (2012) *Energy Technology Perspectives 2012: Pathways to a Clean Energy System* (Internal Energy Agency, Paris).
22. Klimont Z, et al. (October 17, 2016) Global anthropogenic emissions of particulate matter including black carbon. *Atmos Chem Phys Discuss*, 10.5194/acp-2016-880.
23. Stohl A, et al. (2015) Evaluating the climate and air quality impacts of short-lived pollutants. *Atmos Chem Phys* 15:10529–10566.
24. International Institute for Applied Systems Analysis (2016) Global emission fields of air pollutants and GHG. Available at www.iiasa.ac.at/web/home/research/researchPrograms/air/Global_emissions.html. Accessed May 7, 2016.
25. National Bureau of Statistics China (2001–2013) *China Energy Statistical Yearbook* (China Stat Press, Beijing).
26. National Development and Reform Commission (2015) *Approval of the Xinjiang Synthetic Natural Gas Exporting Pipeline Projects* (Natl Dev Reform Comm, Beijing), Rep 2295.
27. Burnett RT, et al. (2014) An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ Health Perspect* 122:397–403.
28. Mao XQ, Guo XR, Chang YG, Peng YD (2005) Improving air quality in large cities by substituting natural gas for coal in China: Changing idea and incentive policy implications. *Energy Policy* 33:307–318.
29. Ministry of Environmental Protection (2012) *National Ambient Air Quality Standard (GB3095-2012)* (Min Environ Prot, Beijing).
30. World Health Organization (2005) *Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide, Summary of Risk Assessment* (World Health Org, Geneva).
31. Liu J, et al. (2016) Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proc Natl Acad Sci USA* 113:7756–7761.
32. Zeng M, Ouyang SJ, Zhang YJ, Shi H (2014) CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis. *Renew Sustain Energy Rev* 39:604–616.
33. Liu GJ, Larson ED, Williams RH, Kreutz TG, Guo XB (2011) Making Fischer-Tropsch fuels and electricity from coal and biomass: Performance and cost analysis. *Energy Fuels* 25:415–437.
34. Kumar S, et al. (2011) LNG: An eco-friendly cryogenic fuel for sustainable development. *Appl Energy* 88:4264–4273.
35. Thomas S, Dawe RA (2003) Review of ways to transport natural gas energy from countries which do not need the gas for domestic use. *Energy* 28:1461–1477.
36. Hebei Provincial Government (2016) *Guidelines on Accelerating the Implementation of Coal Substitution with Electricity and Natural Gas in the Langfang, Baoding District* (Hebei Prov Gov, Shijiazhuang, China).
37. Wang XD, Smith KR (1999) Secondary benefits of greenhouse gas control: Health impacts in China. *Environ Sci Technol* 33:3056–3061.
38. Smith KR, et al.; HAP CRA Risk Expert Group (2014) Millions dead: How do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annu Rev Public Health* 35:185–206.
39. Lu X, et al. (2016) Challenges faced by China compared with the US in developing wind power. *Nat Energy* 1:16061.
40. National Development and Reform Commission (2015) Enhanced actions on climate change: China's intended nationally determined contributions. Available at www4.unfccc.int/Submissions/INDC/Published Documents/China/1/China's INDC - on 30 June 2015.pdf. Accessed October 6, 2016.
41. Qin Y, Edwards R, Tong F, Mauzerall DL (2017) Can switching from coal to shale gas bring net carbon reductions to China? *Environ Sci Technol* 51:2554–2562.
42. National Development and Reform Commission (2015) Notice on decreasing natural gas gate prices for non-residential users. Available at www.sdpc.gov.cn/zcfb/zcfbtz/201511/t20151118_758883.html. Accessed October 6, 2016.
43. Grell GA, et al. (2005) Fully coupled "online" chemistry within the WRF model. *Atmos Environ* 39:6957–6975.
44. Guenther AB, et al. (2012) The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions. *Geosci Model Dev* 5:1471–1492.
45. National Energy Administration (2015) Regulatory reports on guaranteeing a stable natural gas supply to the Beijing-Tianjin-Hebei region. Available at zfxxgk.nea.gov.cn/auto92/201506/t20150604_1933.htm. Accessed October 5, 2016.
46. Jilin Provincial Government (2011) "Gasification Jilin" project was launched in 2015 and will achieve full coverage of natural gas. Available at www.gov.cn/gzdt/2011-12/06/content_2012012.htm. Accessed October 6, 2016.
47. Zhao B, et al. (2013) NOx emissions in China: Historical trends and future perspectives. *Atmos Chem Phys* 13:9869–9897.
48. Intergovernmental Panel on Climate Change (2006) Stationary combustion. *IPCC Guidelines for National Greenhouse Gas Inventories* (Inst Global Environ Strat, Hayama, Japan), Vol 2, pp 11–36.
49. Shen W, Han W, Wallington TJ (2014) Current and future greenhouse gas emissions associated with electricity generation in China: Implications for electric vehicles. *Environ Sci Technol* 48:7069–7075.
50. Zhang Q, et al. (2009) Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos Chem Phys* 9:5131–5153.
51. All China Marketing Research Company (2014) China census data by county, 2000-2010. Available at map.princeton.edu/search/details/#/9107c437-8169-4444-9427-3b6957a09bca. Accessed May 10, 2016.
52. Saikawa E, et al. (2011) The impact of China's vehicle emissions on regional air quality in 2000 and 2020: A scenario analysis. *Atmos Chem Phys* 11:9465–9484.
53. Zhang Y, et al. (2016) Application of WRF/Chem over East Asia: Part I. Model evaluation and intercomparison with MM5/CMAQ. *Atmos Environ* 124:285–300.
54. Metz B, Davidson O, Coninck Hd, Loos M, Meyer L (Eds) (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage* (Cambridge Univ Press, Cambridge, UK).
55. Goto K, Yogo K, Higashii T (2013) A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. *Appl Energy* 111:710–720.
56. Kunze C, Spliethoff H (2012) Assessment of oxy-fuel, pre- and post-combustion-based carbon capture for future IGCC plants. *Appl Energy* 94:109–116.

Supporting Information

Qin et al. 10.1073/pnas.1703167114

SI Materials and Methods

We describe the details of the integrated assessment tools used in this study to estimate the environmental and human health impacts of China's coal-based SNG projects.

Constructing SNG Allocation Scenarios. In this study, we follow the 2010 to 2050 energy projections of the International Energy Agency's Energy Technology Perspectives (ETP) (21). The GAINS model (gains.iiasa.ac.at/models/), developed by IIASA (www.iiasa.ac.at), implements the ETP energy scenario as the ECLIPSE_V5a_CLE scenario (2010 to 2050) (22–24) to reflect and predict air pollution policies and regulations based on China's 12th FYP. Policies and regulations are represented as penetration rates of a variety of control technologies with various removal efficiencies. This study uses the ECLIPSE_V5a_CLE scenario for 2020 as its base case. We then estimate the impacts of a switch to SNG from coal for various end-use applications in China on air pollutant emissions, associated premature mortality, and CO_2 emissions. The focus of our study is the year 2020, for which development plans are relatively clear as multiple large-scale SNG projects have been approved (7). Beyond that year, the further development of SNG is more uncertain due to the negative environmental implications on global climate, local water stress, technology lock-in, and so forth (7, 15).

Through 2013, the Chinese government had approved a total capacity of 37.1 bcm of SNG, with another ∼200 bcm proposed by the industry (7). Government plans for annual SNG production is about 15 bcm to 18 bcm by 2015 and 32 bcm by 2017, with a potential production of ∼57 bcm by 2020 (8–11). Although the government has continuously changed SNG production plans, in this study, we use the potential production of 57 bcm as a sensitivity analysis to identify a superior SNG allocation strategy that brings large air quality and health benefits, with small climate penalties. Discussions of uncertainties in actual SNG production are included in *Discussion*. Of total SNG projected to be produced nationally in 2020, we assume that Xinjiang, Inner Mongolia, Liaoning, and Shanxi have annual productions of about 29, 20, 4, and 4 bcm, respectively, based on SNG development plans (7, 12). According to official plans, Inner Mongolia's SNG is designed mainly to serve gas needs in the BTH region, Inner Mongolia, and Jilin province (45, 46). Similarly, Xinjiang's SNG targets Xinjiang, Gansu, Ningxia, Shaanxi, Shandong, Henan, Hubei, Hunan, Jiangxi, Fujian, Zhejiang, Guangdong, and Guangxi provinces (8, 26). SNG produced in Liaoning and Shanxi provinces is expected to be primarily consumed locally, as these two provinces traditionally have imported gas (25).

About 85% of natural gas in China is consumed in the power, industrial, and residential sectors (25). Thus, this study focuses on the environmental impacts of natural gas substitution for coal in the three dominant sectors. We build three main SNG sectoral allocation scenarios. Each allocation scenario has three subscenarios that use various criteria for coal substitution (Table S1). These allocation scenarios examine the impacts of SNG substitution for coal in the power, industrial, and residential sectors in turn.

Estimating Air Pollutant and Carbon Dioxide Emission Changes from SNG Substitution for Coal. The primary difference in air pollutant emissions between SNG and coal lies in end-use combustion, as gas made from coal can be burned much more cleanly and efficiently than the coal used to make it (20, 28) and relatively few emissions are associated with the centralized gasification process (16). In contrast, SNG substitution for coal leads to a net increase in CO_2 emissions over direct coal use even though the end-use efficiencies are higher with gas (12).

CO_2 emissions due to SNG production from coal are calculated by multiplying the SNG CO_2 emission factors (EFs; 4.25 kg CO_2 emitted per cubic meter of SNG produced) (13) by total SNG produced. The GAINS model provides hundreds of detailed breakdowns of provincial energy uses and mixes, unabated emission factors for various air pollutants and fuel types, combustion technologies, and control technologies with varying removal efficiencies, although with no spatial information within each province. For each combustion situation (unabated EFs for each fuel type, consumption province, combustion technology, and control technology), it provides a specific EF for each air pollutant. Fig. S1 shows the unabated and abated EFs for major air pollutants due to coal combustion in the power, industrial, and residential sectors to illustrate the differences across the three sectors. Power and industrial sectors generally have higher unabated air pollutant EFs than those in the residential sector, suggesting a higher quality of coal allocated to the residential sector; this is also identified in earlier emission inventory studies (18, 47). However, primarily due to increasing penetration of more efficient end-of-pipe control technologies based on China's 12th FYP, particularly in the power and industrial sectors, the abated EFs in these two sectors are significantly reduced in year 2020. Conversely, the abated residential EFs are marginally lower than the corresponding unabated EFs, as few clean-coal technologies can be applied for small and scattered residential coal users (i.e., improved coal stoves) (28). Thus, a large proportion of coal burned in the power and industrial sectors has low abated air pollutant EFs, resulting in lower air pollutant emission reductions, when SNG proportionally substitutes coal in these two sectors, than in the residential sector. Table S2 shows CO_2 EFs and thermal efficiencies for coal and natural gas combustion in the three sectors used in the ECLIPSE scenario. The ECLIPSE scenario uses the same CO_2 EF for the same type of fuel combustion, consistent with the fact that energy-related CO_2 EFs are primarily determined by fuel types (48). In addition, energy efficiencies for coal and gas combustion listed in Table S2 are generally comparable to China's domestic studies (12, 49). The ECLIPSE scenario assumes the same energy efficiency for industrial coal boilers. This is supported by State Administration for Quality Supervision and Inspection and Quarantine (AQSIQ)'s finding that over 95% of China's industrial boilers have an operation capacity of lower than 20 t/h, with an average thermal efficiency of 69% (55 to 75%) and 83% (80 to 85%) for coal- and gas-fired industry boilers, respectively (12, 13). Thus, the relative energy efficiency improvement from a coal-to-gas switch for industrial boilers identified in the ECLIPSE scenario is marginally lower than that estimated using the average efficiency values from the AQSIQ survey. Also, thermal efficiency improvement of a coal-to-gas switch in the residential sector that is larger than in the industrial and power sectors was also identified in earlier studies (28). Thus, at the national average level, the relative thermal efficiency improvement due to switching from coal to gas identified in Table S2 is consistent with other studies. However, more specific information (i.e., operating conditions, equipment maintenance) is needed to conduct case-by-case comparisons, which is beyond the scope of this study. Please refer to Klimont et al. (22), Stohl et al. (23), and the publicly available GAINS model (gains.iiasa.ac.at/models/) for more details.

Following SNG allocation subscenarios in Table S1, we use SNG to substitute coal used in each of the key demand sectors across provinces targeted to receive SNG, using the GAINS model. For instance, SNG_Power medium scenario means SNG proportionally substitutes coal in the power sector across provinces targeted to receive SNG. Integrated gasification combined cycle (IGCC) plants, the cleanest current available coal-fired power plants, are not considered for substitution with SNG as they have air pollutant EFs comparable with NGCC. Air pollutants and CO_2 emission reductions from end-use combustion resulting from SNG substitution for coal under each subscenario are calculated using Eq. **S1**.

$$\Delta E_{a,p,s} = \Delta \mathrm{SNG}_{p,s} * \left(\frac{\mathrm{HV}_{\mathrm{SNG}}}{\mathrm{HV}_{\mathrm{Coal}}} * \frac{\eta_{\mathrm{SNG},s}}{\eta_{\mathrm{Coal},s}} * \sum \mathrm{EF}_{\mathrm{Coal},a,p,s,t} * P_{\mathrm{Coal},a,p,s,t} - \sum \mathrm{EF}_{\mathrm{SNG},a,p,s,t} * P_{\mathrm{SNG},a,p,s,t} \right), \quad \textbf{[S1]}$$

where $\Delta E_{a,p,s}$ is emission reduction for pollutant type a, in province p and subsector s; $\Delta\mathrm{SNG}_{p,s}$ is SNG allocation to province p and subsector s; HV is heating value; η is energy efficiency; EF is control technology (t)-specific abated emission factors; and P is penetration rate of a particular control technology (t).

Evaluating Air Quality Impacts. WRF-Chem v3.6 simulates atmospheric transport, chemistry, and meteorology simultaneously, and is designed for regional-scale air quality simulations (43). Our study domain covers East Asia at a horizontal resolution of 27 × 27 km^2 with 31 vertical levels, from the surface to 50 mb, with a 32-m-thick surface layer. The global 3D chemical transport model MOZART-4, with a resolution of 1.9° latitude × 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 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 MEGAN (44). Forest and savanna fire emissions are from the Global Fire Data (GFEDV3) (www.globalfiredata.org/). Anthropogenic emissions are either from the 2020 ECLIPSE_V5a_CLE scenario (our base case), or our calculated air pollutant emissions under each SNG scenario (*SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes*), with detailed spatial and temporal allocation described below. The Regional Acid Deposition version 2 atmospheric chemical mechanisms and Modal Aerosol Dynamics model for Europe with the Secondary Organic Aerosol Model are used for gas-phase chemistry and aerosol chemistry, respectively.

We estimate provincial total anthropogenic emissions under each medium replacement scenario (Table S1) according to calculations in *SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes*. We assume that, within each province, 2020 emissions follow the same spatial and temporal pattern as that of the 2010 MEIC (www.meicmodel.org). National total emissions for regions outside of China in 2020 are also from the ECLIPSE_V5a_CLE scenario, and we assume its spatial and temporal allocation is the same as that of the 2006 Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) Asian emission inventories (50). Due to data limitations, all anthropogenic emissions are treated in the model surface layer. Spatial distribution of air pollutant emission reductions under various SNG medium scenarios is shown in Fig. S2. Due to high computational demands of these simulations, we simulate January, April, July, and October as representative months for each season, with 1 wk at the end of December, March, June, and September used for spin-up. The mean $PM_{2.5}$ surface concentration for the year is assumed to be the average of these four months. For both the base case and SNG medium scenario simulations, we use the same 2015 meteorology. We evaluate the differences of air quality impacts due to various SNG sectoral allocation strategies by comparing the changes of air pollutant concentrations from the base case among SNG medium scenarios.

Based on our simulated grid-level annual average $PM_{2.5}$ surface concentrations and the spatial distribution of China's population (51), we estimate the P-W [$C_{\mathrm{PW}}(P) = \sum_{i=1}^{n}\mathrm{Pop}_i\ (P)*C_i(P)/\sum_{i=1}^{n}\mathrm{Pop}_i(P)$] annual average $PM_{2.5}$ surface concentrations at the provincial level. $C_{\mathrm{PW}}(P)$ refers to P-W $PM_{2.5}$ concentrations in province P, Pop_i refers to population in each grid i within province P, and C_i refers to model simulated $PM_{2.5}$ concentrations in grid i in province P.

Evaluating Health Impacts. To evaluate the health effects of the SNG allocation scenarios, we estimate the changes in premature mortality that is associated with long-term exposure to ambient $PM_{2.5}$ pollution for both adults (≥25 y old) and children (<5 y old) (27). In China's many cities, annual average $PM_{2.5}$ concentrations can be as high as 5 times that of the WHO guidelines for annual mean $PM_{2.5}$ concentrations (10 μg/m^3) (4, 30). Burnett et al. (27) developed IER functions for $PM_{2.5}$ that cover the global range of exposures, and are suitable for China's high $PM_{2.5}$ concentrations. We use Burnett et al. (27) relative risk (RR) estimates for IHD, cerebrovascular disease (stroke), COPD, LC, and child ALRI. Based on the IER functions and P-W provincial $PM_{2.5}$ concentrations, we estimate the disease-specific PAF from exposure to ambient $PM_{2.5}$ for each province ($\mathrm{PAF}_{i,P} = 1 - 1/\mathrm{RR}_{i,P}$, where $\mathrm{RR}_{i,P}$ are the $\mathrm{RR}_{\mathrm{IER}}$ values corresponding to the P-W $PM_{2.5}$ concentrations for disease i in province P resulting from either the base case or an SNG medium scenario). Thus, premature mortality in each province for disease i due to $PM_{2.5}$ exposure is calculated using

$$\mathrm{Mort}_{i,P} = \mathrm{POP}_{j,P} * \mathrm{Mortbase}_{i,P} * \left(1 - 1/\mathrm{RR}_{i,P}\right), \quad \textbf{[S2]}$$

where $\mathrm{Mort}_{i,P}$ is the number of premature mortality in province P from disease i; $\mathrm{POP}_{j,P}$ is the number of exposed targeted population in province P, either adults (≥25 y old) for IHD, stroke, COPD, and LC or children (<5 y old) for ALRI; and $\mathrm{Mortbase}_{i,P}$ is the baseline mortality rate for either adults or children in province P for disease i. Differences in premature mortality between a medium SNG scenario and the base case are the numbers of avoided premature mortality due to the specific SNG scenario. Disease-specific mortality rates for adults and children at the provincial level are obtained from the 2013 Global Burden of Disease (GBD) study (www.healthdata.org/gbd). China's projected provincial population in 2020 is from the ECLIPSE_V5a_CLE scenario, and we use the provincial-level age distribution in the 2013 GBD study to estimate the population of adults and children in 2020. We assume that the disease-specific mortality rates remain the same between 2013 and 2020. Our method conducts PAF calculations separately for baseline and intervention conditions and reports the difference, which differs from some related approaches but produces more conservative estimates of avoided mortality burdens.

SI Model Evaluation

Earlier studies have evaluated WRF-Chem over the United States and East Asian regions (43, 52, 53). Here we evaluate our 2015 simulations with $PM_{2.5}$ monitoring data across China. The 2015 model configurations are the same as that described in *SI Materials and Methods*, *Evaluating Air Quality Impacts*. For regions within China, we use the 2015 ECLIPSE_V5a_CLE anthropogenic emissions at the provincial level, and use the spatial and temporal distribution of emissions from the 2010 Multi-Resolution Emission Inventory for China to distribute the emissions. For regions outside of China, we use the total regional anthropogenic emissions from the 2015 ECLIPSE_V5a_CLE, and use the same spatial and temporal distribution as in the 2006 INTEX-B Asian emission inventory (50). Simulations are run for January, April, July, and October to represent air quality in winter, spring, summer, and fall.

We calculate the monthly mean $PM_{2.5}$ concentrations from each of the four months of 2015 model simulations, and compare them with observations in China's 31 provinces in 2015. Observation data for Beijing are from the Beijing municipal environmental monitoring center (www.bjmemc.com.cn); data for other provinces are from the PM25.in project (pm25.in). Table S3 describes the monitoring sites. We also compare the observed and simulated daily mean $PM_{2.5}$ concentrations in China's seven regions (Fig. S4). Our simulations generally capture the seasonal and monthly trends in $PM_{2.5}$ concentrations in most parts of China. However, noticeable model underestimation is observed in northeastern and northwestern provinces. This underestimation may occur for a variety of reasons. One possibility is that the GAINS model estimates lower anthropogenic emissions than what actually occurred in these provinces in 2015. Additionally, China's current $PM_{2.5}$ monitoring sites are mostly located in city centers; this is particularly the case in northwestern provinces where population and emission distribution is sparse. Thus, the model resolution of our simulations may miss urban hot spots in these regions. Moreover, our model simulation does not include dust that, particularly in winter and spring, likely contributes to the underestimation of northwestern $PM_{2.5}$ concentrations. Overall, however, our model does a reasonable job compared with observation data, particularly in eastern China, which is the major focus of this study (Fig. S4).

SI SNG Production–Energy Penalty of CCS

During SNG production, coal is first converted to syngas in the gasifier, generally at a high pressure. CO_2 emitted from this process is at a relatively high partial pressure and thus requires low energy for CO_2 separation (16). In addition, CO_2 is separated from syngas before methanation regardless of conducting CCS as the cost for capturing CO_2 is more than paid back by cost savings from better methanation efficiency (due to higher CO and H_2 concentrations) and lower volume of input syngas (smaller reactor volume and costs) (16, 33). Thus, the energy penalty for conducting CCS at SNG plants is substantially lower than that at coal combustion power plants (16). Liu et al. (33) estimated that the energy penalty is 91 kWh per tonne CO_2 captured for coal-based synthetic fuels production (energy needed for compressing CO_2 to 150 bar for pipeline transport to underground storage). We assume this penalty is representative of SNG plants. Electricity needed for conducting CCS along with SNG production can be generated from either gas- or coal-fired power plants. In China, over 98% of existing gas-fired power generation units were NGCC in 2012 (12). Thus, we use NGCC to represent gas-fired power generation in 2020. For coal-fired power plants, we use supercritical, ultrasupercritical, and IGCC power plants to represent the 2020 fleets. For each type of power plant, we examine the implications of including/excluding CCS. We assume CCS can capture 90% of CO_2 emissions during SNG production or power plants operation (54). Thus, when CCS is applied during SNG production, only 10% of CO_2 produced by this process will be emitted to the atmosphere. Power plants providing electricity also emit CO_2 to the atmosphere: either 100% of CO_2 produced from electricity generation (power plants without CCS) or 10% of CO_2 produced from electricity generation (power plants with CCS).

Below we estimate the energy penalties and CO_2 emissions for each type of power plant (with and without CCS), and illustrate the calculation processes for 1 MJ of coal as energy input using Eqs. **S3–S9**. Energy efficiencies for various power plant types, with and without CCS, and the calculated net energy penalties and CO_2 removal efficiencies are listed in Table S4.

SNG Production and Associated CO_2 Emissions from 1 MJ of Coal Input.

$$V_{SNG} = 1\ \text{MJ} * \eta_1/\text{HV}_{SNG} \qquad \textbf{[S3]}$$

$$\text{E1}_{CO_2} = V_{SNG} * \text{EF1}_{CO2}. \qquad \textbf{[S4]}$$

V_{SNG} refers to the volume (cubic meters) of SNG produced from 1 MJ of coal input; η_1 refers to coal-to-SNG conversion efficiency (51%) (12); HV_{SNG} refers to SNG heating value, 34 MJ/m^3; $E1_{CO2}$ refers to CO_2 emissions from SNG production processes (kilograms); and $EF1_{CO2}$ refers to CO_2 EFs for SNG production processes not using CCS, 4.25 kg CO_2/m^3 SNG.

Electricity Needed to Capture CO_2 Generated from SNG Production.

$$\text{ELE} = \text{EP} * \text{E1}_{CO2}/1{,}000. \qquad \textbf{[S5]}$$

ELE refers to total electricity needed to conduct CCS during SNG production (kilowatt hours), and EP refers to the energy penalty for applying CCS for synthetic fuels production, 91 kWh/tonne CO_2.

Energy Consumption to Provide Electricity for Applying CCS During SNG Production.

$$\text{ENE} = \text{ELE} * 3.6(\text{MJ/kWh})/\eta_2. \qquad \textbf{[S6]}$$

ENE refers to energy consumption to provide electricity for applying CCS during SNG production (megajoules); η_2 refers to power plant efficiency (percent).

Net Energy Penalty for Conducting CCS During SNG Production.

$$\text{NEP} = \eta_1/[(1\ \text{MJ} * \eta_1 - \text{ENE})/1\ \text{MJ}] - 1. \qquad \textbf{[S7]}$$

NEP refers to net energy penalty (percent). This uses the equation from Metz et al.'s (54) study: $\Delta E = (\eta_{w/o\ ccs}/\eta_{ccs}) - 1$.

Net CO_2 Emissions from Each System in Table S4.

$$\text{E2}_{CO2} = \text{E1}_{CO2} * (1\text{-}90\%) + \text{ENE} * \text{EF2} * \text{CCS}_{y/n} \qquad \textbf{[S8]}$$

$$\text{RMF} = (1\text{-E2}_{CO2}/\text{E1}_{CO2}) * 100\%. \qquad \textbf{[S9]}$$

$E2_{CO2}$ refers to total CO_2 emissions from each power plant–SNG system in Table S4 (kilograms). EF2 refers to CO_2 EFs for fossil fuel (coal or gas) combustion in the power plants without CCS. We use the values from the GAINS model, which are 94.3 g CO_2 per megajoule coal and 55.8 g CO_2 per megajoule natural gas (Table S4). For unit consistency, we convert the CO_2 EFs to kg CO_2 per megajoule for use in Eq. **S8**. $CCS_{y/n}$ refers to whether CCS is applied in the power plant: It equals 0.1 if applied, 1 if not. RMF refers to net CO_2 removal efficiency from each power plant–SNG system shown in Table S4.

SI Regional SNG Allocation

In addition to the three major sectoral SNG allocation scenarios, we also build two regional allocation scenarios (each with three subscenarios) to evaluate the impacts of regional SNG distribution on air quality, human health, and CO_2 emissions (Table S1). These allocation scenarios examine the benefits of SNG substitution for coal by giving all SNG-receiving provinces equal priority in SNG allocation, or giving provinces with political or economic importance a higher priority.

Following the same processes described in *SI Materials and Methods*, *Estimating Air Pollutant and Carbon Dioxide Emission Changes*, *Evaluating Air Quality Impacts*, and *Evaluating Health Impacts*, we use the WRF-Chem model to estimate the net changes in monthly mean $PM_{2.5}$ surface concentrations for the two medium regional SNG scenarios (Fig. S3 *D* and *E*). Comparing the two medium regional allocation scenarios, grid-level $PM_{2.5}$ concentration reductions are generally below 5 $\mu g/m^3$ when available SNG is allocated proportionally to each province and each sector's original gas needs for coal replacement (SNG_Region_Sector). However, the maximum grid-level $PM_{2.5}$ concentration reductions in Beijing are over 5 $\mu g/m^3$ year-round and can reach ~60 $\mu g/m^3$ in winter when emphasizing gas allocation to affluent provinces (SNG_Province). Notably, differences in $PM_{2.5}$ concentration reductions outside Beijing between the two scenarios are negligible.

We estimate that the national total avoided premature deaths under the two regional allocation scenarios (SNG_Region_Sector and SNG_Province) are 2,700 (1,300 to 3,500) and 3,100 (1,800 to 3,600), respectively, varying depending on the low and high estimates of relative risks. The national total health impacts of the two regional allocation scenarios are similar to that of the SNG_industry scenario. In addition, the impacts of these two regional allocation scenarios on CO_2 emissions are nearly identical, with an additional ~40% increases in CO_2 emissions for SNG without conducting CCS compared with direct combustion of coal (Table S5).

To sum up, prioritizing SNG allocation to affluent provinces significantly improves the air quality in Beijing in comparison with an equal-regional-priority SNG allocation. However, the national total air quality and human health benefits and carbon penalties are similar between these two regional allocation scenarios.

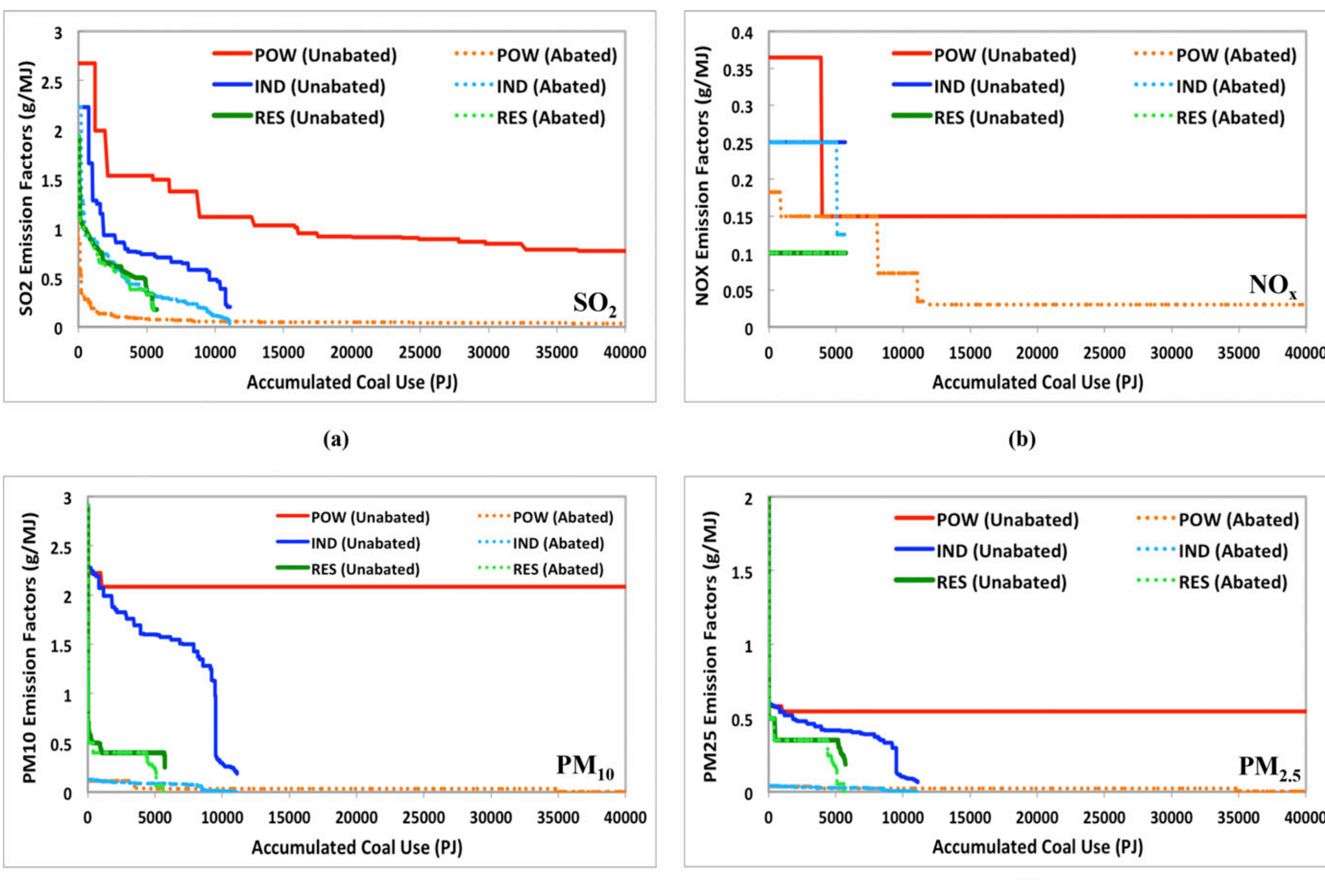

Fig. S1. Unabated and abated EFs for major air pollutants: (*A*) SO_2, (*B*) NO_x, (*C*) PM_{10}, and (*D*) $PM_{2.5}$ due to coal combustion in China's power, industrial, and residential sectors in 2020 under the ECLIPSE scenario. EFs are sorted from highest to lowest for each sector and presented as total accumulated coal uses on the *x* axis.

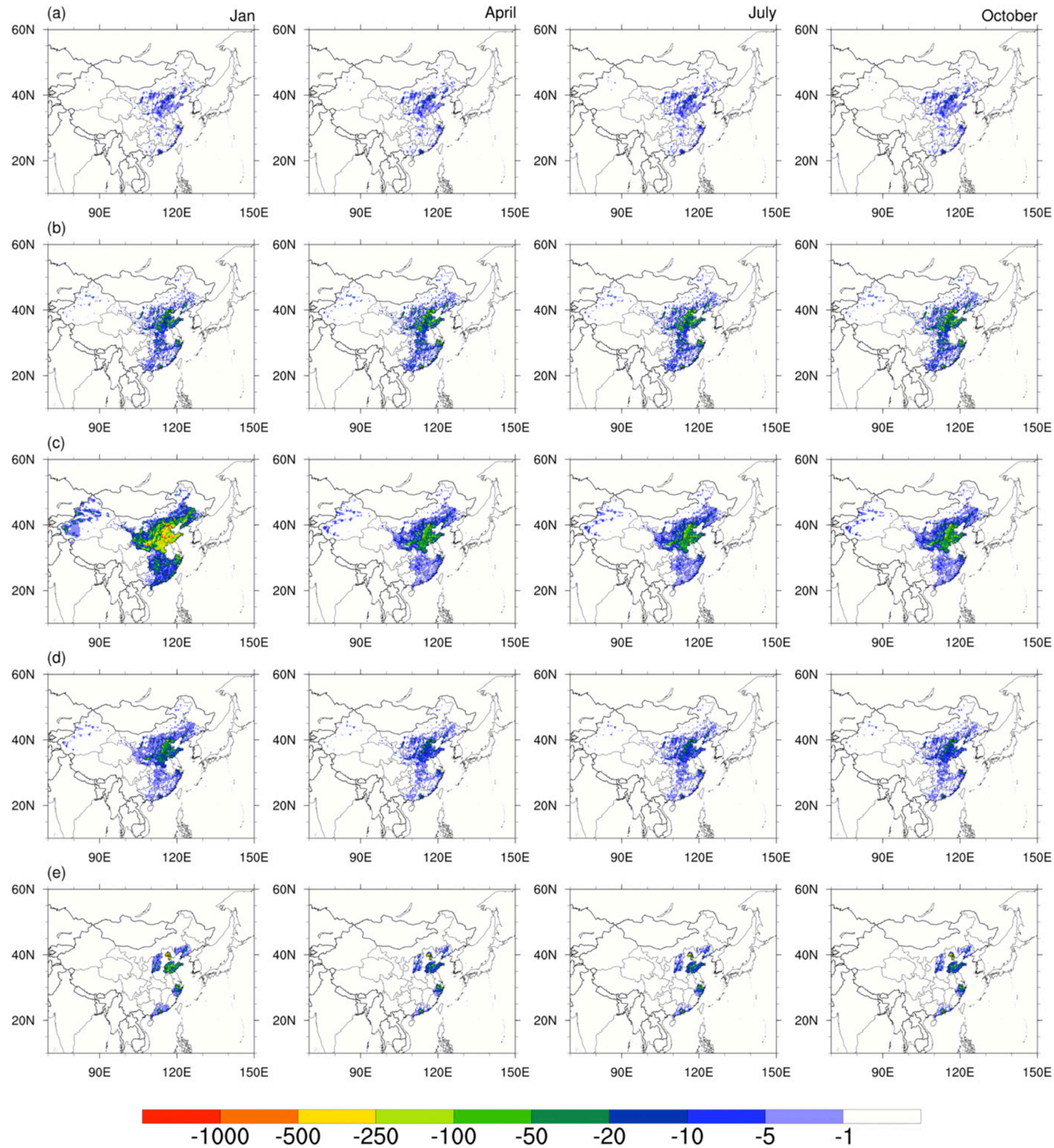

Fig. S2. Spatial distribution of monthly mean SO_2 emission reductions under each medium SNG scenario: (*A*) SNG_Power – Base case, (*B*) SNG_Industry – Base case, (*C*) SNG_Residential – Base case, (*D*) SNG_Region_Sector – Base case, and (*E*) SNG_Province – Base case. (Unit is tonnes/grid.)

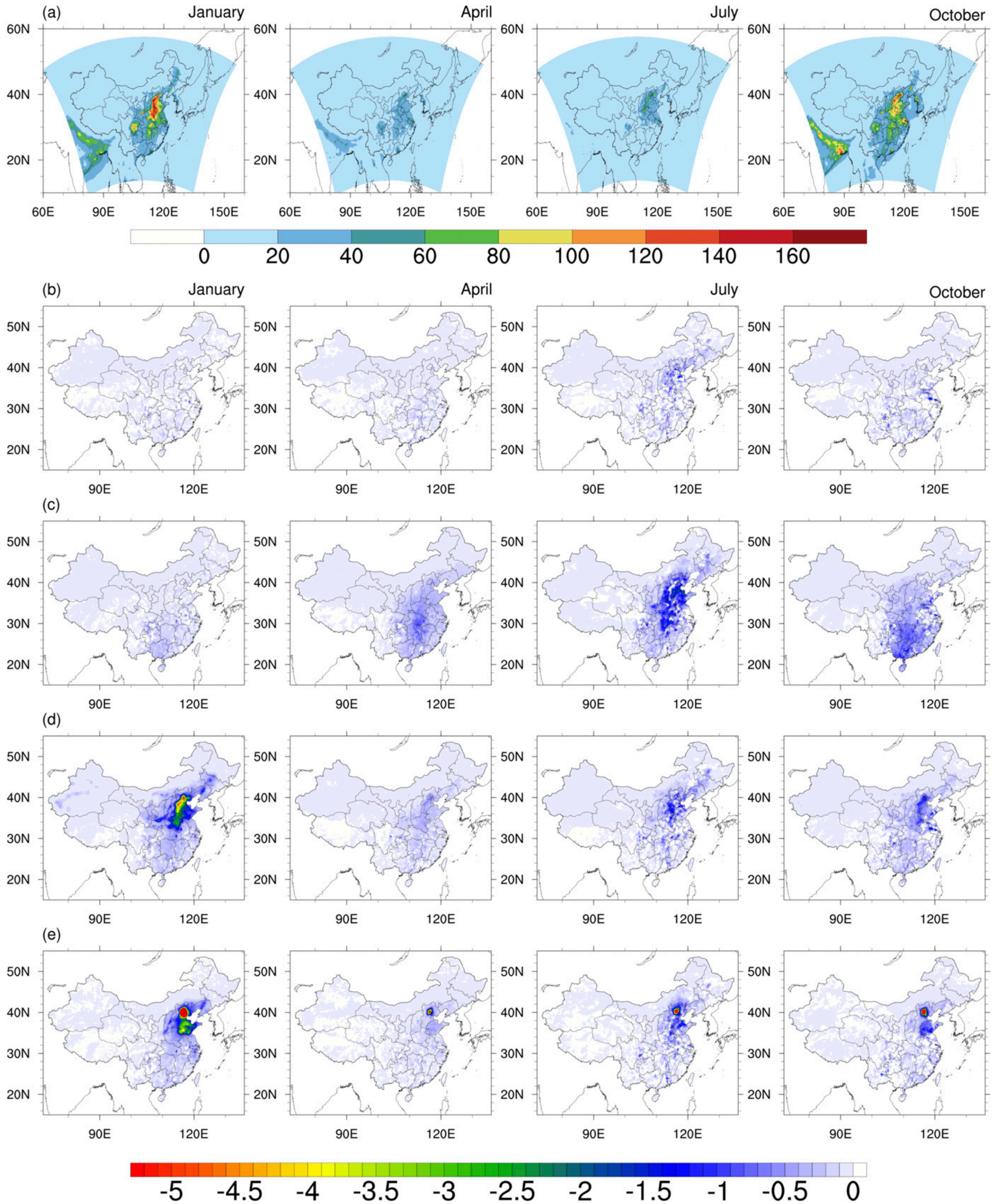

Fig. S3. (*A*) The 2020 base case monthly mean $PM_{2.5}$ surface concentrations. (*B–E*) 2020 monthly mean $PM_{2.5}$ surface concentration changes between various medium SNG allocation scenarios and the base case: (*B*) SNG_Power – Base case, (*C*) SNG_Industry – Base case, (*D*) SNG_Region_Sector – Base case, and (*E*) SNG_Province – Base case. Note that the color scale used in *B–E* is one sixth of that used in Fig. 3 for the residential sector. (Unit is micrograms per cubic meter.)

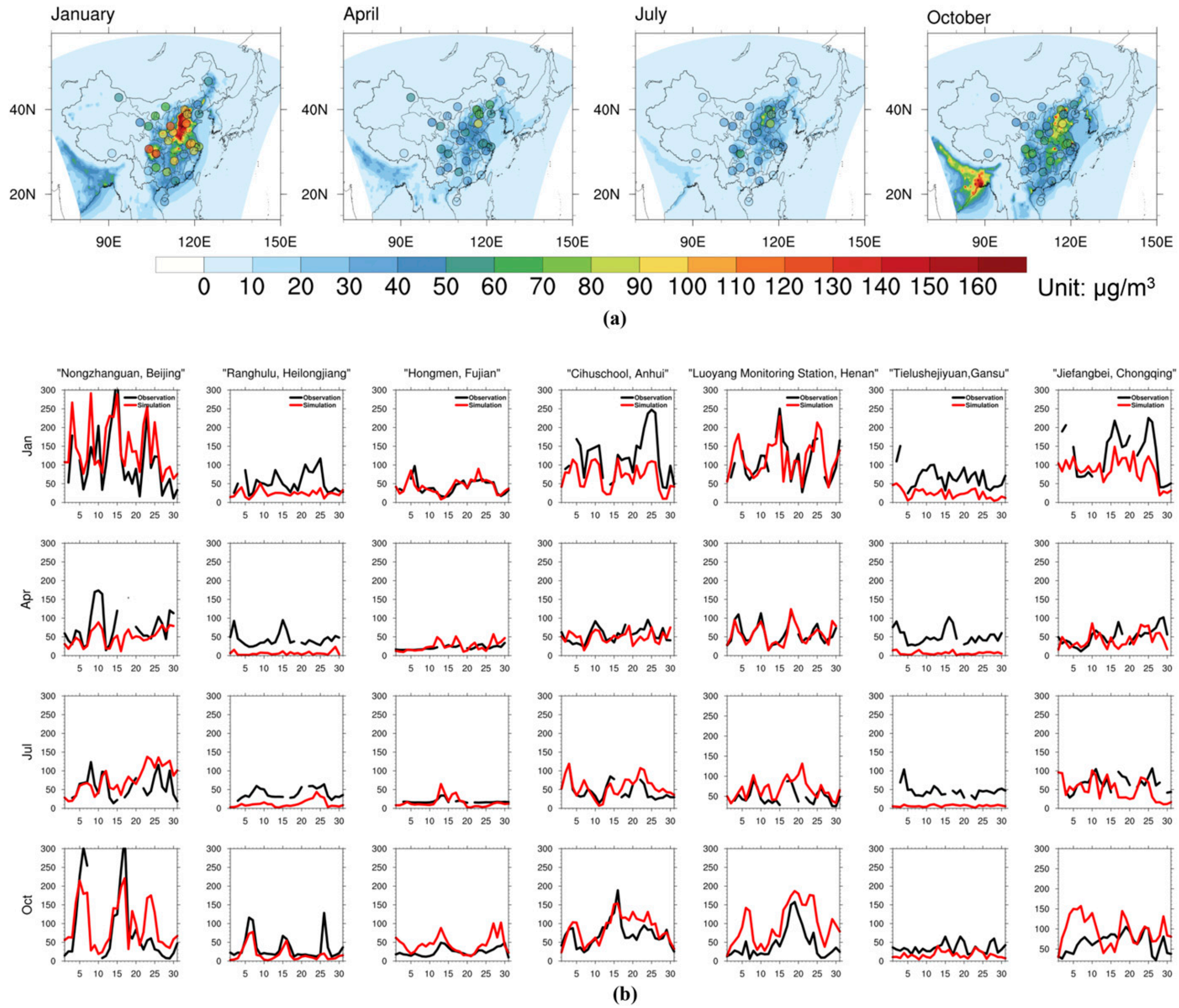

Fig. S4. (*A*) Comparison of observed (dots) and simulated (map) 2015 monthly mean $PM_{2.5}$ concentrations in each province of mainland China. Identical color scales are used for observed and simulated concentrations. Monitoring sites are chosen when less than 6 d of data are missing per month. (*B*) Comparison of observed (black) and simulated (red) 2015 daily mean $PM_{2.5}$ concentrations in China's seven regions. One province (the first name in the alphabet from the region) from each region is presented. Daily average concentrations are calculated when there are less than 6 h of data missing each day (otherwise data are reported as NA). Detailed site information is shown in Table S3.

Table S1. Scenarios for sectoral and regional SNG substitution for coal consumption

Substitution scenarios	Substitution strategy
Sectoral	
SNG_Power	All SNG used in the power sector
SNG_Industry	All SNG used in the industrial sector
SNG_Residential	All SNG used in the residential sector
Regional	
SNG_Region_Sector	SNG allocated to all provinces targeted to receive SNG
SNG_Province	SNG allocated only to provinces with political or economic importance that are targeted to receive SNG†

Under sectoral allocation scenarios, SNG will only be allocated to the specific sector. Under the two regional allocation scenarios, SNG can be allocated to any of the three sectors. Under the medium scenarios, SNG is allocated in each subsector among provinces targeted to receive SNG proportionally to their original gas needs for coal replacement in megajoule units. Original gas needs for coal replacement in each subsector in each SNG targeted province are calculated as: $Q_{\mathrm{coal},s,p} * \eta_{\mathrm{coal},s}/\eta_{\mathrm{SNG},s}$. $Q_{\mathrm{coal},s,p}$ refers to total baseline coal consumption in subsector s in province p, and $\eta_{\mathrm{coal},s}$ and $\eta_{\mathrm{SNG},s}$ refer to energy efficiency for coal and gas combustion in subsector s. Under the upper bound scenarios, SNG displaces dirtiest coal first, while under the lower bound scenarios, SNG displaces cleanest coal first. SNG will first be allocated to substitute for coal that brings the largest (smallest) reductions in SO_2 emissions for each unit SNG (grams of SO_2 per cubic meter of SNG used). This takes into account both the SO_2 EFs and the energy efficiencies of coal and SNG combustion.

†Under the SNG_Province scenario, Inner Mongolia SNG is first allocated to Beijing to satisfy local gas needs; extra gas will then be allocated to Tianjin, and then Hebei and other provinces, due to the political importance of Beijing. Xinjiang SNG is allocated equally to Guangdong, Zhejiang, and Shandong provinces as these three provinces have the highest GDP among provinces targeted to receive Xinjiang's SNG (1).

Table S2. Energy efficiencies and CO_2 EFs for coal and gas combustion in major economic sectors used in the ECLIPSE scenario

		Energy efficiency	
Sector	Subsector	Coal	Gas
Power	Existing large coal-fired plants	32%	—
	New large coal-fired plants	35%	—
	Modern coal-fired plants	38%	—
	Natural gas combined cycles	—	49%
Residential	Cooking	30%	55%
	Heating	60%	90%
Industry	Industry boiler	75%	85%
CO_2 EFs		94.3 (g CO_2 per megajoule)	55.8 (g CO_2 per megajoule)
Heating values		20.7 MJ/kg	34 MJ/m^3

Table S3. $PM_{2.5}$ observational sites used in this study

Site name	Latitude	Longitude
North China		
Nongzhanguan, Beijing	39.97	116.47
Xibeishuiyuan, Hebei	38.84	117.46
Jinan Monitoring Station, Shandong	36.66	117.05
Yongminglu, Tianjin	38.84	117.46
Northeastern China		
Ranghulu, Heilongjiang	46.67	124.81
Baotao Monitoring Station, Inner Mongolia	40.65	109.83
Beihu park, Jinzhou, Jilin	41.14	121.13
Zhoushuizi, Dalian, Liaoning	38.97	121.54
South China		
Hongmen, Fujian	24.48	118.09
Guangzhou Monitoring Station, Guangdong	23.13	113.27
Guilin Monitoring Station, Guangxi	25.27	110.28
Hedong station, Hainan	18.25	109.50
Southeastern China		
Cihuschool, Anhui	31.70	118.35
Ruijinlu, Jiangsu	32.03	118.81
Jingan Monitoring Station, Shanghai	31.20	121.50
Linan government office, Zhejiang	30.23	119.72
Central China		
Luoyang Monitoring Station, Henan	34.67	112.44
Liujiagou, Hubei	32.63	110.80
Xiangtan Monitoring Station, Hunan	27.85	112.90
Lushan meteorology station, Jiangxi	29.42	116.26
Linfen Monitoring Station, Shanxi	36.08	111.52
Changanqu, Shaanxi	34.16	108.95
Northwestern China		
Tielushejiyuan, Gansu	36.04	103.84
Yinhuxiang, Ningxia	38.47	106.27
Xihai zhen Haiyan county, Qinghai	36.96	100.90
Lasa environmental agency, Tibet	29.65	91.12
Hami Monitoring Station, Xinjiang	42.84	93.50
Southwestern China		
Jiefangbei, Chongqing	29.56	106.58
Guiyang environmental agency, Guizhou	26.30	106.50
Liangjiaxiang, Sichuan	30.67	104.06
Qujing Monitoring Station, Yunnan	25.51	103.80

Table S4. CO_2 EFs and energy efficiencies of various power plant types (with and without CCS) (columns 2 and 3)

Power plant type	EFs,[†] g CO_2 per megajoule	Energy efficiency, %	Net energy penalty[‡], %	Net CO_2 removal efficiency[‡], %
Supercritical without CCS	94.3	40[§]	11	82
Supercritical with CCS	9.43	31[¶]	15	89
Ultrasupercritical without CCS	94.3	42[§]	11	83
Ultrasupercritical with CCS	9.43	32[¶,#]	15	89
NGCC without CCS	55.8	49[†]	9	86
NGCC with CCS	5.58	42[¶]	11	90
IGCC without CCS	94.3	45[||]	10	83
IGCC with CCS	9.43	39[¶]	12	89

Net energy penalty and net CO_2 removal efficiency resulting from electricity used to operate CCS with SNG production (columns 4 and 5).

[†]Data from GAINS model.

[‡]Calculations for net energy penalty and CO_2 removal efficiency are illustrated in *SI SNG Production–Energy Penalty of CCS*.

[§]Data from Shen et al. (49).

[¶]Data from Metz et al. (54), who report that CCS energy penalties for supercritical coal, NGCC, and IGCC power plants are ~31%, 17%, and 16%, respectively. Using the equations in Metz et al.'s study, $\Delta E = (\eta_{w/o\ CCS}/\eta_{CCS}) - 1$, we calculate the energy efficiency for supercritical, NGCC, and IGCC power plants with CCS as shown in the table. Goto et al. (55) found the same energy penalty for ultrasupercritical power plants and supercritical power plants for conducting CCS; thus we calculate the energy efficiency for ultrasupercritical power plants with CCS as shown in the table.

[#]Data from Goto et al. (55).

[||]Data from Kunze and Spliethoff (56).

Table S5. CO_2 emissions and the energy content of the coal that is replaced with SNG (columns 2 and 6)

	CO_2 emissions				Energy use			
Medium scenarios	Coal (Mtonnes)†	Conventional gas,‡ %	SNG,§ %	SNG + CCS,¶ %	Coal (PJ)†	Conventional gas,‡ %	SNG,§ %	SNG + CCS,¶ %
SNG_Power	254	−57	38	−48 to −40	2,690	−28	41	54 to 62
SNG_Industry	207	−48	69	−36 to −27	2,200	−12	73	88 to 99
SNG_Residential	323	−66	9	−59 to −53	3,421	−43	11	21 to 28
SNG_Region_Sector	251	−57	40	−47 to −39	2,657	−27	43	56 to 64
SNG_Province	251	−57	39	−47 to −40	2,665	−27	43	55 to 64

Percent changes in CO_2 emissions and energy use when conventional gas, SNG, or SNG with CCS is used to replace coal (columns 3 through 5 and 7 through 9).

†Avoided CO_2 emissions and energy content of coal that is replaced by SNG in each medium scenario. For instance, under the SNG_Power scenario, total SNG can replace 2,690 PJ of coal in end uses (calculated from the GAINS model based on the detailed coal replacement quantity in each subsector and each province under scenarios defined in Table S1). These 2,690 PJ of coal would have emitted 2,690 (PJ) * 94.3 (g/MJ) = 254 million tonnes of CO_2.

‡Percent change in net CO_2 emissions and energy use when the same amount of conventional gas, instead of SNG, substitutes for coal in each scenario; 57 bcm of conventional gas emits ~108 million tonnes of CO_2, thus using conventional gas to replace coal under the SNG_Power scenario can reduce CO_2 emissions by (254 − 108)/254 = 57%. Similarly, 57 bcm of conventional gas contains 1,938 PJ of energy. Using conventional gas to replace coal under the SNG_Power scenario can change the energy intensity by (1,938 − 2,690)/2,690 = −28%.

§Percent change in net CO_2 emissions and energy use when SNG substitutes for coal. CO_2 emissions and energy use for SNG include both SNG production and SNG combustion stages.

¶Percent changes in net CO_2 emissions and energy use when SNG produced using CCS substitutes for coal. CO_2 emissions and energy use include both SNG production (with CCS) and SNG combustion stages. Percent ranges result from different choices of electricity supply for conducting CCS along with SNG production, as discussed in *SI SNG Production–Energy Penalty of CCS* . Using CCS for SNG production leads to net CO_2 emission reductions but results in additional energy use.