Air Quality-Carbon-Water Synergies and Trade-offs in China's Natural Gas Industry

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Abstract

Both energy production and consumption can simultaneously affect regional air quality, local water stress, and the global climate. Identifying the air quality-carbon-water interactions due to both energy sources and end-uses is important for capturing potential co-benefits while avoiding unintended consequences when designing sustainable energy transition pathways. Here, we examine the air quality-carbon-water interdependencies of China's six major natural gas sources and three end-use gas-for-coal substitution strategies in 2020. We find that replacing coal with gas sources other than coal-based synthetic natural gas (SNG) generally offer national air quality-carbon-water co-benefits. However, SNG achieves air quality benefits while increasing carbon emissions and water demand, particularly in regions already suffering from high per capita carbon emissions and severe water scarcity. Depending on end-uses, non-SNG gas-for-coal substitution results in enormous variations in air quality, carbon, and water improvements, with notable air quality-carbon synergies but air quality-water trade-offs. This indicates that more attention is needed to determine in which end-uses natural gas should be deployed to achieve desired environmental improvements. Assessing air quality-carbon-water impacts across local, regional and global administrative levels is crucial for designing and balancing the co-benefits of sustainable energy development and deployment policies at all scales.

Most fossil energy production and combustion processes emit air pollutants and greenhouse gases (GHGs) and also consume significant quantities of freshwater[1-7].

Depending on differences in fuel types, burning conditions, cooling techniques, and existing local environmental stress, energy source choices and end-uses can lead to substantial variations in the resulting air quality, climate, and water impacts[4-9]. Previous studies have concentrated on one or in some cases two, specific environmental impacts in the energy industry[5-11]. Very few analyses have evaluated the air quality-carbon-water interrelationships of the energy sector[12,13], and even fewer have analyzed the nexus from both supply and end-use perspectives[14-16]. Characterizing the interconnections of various environmental impacts resulting from energy source choices and end-use applications is critical in achieving air quality, carbon and water co-benefits while avoiding unintended side effects. Here we examine China's natural gas industry and systematically analyze the synergies and trade-offs among the air quality, carbon, and water impacts due to both natural gas source choices (from where natural gas originates) and deployment strategies (in which region and subsector natural gas is substituted for coal).

Similar to many emerging economies, China has been facing multiple environmental challenges including domestic air pollution, local water scarcity, and global climate change[1-3,17]. A coal-dominated energy structure (~64% of primary energy supply in 2015)[18] is partly responsible for all three environmental stresses[1-3,19]. Natural gas is the cleanest fossil fuel, with relatively low carbon intensity and lower cooling water requirements than coal in most end uses[5,6,20]. Primarily to tackle its severe air pollution and the associated human health impacts[3,21], China has been actively promoting a coal-to-gas end-use energy transition[22]. Specifically, China plans to increase natural gas consumption from approximately 6% (~190 billion cubic meters, bcm) of national total primary energy consumption in 2015 to 10% (~360 bcm) in 2020[17,23]. Until recently, China's natural gas supplies were primarily from domestic conventional gas production (~70%), imported liquefied natural gas (LNG) (~15%), and imported pipeline gas from Central Asian pipeline gas (~15%)[24,25]. To further increase gas supplies, China plans to develop domestic unconventional natural gas. For instance, China's latest government plans (issued in December 2016) aim to have an annual production of approximately 20 and 30 bcm of domestic coal-based synthetic natural gas (SNG) and shale gas, respectively, by 2020[23,26]. Meanwhile, China also plans to expand LNG annual import capacity by 38 bcm, as well as increasing pipeline gas from Russia and Central Asia by 38 and 30 bcm, respectively, by around 2020[27,28].

Substituting conventional natural gas for coal is likely to bring multiple environmental benefits. However, the air quality, carbon, and water impacts, and their interactions at both aggregated and spatially resolved scales can vary depending on gas sources[29-32]. In addition, the magnitude and interdependencies of various environmental impacts of all gas sources can be affected by different end-use deployment strategies[11,33]. Earlier studies evaluated the air quality, carbon, and water impacts of the natural gas industry, with a focus on a specific gas source and on one (or in a few cases two) environmental impact(s)[7,11,31,33-37]. Few studies compared the lifecycle air pollutant or GHG emissions for SNG, LNG and conventional gas in the power sector[30,32], or simultaneously calculated air pollutant emissions, GHG emissions, and water consumption for shale gas-fired electricity[14]. In this work, we integrate the analysis of various natural gas sources and end-uses to identify the underlying air quality-carbon-water synergies and trade-offs, as well as to understand the relative importance of gas source choices and end-uses in determining the environmental outcomes.

We use an integrated assessment approach in conjunction with lifecycle analysis to quantify net changes in China's air quality, carbon, and water impacts resulting from a fixed quantity (30 bcm, Supplementary Methods 1.1) of gas substituting for coal using each of China's six primary gas sources under three different deployment strategies (Supplementary Table 1). Essentially, we estimate changes in China's population-weighted air pollution concentrations, lifecycle GHG emissions, and water stress index (ranging from 0 to 1)[38, 39] weighted water consumption (referred hereafter as 'weighted water consumption') for each of 18 gas-for-coal substitution scenarios (Supplementary Tables 2-7). Comparing the multiple environmental impacts resulting from the deployment of various gas sources in different end-uses, we identify the multi-aspect environmental performance for each gas source and end-use combination, and characterize the resulting air quality-carbon-water interrelationships. Based on government and industrial plans[11, 18, 23, 27, 40], Fig.1 shows, for each gas source, the spatial distribution of China's gas production and (or) the provinces in which each gas source will likely be consumed. For each gas source, we design three gas-for-coal end-use deployment strategies to reflect three different environmental priorities, including 1) air quality-focused substitution (AS), 2) carbon-focused substitution (CS), and 3) water-focused substitution (WS), respectively (Supplementary Table 1). We first estimate changes in air pollutant emissions, CO_2 emissions, and weighted water consumption resulting from end-use substitution of each gas source for coal under each deployment strategy. End-use gas substitution for coal results in an increase in natural gas demand and a decrease in coal demand. Both upstream natural gas and coal processes (i.e., production, processing, transmission, and distribution) emit air pollutants and GHGs

(CO_{2eq}, including both CO_2 and CH_4) due to energy combustion and methane leakage[31], and consume freshwater for dust suppression, coal washing, well drilling and other purposes[41] (Supplementary Table 8). Thus, we further quantify the corresponding environmental impacts due to increases in upstream gas processes and decreases in coal processes (Supplementary Table 9). Integrating upstream and end-use processes, we estimate net changes in air pollutant emissions, GHG emissions, and weighted water consumption for 18 combinations of gas source choices and deployment strategies. Using the Weather Research and Forecasting model coupled with chemistry (WRF-Chem v3.6), we further simulate the resulting changes in $PM_{2.5}$ surface concentrations for each gas source under each deployment strategy and calculate the resulting changes in population-weighted $PM_{2.5}$ concentrations.

Results

Aggregated air-carbon-water impacts from natural gas sources

We estimate net changes in lifecycle air pollutant emissions, GHG emissions, and weighted water consumption for upstream and downstream stages of coal substitution by various gas sources in 2020. Fig.2 shows results for the air quality-focused substitution, which is the most likely scenario given China's current focus on improving air quality. We observe striking air quality-carbon/water trade-offs with SNG, but generally air quality-carbon-water co-benefits for all other gas sources.

As shown in Fig.2, end-use gas substitution for coal dominates net reductions in air pollutant emissions regardless of gas source. Despite net air pollutant emission reductions for all gas sources, SNG upstream gas processes lead to substantial net increases in lifecycle GHG emissions and weighted water consumption. Upstream SNG processes emit roughly 4-7 times more CO_{2eq} than other gas sources. Consequently, SNG substitution for coal increases 2020 lifecycle CO_{2eq} emissions by ~20 (40) megatonnes (Mt) under the 100-year (20-year) global warming potential (GWP). However, depending on the gas source, substituting coal with the same amount of other gas sources leads to approximately 60 to 120 (70 to 140) Mt of CO_{2eq} emission reductions under GWP_{100} (GWP_{20}) assuming a mean methane leakage rate. This is consistent with earlier findings that SNG has substantially higher lifecycle GHG emissions than other gas sources when used for electricity generation[30,32]. Similarly, weighted water consumption from upstream SNG processes is roughly 20-190 times greater than other gas sources, varying depending on which gas source is compared. As a result, SNG leads to an increase of ~200 million cubic meters (Mm^3) of lifecycle weighted water consumption in 2020, while other gas sources result in ~20 to 60 Mm^3 of net reductions. In comparison, water consumption due to upstream SNG processes (~290 Mm^3) is ~10-30 times higher than other gas sources (~10-23 Mm^3) (Supplementary Fig.1). Actually, increased water consumption due to SNG projects alone can require ~10% and ~5% of total industrial water consumption in Xinjiang and Inner Mongolia, respectively. Differences in actual water consumption (~10-30 times) are significantly smaller than differences in weighted water consumption (~20-190 times), indicating that SNG production generally occurs in locations that are comparatively more water scarce than other gas producing regions. We find gas source choice matters for national carbon and water concerns, primarily because SNG results in substantial net carbon and water penalties while having similar air quality benefits as other gas sources.

Other than SNG, all gas sources, when substituted for coal, bring net reductions in lifecycle air pollutant emissions, weighted water consumption, and GHG emissions (assuming a mean methane leakage rate). GHG emissions from upstream gas processes (except for SNG) are largely offset by decreases in GHG emissions due to less coal production. This is partly because China's coal industry has high GHG emission intensities due to substantial underground coal mining associated with high methane emissions and a low methane recovery rate[31]. However, without proper methane leakage control from the natural gas industry, coal substitution with gas sources other than SNG, particularly with shale gas, can also result in net increases in lifecycle GHG emissions under both GWPs (Fig.2, and Supplementary Figures 2 and 3). Also, our estimated upstream weighted water consumption from shale gas processes is relatively small although it consumes twice as much water as upstream conventional gas processes (Supplementary Table 9). This is because China's existing shale gas development is mainly concentrated in water-abundant Sichuan basin, the location of roughly half of China's total shale gas resources[42]. Nevertheless, as a quarter of China's shale gas resources are located in northern water scarce regions[42], further geographic expansion of shale gas development would likely worsen water stress there.

Spatial air-carbon-water impacts from natural gas sources

In addition to evaluating the aggregated environmental impacts, we also explore the spatial characteristics of China's air quality-carbon-water nexus to characterize the unintended redistributive effects. Fig.3 shows the 2020 spatial distribution of net changes in SO_2 emissions, simulated $PM_{2.5}$ surface concentrations, GHG emissions, and weighted water consumption within mainland China for each gas source substituting for coal under the air quality-focused substitution (AS). At the regional level, we find that all gas sources generally bring air quality-carbon-water co-benefits in developed eastern China. However, although promoting SNG can help alleviate the severe air pollution and associated human health impacts in populated eastern China (currently a major objective in China), it results in substantial carbon-water losses in northwestern China, indicating a negative spillover effect of China's air quality improvement policies.

As shown in Fig.3, all gas sources, via substituting for coal, generally bring net reductions in SO_2 emissions and $PM_{2.5}$ surface concentrations in well-developed eastern China, though there are slight increases in northwestern provinces primarily due to SNG or conventional gas production. For each gas source, the largest $PM_{2.5}$ concentration reductions are primarily concentrated in regions where substitution occurs. Although SNG results in only slight increases in $PM_{2.5}$ surface concentrations in northwestern provinces, it leads to substantial increases in GHG emissions and weighted water consumption in northwestern SNG producing provinces. Notably, these regions also suffer from severe water scarcity and have high per capita carbon emissions, due to their coal-dominated energy mix and substantial export of electricity to eastern China, such as Beijing and Tianjin[20,43]. Similar negative spillovers are also observed from the carbon (CS) and water focused (WS) substitution (Supplementary Figs. 4 and 5).

Air-carbon-water impacts from source choices and end-uses

Besides gas source choices, sectoral and regional gas deployment strategies can also lead to large variations in net air quality, carbon and water impacts of gas substitution for coal.

To fully capture the synergies and trade-offs in the natural gas industry, here we integrate six major gas source choices and three end-use deployment strategies that affect the air quality-carbon-water interdependencies.

We find that gas source choice is the most critical factor in shaping the air quality-carbon-water nexus of the natural gas system, primarily because SNG clearly stands out. Unlike other gas sources, SNG worsens carbon emissions and water stress regardless of end-use deployment strategies (Fig.4). That is, SNG causes net increases in GHG emissions and weighted water consumption even under the deployment strategies that aim to achieve the largest reductions in GHG emissions (CS) or weighted water consumption (WS), respectively (Supplementary Figs. 2 and 3).

However, for gas sources other than SNG, end-uses determine the magnitude of the air quality, carbon, and water impacts. We find that within the same gas source (except for SNG), different *deployment* strategies can result in more than 10-50 times differences in China's population-weighted (P-W) $PM_{2.5}$ surface concentration reductions (Fig.4, Supplementary Methods 1.3). Similarly, different *deployment* strategies lead to approximately 1.5-1.6 times and 2-9 times variations in lifecycle GHG emissions (GWP_{20}) and China's weighted water consumption reductions, respectively (Fig.4). In comparison, different gas *sources* lead to only roughly 1-4 times, 1-1.9 times, and 1-3 times differences, respectively, within the same deployment strategy. Thus, gas deployment strategies play a more critical role than gas source choices in determining the environmental impacts of non-SNG natural gas substitution for coal, particularly on air quality.

Additionally, gas deployment strategies are the key to determining the air quality-carbon-water interconnections for gas sources other than SNG. We note substantial air quality-carbon co-benefits but air quality-water trade-offs due to end-use gas substitution for coal. Specifically, depending on the gas source, AS leads to ~ 0.6 to 1.8 μg/m^3 annual average P-W PM$_{2.5}$ surface concentration reductions, but merely ~20 to 60 Mm^3 of weighted water consumption reductions within China in 2020. In comparison, varying on the gas source, WS results in ~ -0.004 to 0.07 μg/m^3 P-W PM$_{2.5}$ mean surface concentration reductions, but ~90 to 200 Mm^3 of weighted water consumption reductions. That is, for the same gas source, AS results in over an order of magnitude greater P-W PM$_{2.5}$ surface concentration reductions than WS. However, WS results in approximately 2-8 times as much weighted water consumption reductions as AS. In comparison, CS generally leads to similar levels of air quality, water stress and carbon emission changes as AS. We find CS actually results in slightly higher net reductions in P-W PM$_{2.5}$ surface concentrations than AS. This is mainly because the least efficient coal combustion happens to be the dirtiest, indicating potential air-carbon co-benefits. Thus, when natural gas is deployed primarily to improve air quality, China's current top priority, it will in most cases bring substantial carbon reduction co-benefits, but have negligible water benefits. However, if natural gas were to be allocated mainly to address water scarcity concerns, in most cases it would only slightly improve air quality, though it would still bring notable carbon reductions. Therefore, there is a fundamental air quality-water trade-off due to end-use gas-for-coal substitution.

To put our estimated environmental impacts in perspective, we also show the percent changes for each impact resulting from each gas source and end-use choice. As shown in

Supplementary Fig.6, 30 bcm of natural gas, by substituting ~1.5% to 2.2% of total coal consumption, can lead to approximately -4.8% to 0.01%, -1.8% to 0.9%, and -0.07% to 0.08% net changes in China's P-W $PM_{2.5}$ surface concentrations, lifecycle GHG emissions (GWP_{20}), and China's weighted water consumption in 2020. Our estimated percent contributions may be scaled up or down depending on actual increases in natural gas supplies. However, the relative trends across gas sources and end-uses in affecting various environmental impacts can be illustrative. Supplementary Fig.6 again demonstrates the determining role of SNG in causing the air quality-carbon/water trade-offs, as well as substantial variations in the resulting environmental impacts (air quality in particular), primarily due to gas substitution for coal in various end-use applications.

Discussion

An energy transition away from fossil fuels and towards an air-, carbon-, and water-friendly future at local, national and global scales is a critical component of sustainable development. A transition from coal-to-gas is taking place as renewable energy comes into wider use. Our study demonstrates that with careful natural gas source choices and end-use designs, switching from coal to natural gas can bring air quality, carbon, and water co-benefits, though with notable air quality-water trade-offs in the magnitude of the resulting improvements. However, gas source choices can be a determining factor in changing this picture due to coal-based synthetic natural gas. Upstream SNG processes, particularly SNG production, significantly increase both water stress and carbon intensity in regions (northwestern China) already suffering from severe water scarcity and high per capita carbon intensity[20,38]. Therefore, although end-use SNG substitution for coal reduces

CO_2 emissions and often reduces water consumption as well, SNG not only leads to an increase in lifecycle carbon and water consumption for China as a whole, but also exacerbates existing environmental injustice caused by energy export to eastern China[20]. Our results clearly show a negative spillover effect of China's "Clean Air Act", the focus on improving air quality in the well-developed eastern provinces may increase CO_2 emissions and water stress in the less-developed northwestern provinces when substituting SNG for coal. Earlier studies identified SNG as a good candidate for conducting carbon capture and storage (CCS), as CO_2 emitted during SNG production is of high partial pressure and high purity[11, 30]. Assuming ~90% CO_2 removal efficiency during SNG production[11], applying CCS with SNG could reduce CO_2 emissions by ~110 Mt, resulting in net GHG reductions from a coal-to-SNG switch. However, development of CCS will further increase water demand in northwestern regions due to water consumption for CO_2 scrubbers and parasitic loads[44, 45]. Thus, though CCS can make SNG a more attractive energy choice from the air quality and carbon perspectives, it exacerbates existing water stress, particularly in northwestern provinces. As energy infrastructure typically operates for multiple decades, our findings indicate the need to identify the air quality-carbon-water interconnections before making large-scale energy investments to avoid unintended side effects at both regional and global levels.

For coal substitution with gas sources other than SNG, we find that end-use gas deployment usually plays a far more important role than gas source choices in determining the magnitude of resulting local air pollution and water stress alleviation, as well as carbon mitigation in most cases. Existing discussions have largely focused on clean energy source choices[46]. However, this study shows that more attention should be placed on designing clean energy deployment strategies, as end-use choices can sometimes result in variations of over an order of magnitude in net environmental impacts.

Our study also illustrates notable air quality-water trade-offs due to end-use sectoral and regional natural gas deployment. This trade-off results from the sectoral differences affecting environmental impacts and the geographic mismatch between regions of high air pollution and high water stress (Supplementary Fig.7). Particularly, under WS, natural gas is primarily distributed to the power sector to substitute for coal (Supplementary Fig. 8a). This allocation can significantly reduce water consumption but brings only small air quality benefits due to widely employed end-of-pipe control technologies in coal-fired power plants[11]. Conversely, when natural gas substitution for coal primarily occurs in the residential sector where it results in the largest reductions in air pollution emissions[11], it does not reduce water consumption. Also, when more gas is allocated to highly water-stressed provinces under WS, it does not necessarily bring large reductions in air pollutant emissions because regions with high water stress and severe air pollution do not closely overlap (Supplementary Fig.8b). Notably, the inherent air quality-water trade-off identified here not only exists for coal substitution with natural gas, but also for coal substitution with renewables. For instance, displacing coal-fired power plants equipped with end-of-pipe controls with wind power will bring water savings but less pronounced air quality benefits. Thus, additional action in the residential and industrial sectors is necessary to achieve desired air quality improvements. Also, the trade-offs we identified may exist in other countries where regions of high air pollution differ from those with high water stress (i.e., India). Thus, we highlight the need for careful coordination of energy and environmental policies to simultaneously and significantly address air quality, climate, and water concerns.

Additionally, both the air quality-carbon/water trade-offs due to energy source choices and the air quality-water trade-offs due to energy end-uses identified here highlight a conflict in decision making at the local, national, and global scales. Such conflicts widely exist across countries facing multiple environmental and energy challenges. Given the complexity of the air quality-carbon-water interactions at different administrative scales, there is no single optimal scenario that can outperform others in all three aspects. However, we do find that the air quality- and carbon-focused substitution scenarios with conventional and imported pipeline natural gas usually bring the most air quality and carbon benefits, and thus help to address China's current primary concerns. Nevertheless, additional efforts are needed to achieve overall environmental improvements. For instance, limiting or curtailing the utilization of energy sources that result in substantial trade-offs (i.e., SNG) or planning a combination of technologies that compensate for potential trade-offs (i.e., gas-for-coal substitution in the residential sector coupled with dry-cooling technology in the power sector) may reduce trade-offs at varying administrative scales. In addition, from the perspective of policy implementation, it is important to consider the economic costs of gas source and end-use options. For instance, unconventional natural gas generally costs more than conventional and imported pipeline gas due to smaller scale production and immature technology for unconventional gas[25, 33]. This further disfavors SNG, whose future production scale should be limited due to carbon and water concerns. Also, although deploying natural gas in the residential sector (mainly under the AS and CS scenarios) brings the most air quality and carbon benefits, it is usually very costly due to the need to install expensive last-meter distribution pipelines[11]. Thus, government subsidies for residential sector gas infrastructure is needed to facilitate an end-use coal-to-gas conversion for residents[25]. Further analysis of the regional variations and dynamic changes in economic costs are needed to better evaluate the feasibility of different gas source choices and end-use designs at finer resolution.

The absolute environmental impacts we estimate may vary depending on actual increases in natural gas supplies, actual baseline energy consumption, the penetration and removal rates of sub-sectoral end-of-pipe control technologies, and the non-linearity of atmospheric chemistry. This non-linearity may also change the order of air quality benefits for scenarios, especially when existing differences across scenarios are small. Due to the large computational resources required to simulate air pollution concentrations for all gas source and end-use combinations, we choose a representative additional gas supply and a widely used emission scenario as the base case in this study (Methodology and Supplementary Methods 1.1)[11,47,48]. We compare the air quality-carbon-water impacts among various gas sources and end-use designs, all of which have the same baseline and the same quantity of additional gas supply. Thus, the underlying air quality-carbon-water synergies and trade-offs resulting from various gas sources and end-uses should remain the same.

Globally, there are large uncertainties in methane leakage rates from upstream natural gas processes. This can potentially make gas source choices a more important factor in affecting net carbon impacts than we identify here. Field measurements of methane leakage along the whole lifecycle chain of the natural gas industry both within and outside China will improve understanding of the carbon impacts of China's natural gas industry and the relative importance of gas source choices and deployment strategies.

The air quality-carbon-water nexus discussed in this study focuses on China's natural gas industry. Due to its enormous economy and population, China's energy plans have important domestic as well as global implications for sustainable development. The framework described here, and its qualitative conclusions could be applied to other countries and regions as they design sustainable energy transition pathways.

Methods

This work uses an integrated assessment approach coupled with lifecycle analysis to evaluate the air quality-carbon-water nexus of China's natural gas industry. Our objective is to understand the differences in impacts resulting from various gas source choices and end-use deployment strategies (Supplementary Table 1).

We quantify the air quality impacts as changes in lifecycle air pollutant emissions and simulated $PM_{2.5}$ surface concentrations. Carbon impacts are calculated as changes in lifecycle greenhouse gas (GHG) emissions. Additionally, water impacts are represented by changes in water consumption weighted by water stress index (WSI) (WSI: the ratio of total annual freshwater withdrawal to hydrological availability, ranging from 0 to 1[38, 39]). WSI weighted water consumption is calculated as actual regional water consumption × region-specific water stress index, referred hereafter as 'weighted water consumption'.

We use the ECLIPSE_V5a_CLE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) emission scenario developed by the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model as our 2020 base case anthropogenic emissions input[49]. The ECLIPSE scenario is designed to reflect provincial energy policies and emission regulations in China's 12th five-year-plan[49], and it provides detailed subsector technology information, energy consumption data, and emissions of major air pollutants and CO_2 at China's provincial level. In addition, we integrate China's provincial-level cooling technology information from the World Electric Power Plants database (https://www.platts.com/products/) (Supplementary Table 2) with end-use technology data (i.e., power plant technologies) provided by the GAINS model (http://gains.iiasa.ac.at/models/) to evaluate water impacts (Supplementary Methods).

We focus on China's six major natural gas sources, including domestic conventional natural gas, domestic coal-based synthetic natural gas (SNG), domestic shale gas, imported liquefied natural gas (LNG), imported pipeline gas from Russia, and imported pipeline gas from Central Asia. For each gas source, the regional deployment is determined by governmental and industrial plans as shown in Fig.1 and Supplementary Table 4. At the sectoral level, we consider natural gas substitution for coal in three major sectors: industry, residential, and power[11].

Based on three possible environmental priorities, for each gas source, we design three end-use deployment strategies for the gas-for-coal substitution for each gas source. 1) Air quality-focused substitution (AS), designed to achieve the largest reductions in SO_2 emissions; 2) Carbon-focused substitution (CS), designed to achieve the largest reductions in CO_2 emissions; and 3) Water-focused substitution (WS), designed to achieve the largest reductions in weighted water consumption (Supplementary Table 1).

To uniformly compare impacts of gas-for-coal substitution, for each combination of gas source and end-use, we assume an additional gas supply of 30 bcm above the baseline to replace coal. This is roughly the quantity of China's currently planned increases for each gas source around 2020[23, 26, 28] (Supplementary Methods 1.1). We then estimate the resulting changes in air pollutant emissions, CO_2 emissions, and weighted water consumption due to end-use gas substitution for coal (Supplementary Tables 2 and 3, Supplementary Fig. 7). Additional gas supply leads to an increase in upstream natural gas production and a decrease in upstream coal production. This results in emission and water consumption changes from upstream natural gas and coal processes (i.e., production, processing, transmission, and distribution) due to energy combustion, methane leakage, and water uses for coal washing, well drilling and so forth[31, 41] (Supplementary Table 5). We quantify changes in upstream emissions primarily using stage-level energy consumption data and methane leakage rates summarized in Qin et al. (2017)[31] (refer to Supplementary Methods 1.2 for details), and country-specific emission factors from the GAINS model (Supplementary Fig. 10). We calculate changes in upstream weighted water consumption using the same energy consumption data and methane leakage rates (Qin et al., 2017[31]), fuel-specific water consumption rates (Supplementary Table 8), and regional water stress indexes. WSI are provided by Feng et al. (2014)[38] (provincial-level WSI for regions within China) and Pfister et al. (2009)[39] (country-level WSI for regions outside China). We assume upstream emissions and water consumption for gas processes occur in places where natural gas is produced. The spatial distribution of reduced emissions and water consumption due to avoided upstream coal processes are identified according to where end-use coal reduction occurs and the corresponding source-receptor matrix of coal production and consumption[50].

Combining both upstream and end-use processes, we estimate net changes in air pollutant emissions, GHG emissions, and weighted water consumption for each gas source under each gas-for-coal deployment strategy. We then use the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem v3.6) to simulate resulting changes in 2020 annual average $PM_{2.5}$ surface concentrations. Method details are summarized in the Supplementary Methods.

Data availability

Data used to perform this work can be found in the Supplementary Information. Any further data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author Contributions

Y.Q. and D.L.M. designed the study, Y.Q. performed the research, L.H.I, E.B., K.F., F.W., and W.P. contributed data for analysis, Y.Q., L.H.I, E.B., and K.F. analyzed data, and Y.Q., D.L.M., and L.H.I wrote the paper.

Competing interests

The authors declare no competing financial interests.

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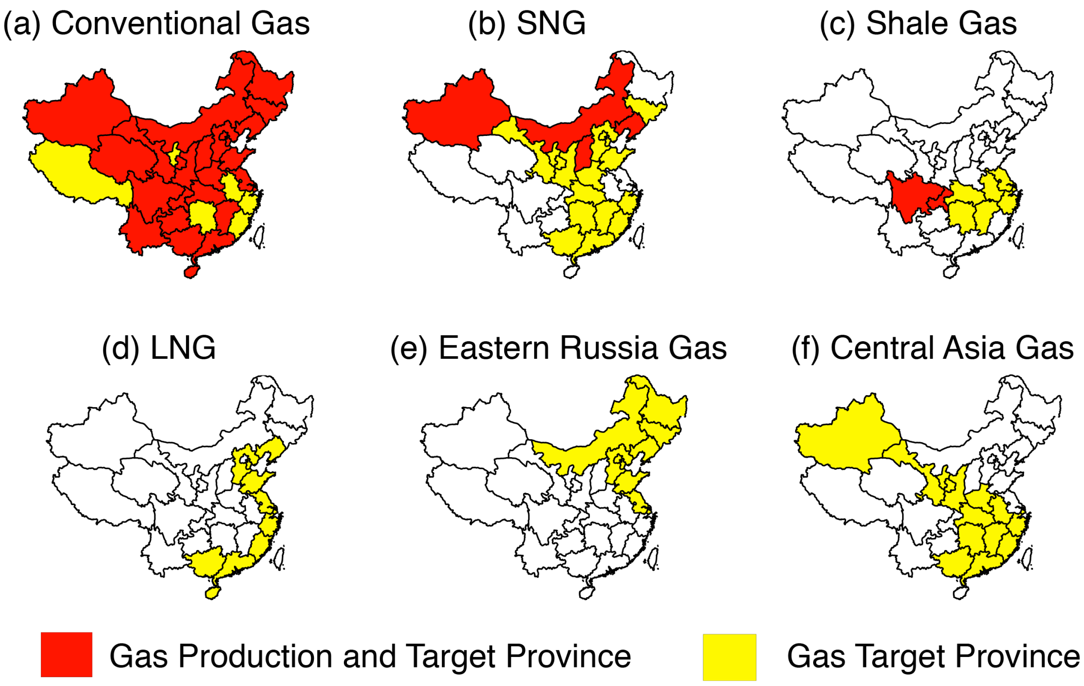

Fig. 1 Production and target (potential consumption) regions for mainland China's six major natural gas sources based on government and industrial plans for 2020[11, 18, 23, 27, 40]. Refer to Supplementary Table 4 for details and the underlying assumptions about the spatial distribution of gas production and consumption. Imported LNG is mainly produced in Qatar, Australia, Indonesia, and Malaysia[51]. Imported Eastern Russia Gas and Central Asia Gas are produced in Russia and Central Asian countries (Turkmenistan, Kazakhstan, and Uzbekistan), respectively[27,28].

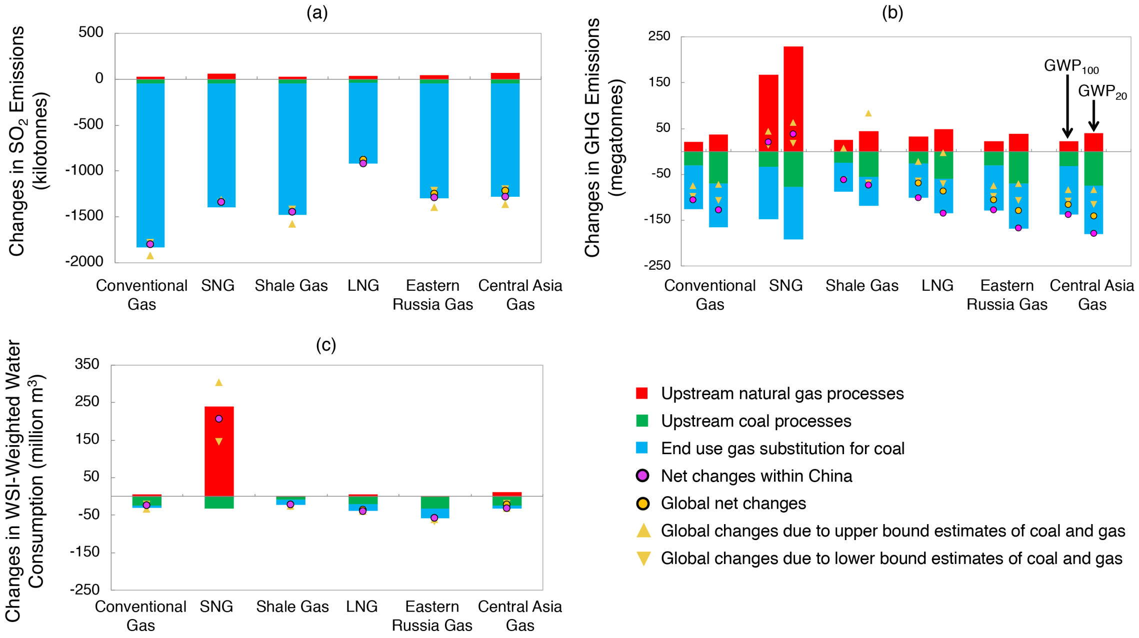

Fig. 2 **Air quality-focused substitution (AS).** Changes in upstream and downstream SO_2 emissions, greenhouse gas emissions (CO_{2eq}, including both CO_2 and CH_4), and water stress index (WSI) weighted water consumption for coal substitution by 30 bcm of gas from various sources (Conventional gas, SNG, Shale gas, LNG, Eastern Russia gas, and Central Asia gas) in 2020. **Net changes within China** are obtained by considering emission or weighted water consumption changes occurring **within China's border** from upstream gas processes (upstream gas production, processing, transmission, and distribution), upstream coal processes (upstream coal production, processing, and transport), and end-use gas substitution for coal. **Global net changes** represent the emission or weighted water consumption changes resulting from the differences between the mean estimates of coal and the mean estimates of natural gas, which occur **both within and outside of China**. Global changes due to upper and lower bound estimates (mainly due to methane leakage rates) of coal and natural gas, respectively, are also shown in the graph. Note that differences between the mean estimates of coal and the mean estimates of gas are not necessarily the mean differences between coal and natural gas. Results for carbon-focused (CS) and water-focused (WS) gas-for-coal substitution are shown in Supplementary Figs. 2 and 3.

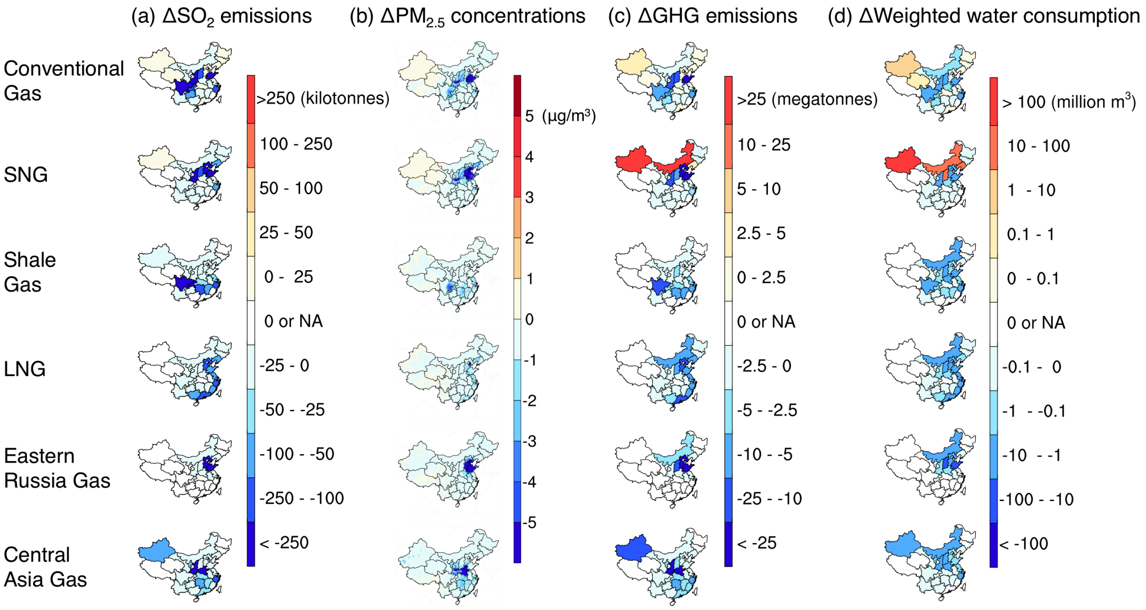

Fig. 3 **Air quality-focused substitution (AS).** Mainland China's 2020 spatially resolved changes in air quality (SO_2 emissions and population-weighted $PM_{2.5}$ surface concentrations), carbon (lifecycle greenhouse gas emissions under GWP_{100}, including CO_2 and CH_4, assuming mean methane leakage rates), and water (weighted water consumption) impacts of 30 bcm of gas from various sources substituting for coal. Changes in SO_2 emissions, GHG emissions, and weighted water consumption are shown at the provincial level; changes in $PM_{2.5}$ concentrations are shown at the grid level (27 km×27 km). Results for carbon-focused (CS) and water-focused (WS) gas-for-coal substitution are shown in Supplementary Figs. 4 and 5.

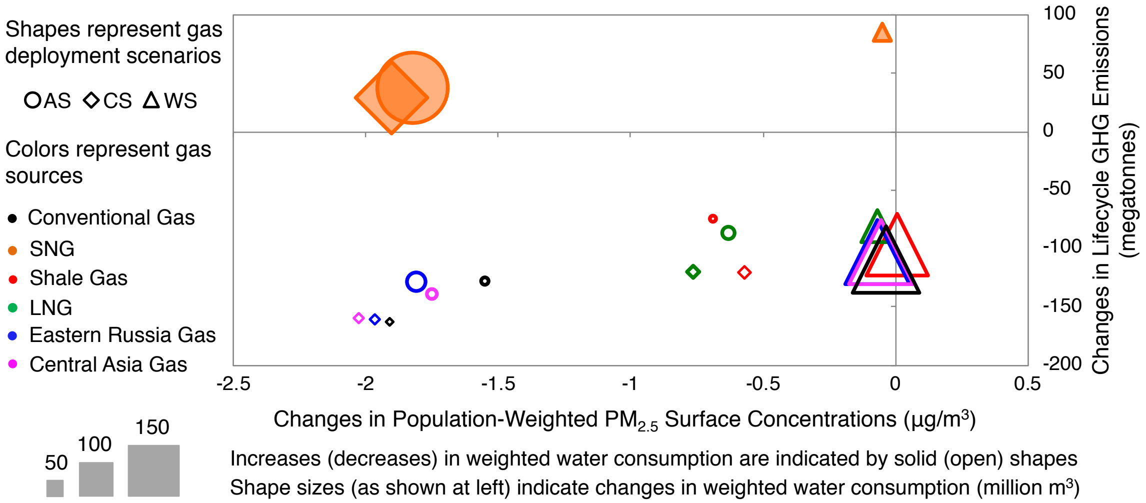

Fig. 4 Comparison of net changes in air quality (China's population-weighted PM$_{2.5}$ surface concentrations), carbon (lifecycle greenhouse gas emissions under GWP$_{20}$, assuming mean methane leakage rates), and water impacts (China's weighted water consumption) from substituting 30 bcm of gas from various sources for coal under three deployment strategies in 2020. Negative changes in PM$_{2.5}$ surface concentrations, lifecycle GHG emissions, and weighted water consumption represent an improvement in air quality, carbon, and water impacts from gas substitution for coal, and vice versa. AS: air quality-focused substitution, CS: carbon-focused substitution, and WS: water-focused substitution. Detailed breakdowns are shown in Supplementary Fig. 9.