



Challenges of using natural gas as a carbon mitigation option in China

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ABSTRACT

Under the Paris Agreement, China committed to peak its carbon dioxide emissions on or before 2030. Substituting natural gas for coal may facilitate it meeting this commitment. However, three major challenges may obstruct progress towards desired climate benefits from natural gas. 1) A fundamental price dilemma disincentivizing a coal-to-gas end-use energy transition: low city-gate gas prices discourage an increase in gas supplies while high end-use gas prices impede an increase in gas demand. 2) Insufficient and constrained access to natural gas infrastructure hinders connections between gas supplies and end-users, and obstructs a balance in seasonal supply and demand. 3) Methane leakage from the natural gas industry compromises the direct greenhouse gas emission reductions from combustion. To address these challenges, government and industry must work together to facilitate natural gas market reform, increase investment in natural gas infrastructure, and control methane emissions.

1. Introduction

China's rapid economic growth over the past two decades has been accompanied by substantial increases in national energy consumption and resulting air pollutants and CO₂ emissions (Qin and Xie, 2011a; Sheehan et al., 2014). Currently China, with 19% of global population, contributes 16% of global gross domestic product (GDP) and 30% of global CO₂ emissions (The World Bank, 2017). China is by far the world's largest emitter of CO₂ and has pledged to peak national CO₂ emissions by 2030 or sooner (NDRC, 2015a). Meanwhile, the Chinese government is committed to reducing China's severe domestic air pollution (Sheehan et al., 2014; State Council, 2013a). Many air-quality improvement measures, including substituting natural gas for coal (NDRC, 2015a), may also bring climate benefits. Indeed, in its Nationally Determined Contributions (NDC), the Chinese government plans to increase the use of natural gas to over 10% of national primary energy consumption by 2020 (NDRC, 2015a). Here we examine the key challenges that may constrain the carbon mitigation potential of natural gas uses in China. These include a need to expand natural gas supplies, encourage coal-to-gas substitution, and ensure a lower lifecycle carbon footprint for natural gas than coal.

2. China's natural gas supply

Primarily for geologic reasons, China has abundant coal reserves but is relatively poor in conventional natural gas resources (IBP, 2012). Abundant and cheap coal has dominated China's energy supply throughout its industrialization and modernization. As a result, even with government incentives, natural gas use barely reached 6% of China's total primary energy consumption in 2015, compared with 64% from coal (NBSC, 2016). In 2014, China's total natural gas supply was about 187 billion cubic meters (bcm), with 64%, 0.7%, 4%, 0.4%, 14%, 2%, and 15% from domestic conventional gas, shale gas, coalbed methane (CBM), coal-based synthetic natural gas (SNG), imported liquefied natural gas (LNG), and imported pipeline gas from Myanmar and Central Asia, respectively (NBSC, 2016). To further increase natural gas supplies, the Chinese government has actively promoted exploration and production of domestic unconventional natural gas. The central government has set production goals for year 2020 at approximately 30–100, 20–40, and 20–60 bcm of shale gas, CBM, and SNG, respectively (NDRC, 2016a, 2016b; NEA, 2012a, 2012b, 2014a, 2014c, 2016). Meanwhile, China has established natural gas import contracts with major gas producing countries (NDRC, 2012, 2016b). According to the existing contracts, China's natural gas import capacity in 2020 will

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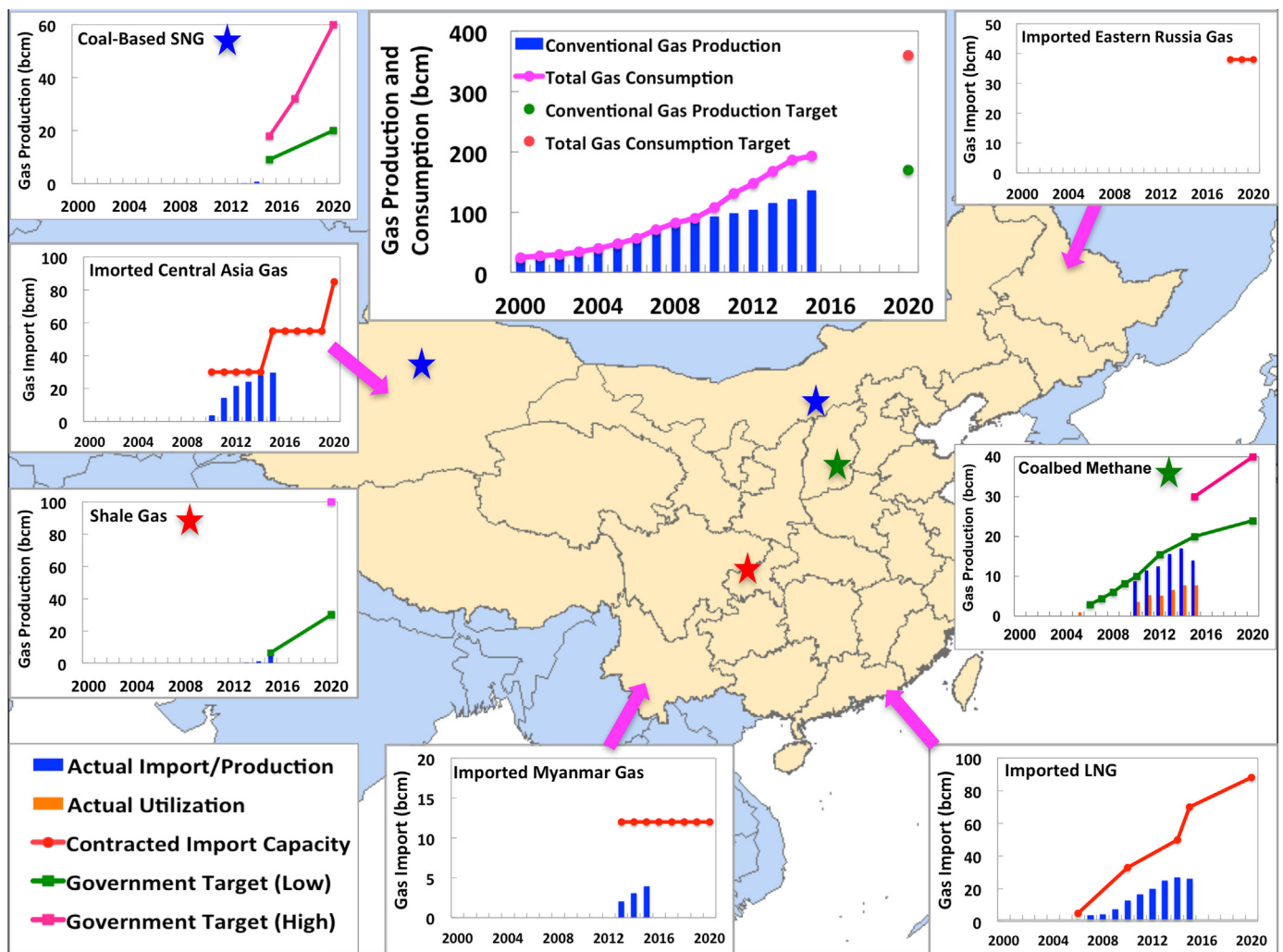


Fig. 1. Historic and planned natural gas supplies from China's major natural gas sources. Information is gathered from government documents (for government targets) (NDRC, 2012, 2016a, 2016b; NEA, 2014b; State Council, 2013b), a statistical database (for historical gas production and consumption) (NBSC, 2016), published literature (Paltsev and Zhang, 2015), and news articles (when no other information is available). Representative production regions and import locations for major gas sources are illustrated on the map with colored stars (shale gas with red stars, coalbed methane with green stars, and coal-based synthetic natural gas with blue stars). Pink arrows point to major provinces importing pipeline gas and LNG from indicated regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increase to 85 bcm/yr (via pipelines from Central Asia, ~55 bcm/yr in 2015), 38 bcm/yr (via pipelines from eastern Russia, contracts will start in 2023), and 88 bcm/yr (via LNG from Qatar, Australia, Malaysia, and Indonesia; ~50 bcm/yr in 2014) (Dong et al., 2014; Paltsev and Zhang, 2015).

In Fig. 1, we summarize historical natural gas supplies and near-term production or import goals for China's primary natural gas sources. We find that despite strong political interest in increasing natural gas supplies, domestic unconventional natural gas production and actual natural gas imports are consistently below the government's targets (NDRC, 2012, 2016b; NEA, 2012b, 2014b; Paltsev and Zhang, 2015). Furthermore, the Chinese government has continuously lowered production targets for all types of unconventional gas over the past five years to adjust for slow growth in natural gas supplies (NDRC, 2012, 2016a, 2016b; NEA, 2012a, 2014a, 2014c, 2016). For example, in 2012, the central government planned to have annual shale gas production of 60–100 bcm by 2020; this target was reduced to 30 bcm four years later (announced in 2016) (NEA, 2012a, 2016).

Slower-than-expected domestic natural gas development is partly due to constraints such as unfavorable geology and immature technology (Chang et al., 2012; Yang, 2015). Shale gas has experienced such development constraints and we list the main barriers for China's shale gas development compared to the U.S. in Table 1. Geological

constraints such as deeper shale resources and insufficient water availability cause substantially higher costs for shale gas production in China than in the U.S. Meanwhile, market barriers have also played an important role in delaying natural gas development in China. Until now, China's natural gas market was essentially controlled by three national oil companies (NOCs) that own virtually all natural gas production facilities and pipeline infrastructure. Natural monopolies result in an uncompetitive gas production market. This, consequently, leads to low incentives for NOCs to invest in technology advancement and efficiency improvement, which could have significantly reduced gas production costs (Victor et al., 2011).

More importantly, natural gas markets in China are heavily regulated by central and provincial governments. In Fig. 2, we illustrate China's natural gas pricing mechanisms. As shown in Fig. 2, under the traditional pricing mechanism, city gate natural gas prices are determined by the wellhead gas prices and long-distance pipeline transmission prices, both of which are regulated by the central government. City gate gas prices, for which natural gas distribution companies pay the pipeline companies (subsidiaries of the three NOCs), are thus regulated wholesale natural gas prices (Paltsev and Zhang, 2015). China started to implement a new pricing mechanism nationwide in 2013. Under the new pricing mechanism, city gate natural gas prices are associated with two imported substitutes: fuel oil and liquefied

Table 1
Comparison of geological, technical, economic, and political factors influencing shale gas development in China and the United State.

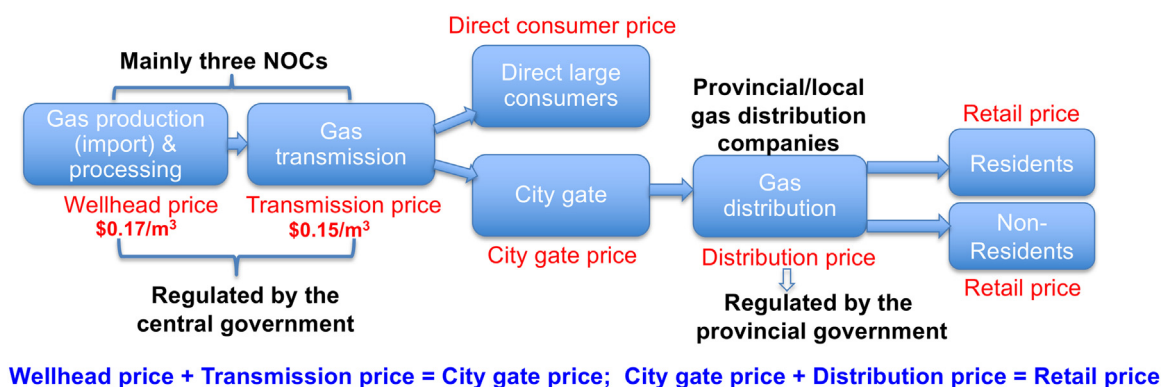
	China	United States
Technically recoverable resource	31.6 trillion cubic meters (tcm) (EIA, U.S, 2015b); 25.1 tcm (excluding Tibetan and Qinghai) (Zhao et al., 2013)	32.9 tcm (ARI ^a); 18.8 tcm (EIA, 2017)
Embedded depth	Mainly deep reservoir (~2000–5000 m) (Qin et al., 2017a)	Mainly shallow reservoir (~1200–3000) (Qin et al., 2017a)
Surface condition	Mainly in rugged region with high population density (NDRCERI, 2013)	Mainly in rural areas with good surface conditions and low population density (NDRCERI, 2013)
Water resource	Mainly in regions with water scarcity (NDRCERI, 2013)	Mainly in water sufficient regions (NDRCERI, 2013)
Technology	Still developing and localizing (NDRCERI, 2013)	Mature (NDRCERI, 2013)
Extraction cost	On average US \$12 million per well drilled (EIA, 2015a)	On average US \$4–6 million per well drilled (EIA, 2015a)
Participants	Primarily three big National Oil Companies (NOCs) and some other state-owned enterprises (SOEs) (Tian et al., 2014)	Initiated by small companies, which were later bought by larger energy companies (Tian et al., 2014)
Pipeline infrastructure	Underdeveloped (~64,000 km) and mainly controlled by three NOCs (CNPC in particular) (NDRC, 2016b)	Developed (~500,000 km) with unbiased access for producers (Zhao et al., 2013)

^a Advanced Resources International (ARI) estimates from earlier published studies. <https://www.eia.gov/todayinenergy/detail.php?id=11611>.

petroleum gas (LPG). The intention was to link domestic natural gas prices to international oil markets and to provide an automatic mechanism to frequently adjust natural gas prices. In reality, however, the city gate gas prices were only occasionally adjusted by China's national development and reform commission (NDRC), even though fuel oil and LPG prices have indicated much more frequent and significant changes in natural gas prices would have been appropriate (NDRC, 2013a, 2015b; Paltsev and Zhang, 2015).

Production or import costs of natural gas can be higher than the city gate natural gas prices that are essentially set by China's central government (Fig. 2). As a result, artificially low city gate gas prices have led to substantial economic losses for the three NOCs (Paltsev and Zhang, 2015). The central government has provided financial subsidies – a lump sum annual payment to the NOCs, but these subsidies only partly compensated for the losses (Paltsev and Zhang, 2015). Financial losses in upstream natural gas businesses have further dis-incentivized

(a) Traditional natural gas pricing mechanism



(b) New natural gas pricing mechanism

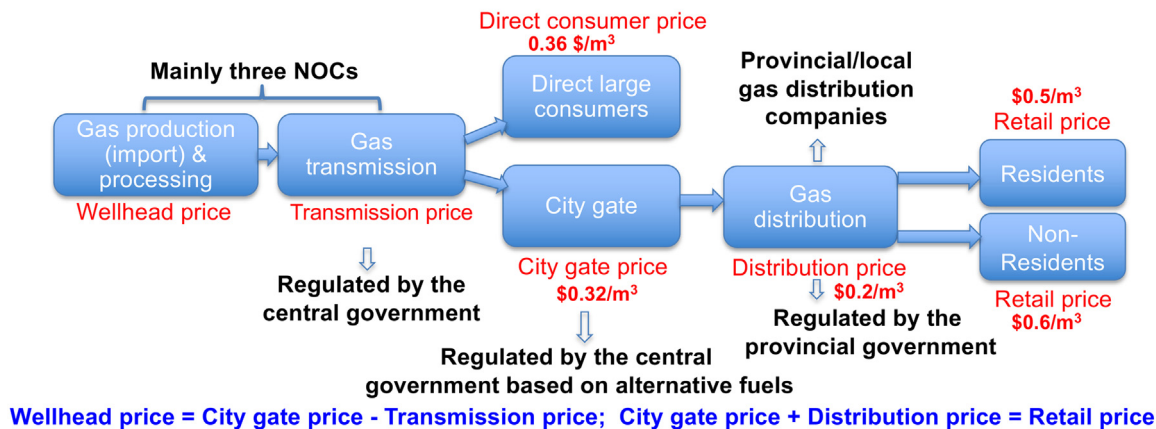


Fig. 2. A simplified illustration of China's (a) traditional and (b) new natural gas pricing mechanisms (Adopted from Paltsev and Zhang (2015)). The new pricing mechanism was implemented across China in 2013. City gate prices are the prices that provincial distribution companies pay to the three national oil companies (NOCs) that produce (or import), process, and transport natural gas from gas fields to the consuming province. Indicative prices for pipeline-transported conventional natural gas consumed in Guangdong (one of the provinces with the longest gas transmission pipelines) are listed in the figure to illustrate the prices at each stage of the natural gas market (Duan and Fan, 2017a; PETRI, 2017).

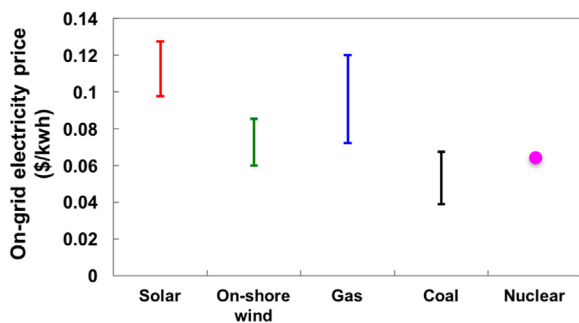


Fig. 3. China's on-grid electricity prices for various energy sources as regulated by the National Development Reform Commission up till 2017 (NDRC, 2013b, 2014, 2015c, 2016c). Price ranges for each energy source indicate variations across provinces.

industrial investments in gas production and import, which partially explains the lower-than-expected increases in China's natural gas supplies.

3. China's natural gas demand

Natural gas and coal can both be used in the industrial, residential, and power sectors (Qin and Xie, 2011b). Even though the regulated city gate natural gas prices can be lower than production or import costs, end-use natural gas prices are still not competitive with cheap coal (Fig. 3). This has consequently hindered a large-scale coal-to-gas end-use transition. As shown in Fig. 3, the on-grid electricity prices of natural gas are approximately twice that of coal, indicating substantial challenges for natural gas to compete with coal in the electricity sector. In addition, on-grid electricity prices for both on-shore wind and nuclear power are already lower than natural gas. Similarly, the costs of residential space heating using natural gas (\$4.7/m² space heating) are higher than using coal (\$3.5/m² space heating) (Shao, 2017). Furthermore, if the enormous costs of building new natural gas distribution networks and the costs of retrofitting existing coal-burning equipment are included, natural gas appears even less cost-competitive with coal.

4. The price dilemma in China's natural gas market

Essentially, China is facing a fundamental price dilemma in the natural gas market: a relatively low (relative to the costs of production, import and transport) city gate natural gas price which discourages investment and development of the natural gas supply while a relatively high (relative to coal) end-use gas price which disfavors a gas-for-coal transition in end-use applications.

To resolve this price dilemma, we propose efforts in both gas production and consumption markets. On the production side, we suggest a two-step strategy. First, create a competitive natural gas supply market that allows more investors to enter the market, thus increasing competition and incentivizing cost reductions. Second, let the market determine city gate gas prices after appropriately resolving the natural monopoly issue. By following these two steps, we expect an improved gas supply market that can increase gas supplies at a reduced cost. On the consumption side, a primary goal is to decrease end-use gas prices relative to coal. Recent studies indicate that one important factor affecting retail gas prices is the high transport costs and access fees from provincial/local gas distribution pipeline networks (Duan and Fan, 2017b). Thus, we suggest China move towards a competitive natural gas distribution market in which gas suppliers can directly negotiate contracts with local natural gas distribution companies and large consumers without the intervention of provincial gas distribution companies. According to Duan and Fan (2017), such open gas distribution pipelines can significantly reduce end-use natural gas prices as a result of lower distribution costs.

5. Natural gas infrastructure

We also emphasize the importance of natural gas infrastructure, which plays a crucial role in connecting natural gas supplies with end-users. China currently has only ~10% of the long-distance gas pipelines as the U.S., and over 70% of existing pipelines are owned by one NOC, China National Petroleum Corporation (CNPC) (Table 1). It is not uncommon for CNPC to turn down gas transmission requests from other natural gas producing companies. Under-developed pipeline infrastructure and its monopoly control by CNPC have caused several issues. First, lack of a well-developed and easily accessible gas pipeline network discourages existing gas producers from investing in gas production, and, at the same time, creates a higher entrance bar for potential gas producers. Second, it hinders the expansion of China's natural gas consumption due to the geographic mismatch between major gas supplies in western China and major gas demand centers in southern and eastern China. Similarly, inadequate provincial gas distribution pipelines, most of which are under the control of provincial gas distribution companies, further impede efficient and cheap gas distribution.

Natural gas storage infrastructure is also important in meeting gas demand efficiently and reliably. In recent years, we observe an increasing variation in seasonal gas demands primarily driven by escalating winter heating gas needs. For instance, Beijing's recent gas demand was 6–8 times higher in winter than in summer. China's current national gas storage accounts for merely 3% of annual gas consumption, far below the global average of 16% (Ding, 2011). The lack of natural gas storage facilities has resulted in severe winter gas shortages in the Beijing-Tianjin-Hebei region in 2017, and will make it increasingly challenging to meet growing gas demands throughout the year.

6. Carbon footprint of using natural gas to meet end uses

In addition to the price dilemma and immature infrastructure, we identify another uncertainty in realizing the intended climate benefits of the coal-to-natural gas end-use transition: the lifecycle carbon footprint of China's natural gas relative to coal.

Compared to coal, when combusted, natural gas emits approximately half the CO₂ per unit of energy output (Jaramillo et al., 2007). As a result, substituting natural gas for coal is considered a bridging solution that reduces climate change. However, natural gas may have a larger-than-coal lifecycle carbon footprint if substantial methane leakage occurs from the natural gas system (Qin et al., 2017a). In Fig. 4, we estimate changes in CO₂ and CH₄ emissions assuming all natural gas produced in 2010, 2020, and 2030 (using mean government targets) were used to replace coal consumption in each specific end-use (power generation, residential cooking, or industrial heat generation). Such hypothetical allocation can indicate the sign and magnitude of emission changes within each sector resulting from a coal-to-gas transition.

As shown in Fig. 4, increasing natural gas consumption from 2010 to 2030 does not necessarily reduce total greenhouse gas (GHG) emissions. This is partly due to large variations in lifecycle emissions among different natural gas sources. First, if all natural gas produced and consumed were SNG, it would have increased China's 2010 CO₂ emissions (~9 billion tonnes) by 2–4%, and could increase China's predicted CO₂ emissions in 2020 (~12 billion tonnes) and 2030 (~14 billion tonnes) by 4–10% and 4–11%, respectively. Thus, a significant use of SNG is inconsistent with China's commitment to peak CO₂ emissions on or before 2030 (NDRC, 2015a). In contrast, assuming all natural gas produced and consumed were conventional natural gas, CO₂ emissions would have been reduced by 1–4% in 2010, and could lead to 4–9% and 4–11% reduction in CO₂ emissions in 2020 and 2030, respectively.

Imported gas and shale gas may have slightly higher CO₂ emissions than conventional gas due to larger energy consumption for long distance transport, liquefaction and regasification, and hydraulic fracturing (Jaramillo et al., 2007; Qin et al., 2017a). Nevertheless, except for SNG, substituting natural gas for coal facilitates China's efforts to

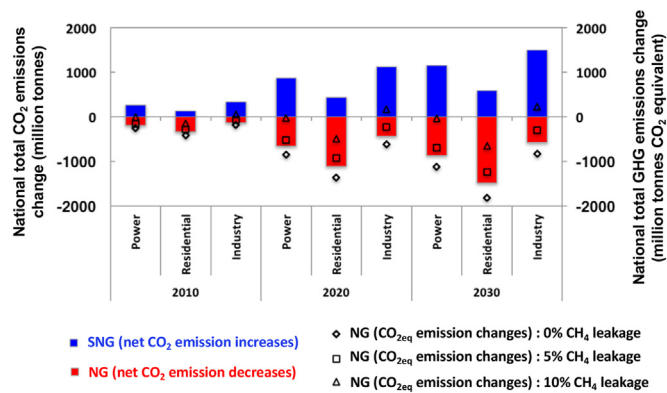


Fig. 4. Changes in China's CO₂ alone and total greenhouse gas (GHG, including CO₂ and CH₄) emissions when coal-based synthetic natural gas (SNG) or conventional natural gas (NG) substitute for coal in 2010, 2020, and 2030, respectively. Changes in CO₂ emissions are shown with colored bars using the left axis, and changes in GHG emissions (GWP₁₀₀) are shown with black markers using the right axis. Total natural gas consumption in 2010 (historical consumption), 2020 and 2030 (government consumption targets) are 108, 360, and 480 billion cubic meters (bcm), respectively (NDRCC, 2016b). Here we assume all natural gas is either used for power generation (replacing supercritical coal-fired power plants), residential cooking, or industrial heat generation. We consider multiple methane leakage rates (0%, 5%, and 10%) from natural gas systems and use the 100-year global warming potential. Note that methane leakage also occurs during coal mining and post-mining processes (IPCC, 2006), with those emission factors summarized in Qin et al. (2017a). Therefore, assuming a 0% methane leakage rate in natural gas systems, net GHG emission changes from a coal-to-NG switch include reductions in both CO₂ and CH₄. Calculations are adapted from (Qin et al., 2017a, 2017b).

accomplish its NDC commitment by reducing CO₂ emissions. However, this does not guarantee net climate benefits because the NDC commitment does not explicitly include methane emissions from the natural gas industry. Methane is a strong greenhouse gas with a global warming potential of 84 over 20 years and 28 over 100 years compared to CO₂ (IPCC, 2013). As we show in Fig. 4, only with a low methane leakage rate can natural gas substitution for coal help China both achieve its NDC commitment and result in net GHG emission reductions.

Finally, we note substantial differences in emission impacts across end uses. Natural gas use in the residential sector is likely to bring larger GHG emission reductions than use in other sectors. Importantly, per unit of natural gas consumed, this is also the sector that can bring the largest air quality and associated human health co-benefits (Qin et al., 2017b). Qin et al. (2017b) found that deploying the same amount of SNG in the residential sector reduces approximately 10 and 60 times more air-pollution associated premature deaths than if deployed in the industrial and power sectors, respectively. Thus, to maximize current co-benefits for air pollution and climate change, it is crucial to prioritize natural gas substitution for coal in the residential sector. As the cost of using natural gas is higher than using coal for residents, we see government subsidies that support 'last-meter' gas distribution infrastructure and retrofit coal-burning equipment to burn natural gas ones in the residential sector as important to motivate residents to shift from coal to natural gas.

Market reform efforts and carbon price policies in China are likely to re-adjust the relative prices of natural gas over coal across end-uses. These efforts shall facilitate coal-to-gas end-use transitions in both residential and non-residential sectors, thus significantly increasing natural gas consumption and reducing air pollutant and GHG emissions, assuming methane leakage is well controlled.

7. Policy implications

To reduce the uncertainties in using natural gas as a carbon mitigation option in China, political and industrial efforts are needed to address the fundamental price dilemma in China's natural gas markets, to increase investment in natural gas infrastructure, and to reduce the

lifecycle carbon footprint of China's diversifying gas sources by minimizing methane leakage wherever possible.

Some efforts have been made in our suggested areas in recent years. However, many practical barriers still exist. For instance, two rounds of shale gas auctions were held to increase competition in natural gas production markets. However, the auctions were only open to domestic state-owned enterprises and selected private companies. Furthermore, except for the three NOCs, other Chinese companies rarely have technical expertise in the oil and gas production industry. Also, shale gas, and unconventional gas in general, accounts for only a small fraction of China's current total gas supplies. Thus, we suggest opening the whole upstream natural gas market to all interested investors. To encourage the participation of companies other than the three NOCs, it is crucial to allow fair competition among professional natural gas service companies both inside and outside of China.

Likewise, the government has been gradually deregulating natural gas prices via measures such as establishing the Shanghai natural gas hub. Such efforts are a movement towards a market-based pricing mechanism. However, the natural monopoly issue in the gas production market needs to be addressed before a market-oriented pricing mechanism can perform well. Meanwhile, the Chinese government is also encouraging gas infrastructure investment and pushing forward unbiased pipeline access at the national level. However, reform of the long-distance gas pipeline market is still an on-going process, with little evidence regarding how well it will actually be implemented. In addition, to facilitate gas use expansion, effort is needed to develop a competitive and open natural gas distribution network at the provincial level that encourages cheap and efficient gas distribution.

Nevertheless, competitive and mature gas supply and distribution markets still cannot fully resolve the price dilemma. This is because the negative environmental externalities of natural gas and coal are not taken into account. A reasonably high carbon price is needed to increase the price competitiveness of natural gas over coal. Importantly, this not only helps to facilitate a coal-to-gas transition but also helps to shift the country towards an eventually zero-carbon development path. Non-fossil fuels are becoming cheaper, with wind and nuclear power already competitive with natural gas in the power sector (Fig. 3). Solar electricity costs have also dramatically fallen over the past seven years, from \$0.17/kWh in 2010 to \$0.1–0.13/kWh in 2017. In 2017, China established a national carbon trading market based on seven provincial pilot carbon markets started in 2011. However, the current carbon prices in the pilot carbon markets (US \$1–15/tonne CO₂) will likely need to increase significantly to fully capture the carbon advantage of low- and no- carbon energy (<http://www.tanpaifang.com>).

Natural gas sources other than SNG can contribute to China's NDC by substituting for coal. However, methane leakage from natural gas systems will partly offset the CO₂ reduction benefits from a coal-to-natural gas transition and is important to minimize. We therefore emphasize the need for the next round of NDC to include methane leakage from the oil and gas industry to ensure effective GHG mitigation efforts.

Assuming the challenges discussed above are carefully addressed, natural gas can play an important bridging role in China's low-carbon energy transition in the near future, while bringing notable air quality and energy security co-benefits. In the long run, however, it is critical to further decrease the carbon intensity of China's economy. Electrification of the economy (i.e., the residential, industrial and transportation sectors) with increasing amounts of non-fossil generation appears a promising route to ultimately achieve a zero-carbon economy (Tong et al., 2017). Existing and proposed natural gas infrastructure may lead to lock-in of some fossil-based technology. However, renewable energy is unlikely to overtake coal to dominate China's electricity mix within the next 1–2 decades (coal still accounted for over 65% of China's electricity generation in 2016 (NBSC, 2016)). Therefore, natural gas (with methane leakage well controlled) may be a viable bridge, within the lifetime of natural gas infrastructure, to deliver rapid reductions in carbon emissions. In addition, a coal-to-gas transition can

bring substantial co-benefits in other areas. For instance, deploying gas in the residential sector to replace coal combustion would bring large air quality benefits both indoors and to the North China Plain in winter (Qin et al., 2017b). Also, retrofitting coal-fired power plants with natural gas combined cycles can significantly reduce cooling water demands when using the same cooling technology (Qin et al., 2018). In addition, greater natural gas availability in the future could be used in fast ramping electric power plants to smooth the intermittency of renewable electricity generation, thus facilitating renewable energy penetration via maintaining the grid stability.

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