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Potential role of natural gas infrastructure in China to supply low-carbon gases during 2020–2050

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HIGHLIGHTS

- Supply low-carbon gas in NG infrastructure during 2020–2050 in China for scenarios.
- Estimation of production of biomethane, bio-SNG, low-carbon SNG, and H_2.
- Assess provincial gas flow and gas infrastructure capacity in network flow model.
- Techno-economic and GHG emissions assessment of low-carbon gas supply chains.
- By replacing natural gas, avoided GHG emissions and GHG avoidance cost are defined.

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ABSTRACT

As natural gas (NG) demand increases in China, the question arises how the NG infrastructure fit into a low greenhouse gas (GHG) emissions future towards 2050. Herein, the potential role of the NG infrastructure in supplying low-carbon gases during 2020–2050 for China at a provincial resolution was analyzed for different scenarios. In total, four low-carbon gases were considered in this study: biomethane, bio-synthetic methane, hydrogen, and low-carbon synthetic methane. The results show that the total potential of low-carbon gas production can increase from 1.21 EJ to 5.25 EJ during 2020–2050, which can replace 20%–67% of the imported gas. In particular, Yunnan and Inner Mongolia contribute 17% of China's low-carbon gas production. As the deployment of NG infrastructure can be very different, three scenarios replacing imported pipeline NG were found to reduce the expansion of gas infrastructure by 35%–42%, while the three scenarios replacing LNG imports were found to increase infrastructure expansion by 31%–53%, as compared to the base case. The cumulative avoided GHG emissions for the 6 analyzed scenarios were 6.0–8.3 Gt CO_2. The GHG avoidance costs were highly influenced by the NG price. This study shows that the NG infrastructure has the potential to supply low-carbon gases in China, thereby significantly reducing GHG emissions and increasing both China's short- and long-term gas supply independence.

1. Introduction

For over 20 years, China has been the world's largest energy consumer, with coal as their dominant energy source [1]. Energy transit for China is inevitable for sustainable growth. Natural gas (NG) is the cleanest and fastest-growing fossil fuel in China, emitting 29%–44% less CO_2, 79%–80% less NO_x, 99.9% less SO_2, and 92%–99.7% fewer particulates than oil and coal [2]. Since 2017, NG consumption has surged in China as a result of "coal to gas switching" to mitigate air pollution [3]. However, NG combustion still emits a large amount of greenhouse gas (GHG) as compared to renewable energies. Thus, NG acts as a short-term bridge from a fossil-dominated energy system to a low-carbon future [4]. Long-term, NG will be gradually replaced by renewable energy [1]. Low-carbon gases are a promising substitute for NG as they can fit in the existing NG infrastructure with little or no modification. The low-carbon gas in this paper is referring to biomethane and bio-synthetic methane from biomass conversion, hydrogen from power-to-H_2, and low-carbon synthetic methane from power-to-methane.

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According to studies from the International Energy Agency (IEA) World Energy Outlook [5] and the China Renewable Energy Outlook (CREO) [6], NG consumption in China will continue to increase until 2035. China's domestic NG production cannot meet the demand for NG. Domestic NG production in China was 157.5 billion m^3 (BCM) in 2018, while the NG consumption reached 280.3 BCM [7]. This means that half of China's NG is imported via long-distance pipeline or liquefied natural gas (LNG) transport. As NG consumption is expected to increase (2020–2035), new NG infrastructure is being planned or under construction to deliver NG from domestic and international gas fields to end-users [8]. As NG consumption is expected to peak in 2035 as a result of efforts to control GHG emissions, we must consider how to build NG infrastructure that will aid a low-carbon future in 2035–2050. The role of NG infrastructure is important in energy transitions to a low emissions future as it can deliver twice as much energy as electricity grids, is a major source of flexibility, and has the potential to deliver low-carbon gas produced from renewable. Thus, the short-term investment of NG infrastructure will have major long-term implications [5].

IEA World Energy Outlook [5] have pointed out that over 7% of global gas supply are low-carbon gas in 2040 with a steep upward trajectory as shown in Fig. 1, but the detailed development of low-carbon gas supply and NG infrastructure are missing. Various studies have focused on NG infrastructure development towards a sustainable future, and they have investigated the NG infrastructure development to balance gas demand and supply under various scenarios in Europe, North America, and China. However, they did not investigate the possibility of transporting low-carbon gas in the NG infrastructure. Gillessen et al. [9] discussed the role of NG in energy transition from a fossil-based to a renewable energy system in Germany with focus on the impact of NG infrastructure expansion. With scenario analysis, they found out that the gas demand is decreasing in long-term and the further expansion of NG infrastructure should be assessed carefully considering technically necessary and economic feasibility. They also recommend future study to investigate the possibilities to supply hydrogen in NG infrastructure. Dieckhöner et al. [10] applied a high-resolution European NG infrastructure model to a variety of scenarios to analyze the impact of demand on gas flows and infrastructure in 2019. They found that most of the European NG market is well integrated, with the exception of Germany, Denmark, and Eastern Europe, in which infrastructure expansion is needed to the demand. Charalampos et al. [11] investigated the impact of coordination level of renewable energy between U.S., Canada, and Mexico on NG demands and infrastructure developments. The results shown that the coordination of renewable energy will decrease the usage rate of NG infrastructure and further phase out the NG infrastructure in the long term. However, supplying low-carbon gas is not considered. Feijoo et al. [12] coupled a socioeconomic model with a NG infrastructure investment model to investigate future infrastructure development in the U.S. Their results showed that the existing pipeline infrastructure is insufficient to satisfy the short-term demand, investment is heterogeneous in different parts of the U.S., and there are long-term risks of under-utilizing the pipeline infrastructure. Zhang et al. [8] aimed to optimize NG supply costs and pipeline infrastructure deployment of a simplified gas network in China by considering the pipeline import and LNG import prices, domestic gas production cost, and possible geopolitical influence. Their results indicated that the growth of domestic unconventional gas production will reduce the gas supply cost in North China, while increases in the pipeline and LNG import costs will increase the infrastructure construction cost. Xu [13] built a gas pipeline network model to estimate the sufficiency of pipeline capacity to supply shale gas in China. The simulation results show that the existing and planned pipeline capacity is insufficient to meet the 2020 demand with a maximum transmission capacity of 341 BCM.

The abovementioned the studies have concluded that the existing NG infrastructure is not sufficient to meet the NG demand in short term but the expanded NG infrastructure may be under-utilized in long term due to energy transition. There are engineering studies that have confirmed the techno-economic possibility of utilizing NG infrastructure to supply low-carbon gas. Wang et al. [14] proposed a mixed integer linear programming model for the reformation of NG pipeline network with hydrogen injection and proved its techno-economic feasibility for hydrogen transportation. Liu et al. [15] identified the positive economic benefits of utilizing surplus wind and solar electricity to produce hydrogen and injecting hydrogen into NG pipeline. Wald et al. [16] assessed regional biomethane supplies and possible deviations in gas quality in California. The results showed that the majority of biomethane projects were economically feasible and within interchangeability range. Singlitico et al. [17] integrated life cycle and techno-economic analysis in a spatially-explicit model to optimize the bio-based low-carbon gas supply chain in Ireland. The results showed that large-scale production was the best solution considering environmental impact and economic performance. The production of low-carbon gas normally takes place other than fossil based NG, the influence on NG infrastructure by supplying low-carbon gas is not yet investigated in previous studies. As highlighted by Singlitico et al. [18], there is a need for a hybrid life cycle assessment, which integrates process-based models and spatial-based infrastructure models, to identify the techno-economic performance, environmental impact and infrastructure potential for the low-carbon gas supply chain. Therefore, the knowledge gaps remain on that none of previous studies have considered the possibility of NG infrastructure to supply low-carbon gas produced from renewable energy and its influence on NG infrastructure development in both the short term and the long term. As mentioned earlier the NG infrastructure in China is developing quickly and the NG demand will probably decrease after 2035 [5,6], it is important to consider how to build the NG infrastructure in a sustainable way avoid expensive stranded investments. Thus, China is an extremely relevant case for this question because of the sheer size of the energy markets, the very rapid growth of natural gas use and infrastructure capacity, and the ambitious

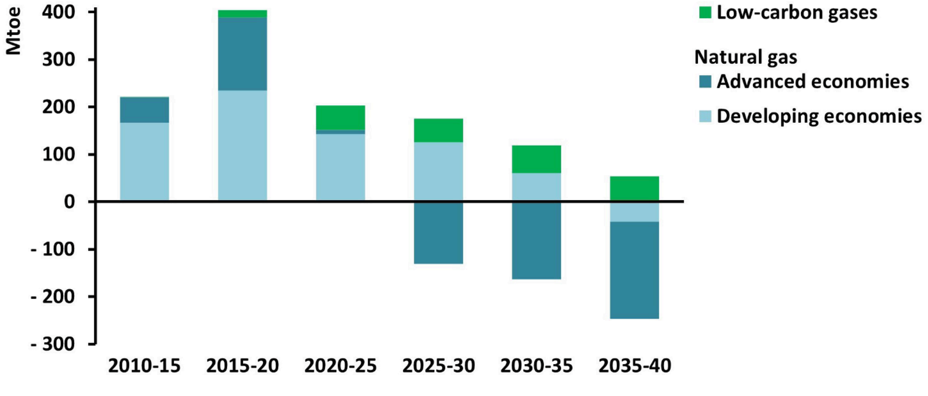


Fig. 1. Changes of global gas demand during 2010–2040 including low-carbon gas. Source: IEA World Energy Outlook [5].

plans to decarbonize the energy system in the coming three decades. In this study, our work aims to fill the knowledge gaps by completing a provincial level analysis on low-carbon gas supply in China, which combined the inputs from energy scenario results for low carbon energy future and a network flow model to represent the future gas infrastructure capturing gas demand and diversified supply.

Herein, four supply chains producing low-carbon gases were considered: biomass through anaerobic digestion and the upgrading process to biomethane; biomass through gasification and methanation processes to bio-synthetic methane (bio-SNG); and two supply chains for power-to-gas (PtG): renewable electricity through electrolysis (power-to-H_2 (PtH)) to hydrogen and a methanation process (power-to-methane (PtM)) to low-carbon synthetic methane (low-carbon SNG). Biomethane, bio-SNG, and low-carbon SNG are three types of low-carbon methane referred to in this study. As the GHG emissions and costs of different supply chains vary in different levels [5], they must be

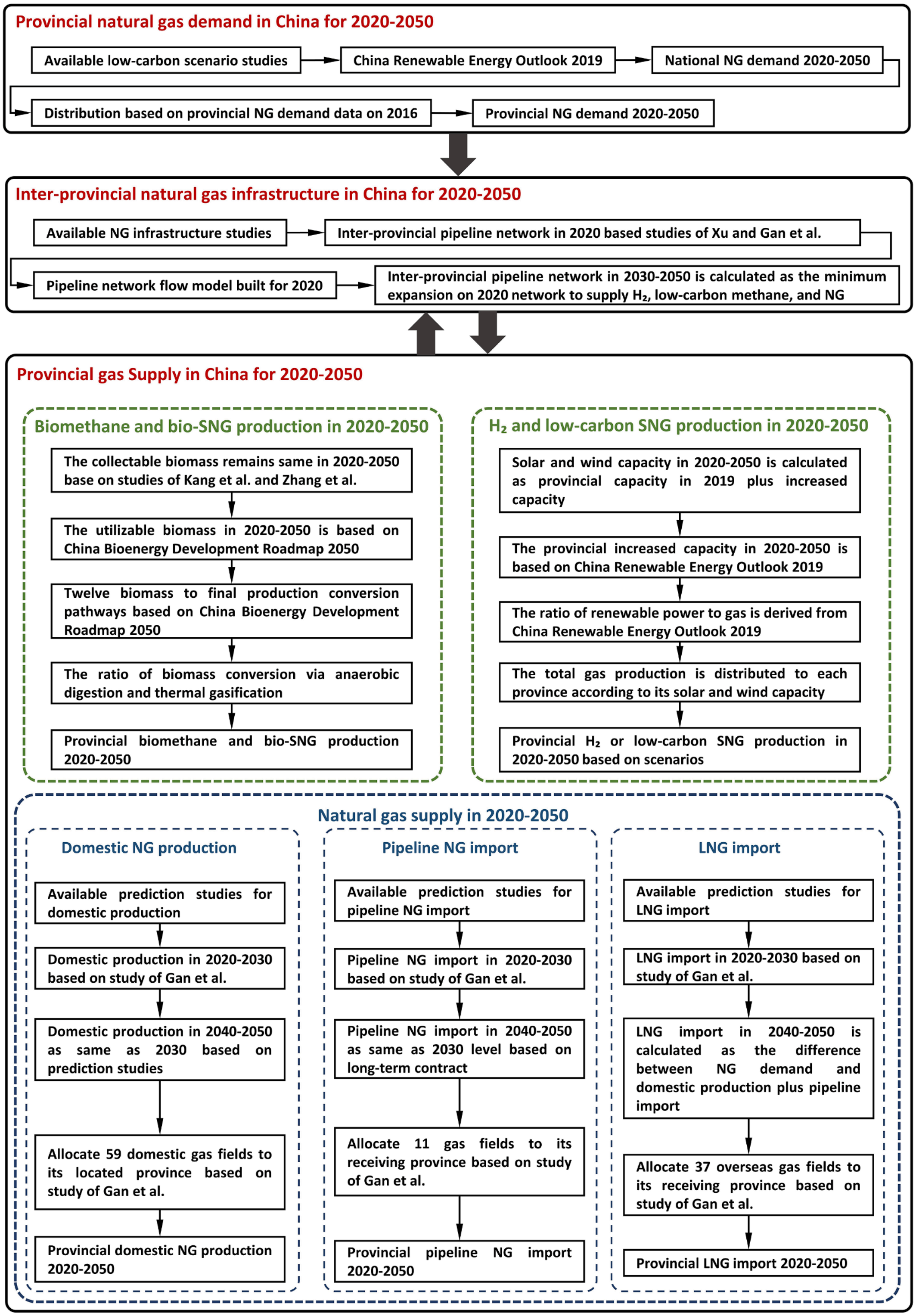


Fig. 2. Input data collection and calculation steps for gas system in China during 2020–2050.

quantified in the context of China. Therefore, this study has the following specific objectives:

- To investigate the potential role of NG infrastructure to supply low-carbon gas for 2020–2050 in China at the provincial level
- To quantify the total production potential of low-carbon gases in China with specific GHG emissions and costs for four supply chains for 2020–2050
- To explore the possibility of NG infrastructure to supply low-carbon gases and quantify the corresponding GHG emissions and costs for 2020–2050 at the provincial level

Herein, the research approach begins by harmonizing the data from scenario studies for NG demand and supply, biomass potential, and solar and wind capacity at the provincial level. Then, we establish low-carbon gas supply chains based on a process-based model, before examining the results regarding GHG emissions and the cost of utilizing the NG infrastructure to supply low-carbon gases with a scenario analysis.

2. Modeling approach, structure, and system boundary

In this study, we collected data from various sources to establish the inputs, as shown in Fig. 2. The model structure and system boundary are illustrated in Fig. 3. The basic concept of approach is to use scenario study-based inputs, network flow models, and engineering-based models to calculate the energy, mass flow, GHG emissions, and costs

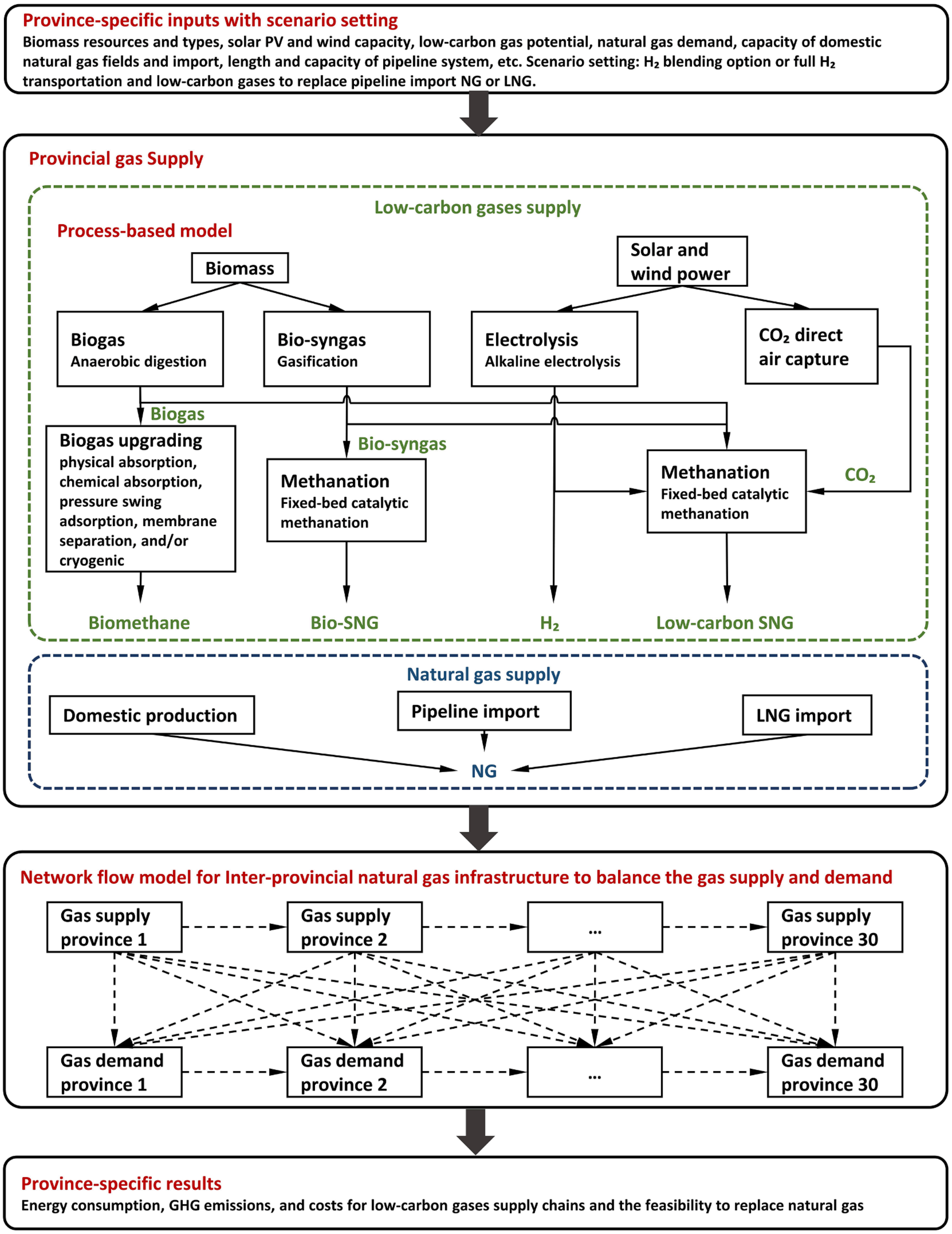


Fig. 3. System boundary and structure of low-carbon gases supply chains and network flow model in China.

for low-carbon gas supply from each province of China. The analysis steps for the inputs are as follows:

1. The national NG demand is derived from the low-carbon future study CREO [6] Below 2 scenarios for 2020–2050. The national NG demand is distributed to the provincial NG demand based on historical data from 2016.
2. The predicted 2020 NG pipeline network was obtained from Xu [13] and supplemented by Gan et al. [19]. The pipeline network in 2030–2050 was based on our simulation as a minimum expansion on the 2020 network to supply NG and low-carbon gases in 2030–2050.
3. Domestic NG production in 2020–2030 was derived from Gan et al. [19], wherein production is the same as 2030 in 2040–2050, as determined using various studies. Overall, 59 domestic gas fields were distributed to their specific provinces to obtain the provincial domestic production data.
4. Pipeline NG import in 2020–2030 were derived from Gan et al. [19], wherein the 2040–2050 value is the same in 2030 as pipeline imports are normally based on long-term contracts. Provincial pipeline import data were obtained by allocating imports from 11 gas fields to their receiving provinces.
5. LNG import data in 2020–2030 were derived from Gan et al. [19], and LNG imports in 2040–2050 were calculated as NG demand minus domestic production and pipeline imports. The provincial LNG import data were obtained by allocating LNG imports from 37 overseas gas fields to their receiving provinces.
6. The provincial biomethane and bio-SNG potential data were derived from Kang et al. [20], Zhang et al. [21], and the China bioenergy development roadmap 2050 (CBDR 2050) [22].
7. The provincial solar and wind capacities and PtG potential were derived from the CREO [6] Below 2 scenarios. The conversion of H_2 to low-carbon SNG was based on scenarios proposed in this study. The detailed methods are presented in the Section 2.4.

With the established inputs, we conducted scenario analyses considering different H_2 transportation options and part replacements of NG by low-carbon gases. We developed a Microsoft-Excel based model to estimate the capacity of the NG infrastructure, GHG emissions, and cost to supply low-carbon gases in China for 2020–2050. The supply and demand balance of the NG infrastructure at the provincial level was estimated using a network flow model based on linear programming [23]. The process-based material and energy flow analysis method was applied to estimate the energy and mass flow of four low-carbon gas supply chains [24]. A life cycle assessment of the GHG emissions for low-carbon gas supply chains followed the International Organization for Standards (ISO) 14040/44 [25,26]. The cost estimation was based on annualized costs and yields [27]. Herein, the developed Microsoft-Excel based model was compiled by integrating the China National Renewable Energy Center's energy system, which models NG consumption, bioenergy development, and solar and wind power development, with studies on low-carbon methane supply chains as well as a simplified network flow model based on linear programming.

2.1. Representative low-carbon energy scenarios for China

To determine the energy transition status of China, we harmonized and compared six scenario studies. These scenarios have wide coverage on the future low-carbon pathway for China, including no policy, current policy, policy targets, below 2 °C, below 1.5 °C, sustainable development, and zero-carbon emission. This coverage represents almost the widest range of possibilities for the future energy system of China and related GHG emissions. Considering the national target is to comply with the Paris agreement, we focus on below 2 °C scenario as the basis for our analysis in this paper. The total primary energy demand and CO_2 emissions per year are shown in Fig. 4. Among these studies, the IEA and CREO scenarios are the most comprehensive, containing detailed data for NG, bioenergy, and solar and wind capacities. The data used for this study were mostly collected from the CREO Below 2 scenario [6], which outlines a pontential pathway for China to fulfill the Paris agreement. The total primary energy demand peaks in 2025 and lowers gradually as energy efficiency increases. Meanwhile, CO_2 emissions peak in 2018 and decline dramatically until 2040 as a result of the replacement of fossil energy (mainly coal) by renewable energy.

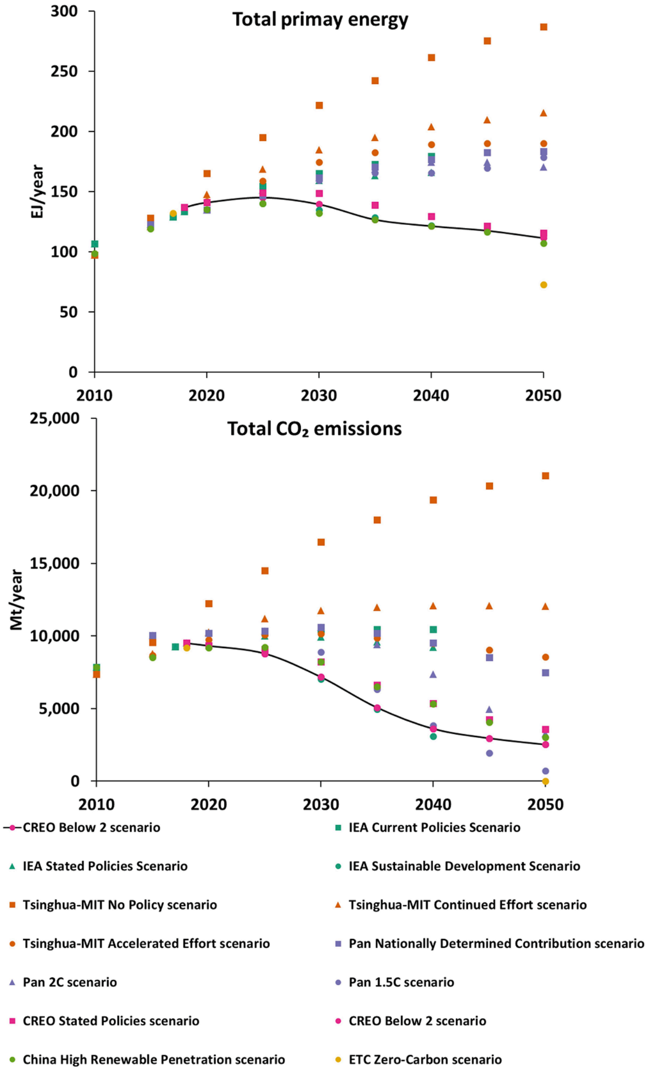


Fig. 4. Total primary energy demand and total CO_2 emissions of China under various scenarios. 1. International Energy Agency (IEA) world energy outlook 2019 [5]; 2. Zhang et al. 2016 (Tsinghua-MIT) [28]; 3. Pan et al. 2020 [29]; 4. China Renewable Energy Outlook (CREO) 2019 [6]; 5. China 2050 high renewable energy penetration scenario [30]; 6. China 2050–a fully developed rich zero-carbon economy (Energy Transitions Commission (ETC)) [31].

2.2. NG demand and supply

Promoting NG consumption in the short- to mid-term (2030) might cause a long-term under-utilization of the expanded NG infrastructure (2050). Thus, if the NG infrastructure is going to expand in the short- to mid-term, what might be sustainable options for the expansion in the long-term? Answering this question will help to establish an environmentally and economically friendly pathway for developing NG infrastructure.

In this study, we choose CREO Below 2 scenario to represent the NG demand in 2020–2050, wherein the gas demand are 388 BCM (2020), 576 BCM (2030), 611 BCM (2040), and 500 BCM (2050). To estimate the gas demand for each province, it was assumed that the provincial share of demand from 2020 to 2050 is the same as that in 2016.

To estimate the domestic production of NG in China, we harmonized and compared six studies, as shown in Fig. 5. To obtain provincial-level data, we derived the data from Gan et al. [19], wherein the production forecast of 59 gas fields in China in 2020 and 2030 were provided. We allocated each gas field to its corresponding province to obtain provincial gas production in 2020 and 2030. According to the CREO Below 2 scenario, China's NG demand will peak in 2030–2035. Therefore, we assumed that domestic production will peak by 2030 and remain at its 2030 yield level in 2030–2050 based on a comparison of the six studies. To estimate the provincial domestic gas production in 2030–2050, we assumed that the provincial share of domestic production in 2030–2050 will be the same as in 2030. A comparison of the former assumption and the six previous studies is shown in Fig. 5.

The pipeline gas import data for 2020 and 2030 were based on data derived from Gan et al. [19]. The import routes are Turkmenistan to Xinjiang, Myanmar to Yunnan, Russia to Xinjiang and Heilongjiang, and Uzbekistan to Xinjiang, and include 11 gas fields. Because pipeline import contracts are normally long term, we assumed that pipeline imports would peak by 2030 and remain at 2030 import levels during 2030–2050. According to Zou et al. 2018 [35] and Ji et al. 2018 [36], the pipeline import capacity in 2020 is 106 BCM. In this study, the pipeline import estimation for 2030 is 156 BCM, which is within the maximum pipeline import capacity of 165 BCM for 2030–2050 [35,36].

The LNG import is the most flexible import option, as its supply capacity and destination can be easily adjusted based on short-term contracts [38]. For 2020–2030, the LNG import volume was based on data derived from Gan et al. [19]. Due to a lack of data, the LNG import volume for 2040–2050 was determined using the difference between gas demand and domestic production plus pipeline imports. The provincial LNG import volume was obtained by allocating LNG imports from 37 overseas gas fields in Qatar, Oman, Russia, Australia, Papua New Guinea, Nigeria, Trinidad Tobago, Indonesia, Norway, Malaysia, and the U.S. The LNG import volume must be lower than the LNG receiving capacity. The LNG receiving capacity of China is 148 BCM and 260 BCM in 2020 and 2030, respectively [39].

2.3. NG infrastructure and network flow model

We established a network flow model based on Zhang et al. [8] and Bazaraa et al. [23] to simulate the gas flow of the gas pipeline infrastructure in China, as shown in Fig. 6. The pipeline data were collected from Xu [13] and Gan et al. [19], and include 196 pipeline segments and 118 transmission stations. The NG infrastructure data for 2020 are illustrated in Fig. 6. To simplify the pipeline network, we aggregated the transmission station located in one province with a single node n_i to which the NG demand, supply, pipelines, and LNG terminal data are assigned. Then, we combined pipelines connected between two provinces to a single arc a_{ij}. The combined pipelines capacities were summarized, and the lengths were calculated as the weighted average value. In total, we obtained 30 nodes and 73 arcs as simplified NG pipeline networks for China. Herein, node n_i is a transmission station, $b_i$is the demand of node n_i (negative value means supply), a_{ij} is the arc (pipeline) from n_i to n_j, x_{ij} is the volume flow in a_{ij}, l_{ij} is the pipeline length of a_{ij}, and u_{ij} is the upper boundary of a_{ij}, which represents pipeline capacity according to data from Xu [13] and Gan et al. [19]. The Simplex linear programming method was used to determine the results.

The NG pipeline infrastructure in 2030 was established as the minimum expansion at the 2020 level to supply peak gas demand in China. Thus, we assumed that the NG pipeline infrastructure in 2030–2050 is the same as that in 2030.

The objective function herein was to minimize the gas transportation in the gas network:

$$Min\left(\sum\left(|x_{ij}| \times l_{ij}\right)\right) \tag{1}$$

Constraints were used to balance the gas demand and supply for each province as follows:

$$\sum_{n_i,in} x_{ij} - \sum_{n_i,out} x_{ij} = b_i, \tag{2}$$

$$b_i = (Consumption - Production - Pipelineimport - LNGimport)_{n_i}, \tag{3}$$

$$\sum b_i = 0, \tag{4}$$

$$-u_{ij} \leq x_{ij} \leq u_{ij}. \tag{5}$$

2.4. Low-carbon gases supply chain model

2.4.1. Biomethane and bio-SNG production in China for 2020–2050

The biomass potential input data are collected from Kang et al. [20] and Zhang et al. [21], which are up-to-date studies focusing on biomass potential in China. The availability for biomethane and bio-SNG production are based on coefficients and proportions derived from CBDR 2050 [22] and China agricultural statistics [40].

The biomass considered in this study included animal manure (AM), crop residues (CR), forest residues (FR), and energy crops (EC). The collectable potential of biomass is defined as the amount of theoretical potential that can be obtained under technical and logistical restrictions. We assumed that the collectable biomass potential of China will remain at the same level in 2016 from 2020 to 2050. The AM, CR, and FR data

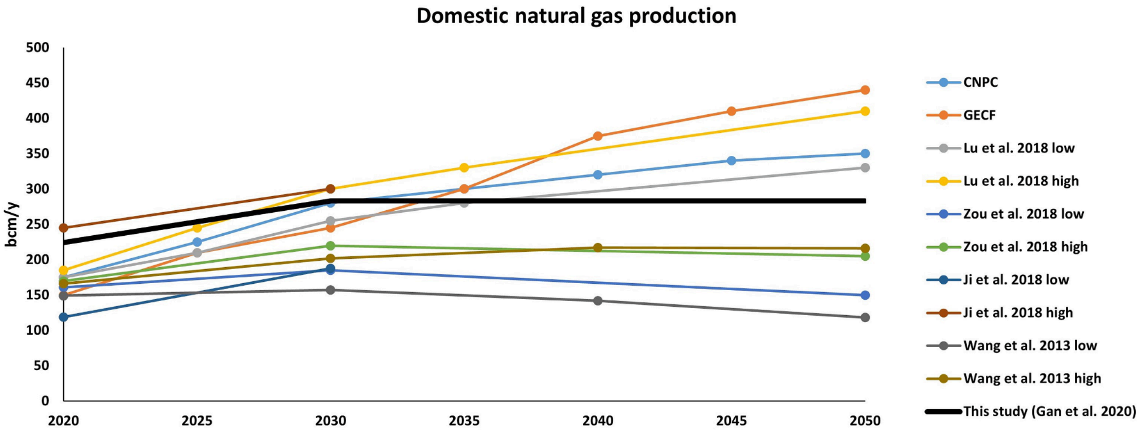


Fig. 5. Domestic natural gas production of China in 2020–2050. 1. China National Petroleum Corporation Economics & Technology Research Institute (CNPC ETRI) [32]; 2. Gas Exporting Countries Forum (GECF) Moghaddam [33]; 3. Lu et al. 2018 [34]; 4. Zou et al. 2018 [35]; 5. Ji et al. 2018 [36]; 6. Wang et al. 2013 [37].

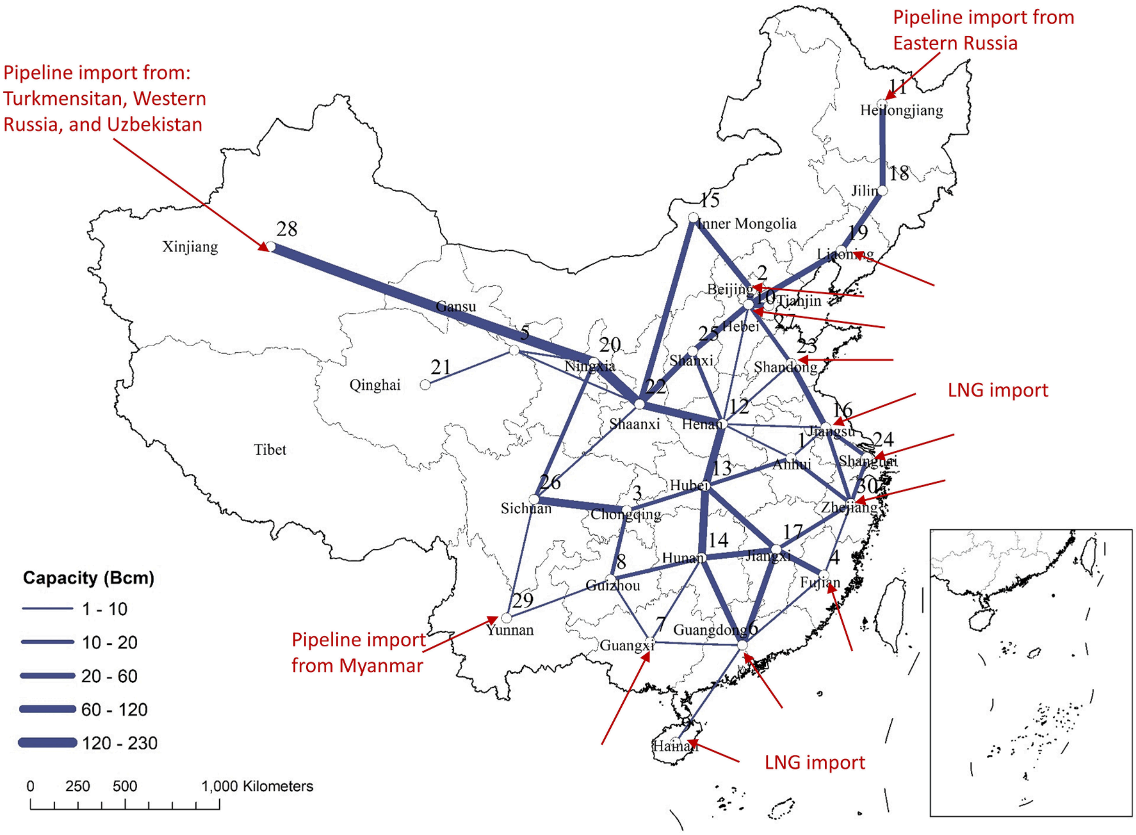


Fig. 6. Natural gas network flow model for China with pipeline capacity in 2020.

for each province were collected from Kang et al. [20], and the EC data were collected from Zhang et al. [21] for each province.

The utilizable potential is defined as the amount of collectable potential used as energy, excluding other competing uses such as fertilizer, livestock feed, and industrial raw material. The CBDR 2050 [22], which is prepared by China National Renewable Energy Center, proposed a target, development roadmap, and steps for China's bioenergy industry. The utilization coefficients for each type of biomass were collected from CBDR 2050 [22], and the calculated utilization potentials are summarized in Table 1.

There are twelve biomass feedstock to final product conversion pathways listed in CBDR 2050 [22]. Herein, we consider the two, both of which produce bio-based low-carbon methane: AM via anaerobic digestion to biomethane, and CR, FR, and EC via gasification to bio-SNG. The exploitative proportions for each type of biomass, total biomethane, and bio-SNG production are summarized in Table 2. The biomass availability to produce biomethane and bio-SNG per province in China during 2020–2050 is shown in Fig. 7.

Table 2
Biomethane and bio-synthetic methane (bio-SNG) exploitative proportion in China for 2020–2050.

	2020	2030	2040	2050
Animal manure (AM)				
Exploitative proportion for anaerobic digestion	1	1	1	1
Total biomass availability (EJ)	2.07	3.64	4.14	4.51
Biomass availability to biomethane (EJ)[a]	1.20	2.11	2.40	2.62
Crop residues (CR), forest residues (FR), and energy crops (EC)				
Exploitative proportion for gasification	0.076	0.108	0.093	0.098
Biomass availability to Bio-SNG (EJ)	0.96	2.11	2.07	2.21

[a] . The total biogas output of large-scale (including super large-scale) biogas plants accounted for 58% of the total biogas produced from agricultural waste during 2014–2017 [40]. Thus, it is assumed that 58% of biogas production is large-scale and suitable for upgrading to biomethane in 2020–2050.

2.4.2. Solar and wind capacities for PtH and PtM in China for 2020–2050

The increases in solar and wind capacities from 2020 to 2050 for each province were calculated based on China renewable energy outlook [6]. We assumed that the utilization hours of solar and wind from 2020 to 2050 would stay at the same levels as those in 2019, due to the almost same geographic distribution of solar and wind capacities during 2020 to 2050 based on CREO [6]. As there is an increasing share of highly

Table 1
China biomass utilization coefficients and potentials.

Biomass type	Utilization coefficients				Utilization potential (EJ)			
	2020	2030	2040	2050	2020	2030	2040	2050
Animal manure (AM)	0.33	0.58	0.66	0.72	2.07	3.64	4.14	4.51
Crop residues (CR)	0.42	0.65	0.74	0.75	4.36	6.75	7.69	7.79
Forest residues (FR)	0.42	0.65	0.74	0.75	2.11	3.27	3.72	3.78
Energy crops (EC)	0.42	0.65	0.74	0.75	12.62	19.53	22.23	22.53
total	–	–	–	–	21.16	33.19	37.78	38.61

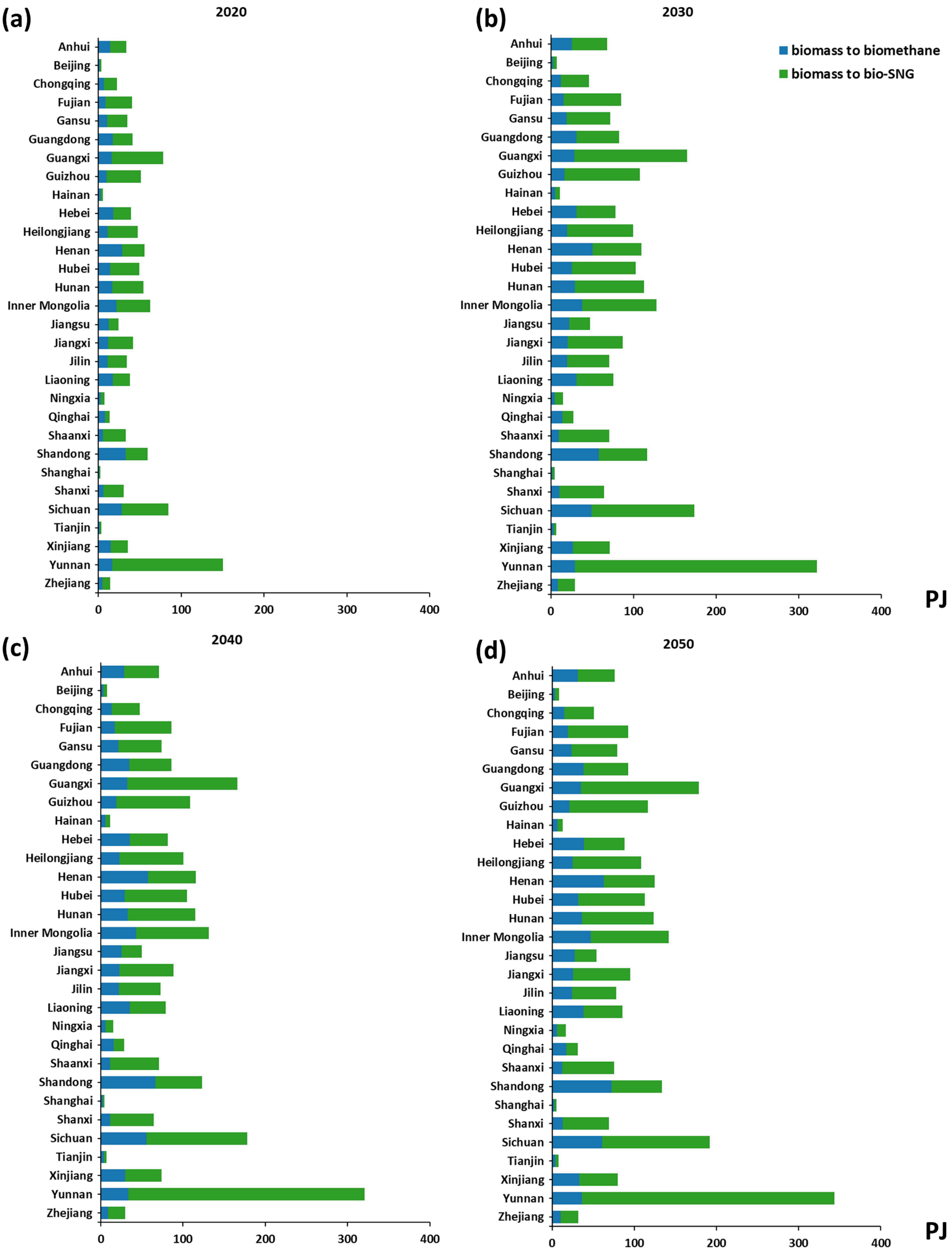


Fig. 7. Biomass availability to produce biomethane and bio-synthetic methane (bio-SNG) per province in China during 2020–2050.

fluctuating power generation from wind and solar, the power system must have flexible sources to balance generation and consumption. One flexible source option is pumped hydro storage, which is a well-developed storage technology. However, its availability is constrained by reservoirs and water resources. The other promising option is to convert excess electricity to hydrogen, which can be possibly further processed to methane, which is a versatile energy agent for decarbonizing all sectors. As the aim of this study is to investigate the role of NG infrastructure in the future, we focused on hydrogen and low-carbon SNG as the flexible sources for wind and solar power systems. The total potentials of H_2 and low-carbon SNG produced from solar and wind renewable electricity were derived from the output of an integrated energy system model of CREO [6] Below 2 scenarios, which considers various flexible sources, including vehicle to grid, load shifting, battery energy storage, pumped hydro storage, thermal power plants, and hydrogen production. The proportion of PtG electricity consumption to total solar and wind capacity during 2020 to 2050 are 1.0% (2020), 9.2% (2030), 11.4% (2040), and 11.6% (2050). The provincial PtG electricity consumption was obtained by distributing the total amount to provincial wind and solar capacities, as shown in Fig. 8.

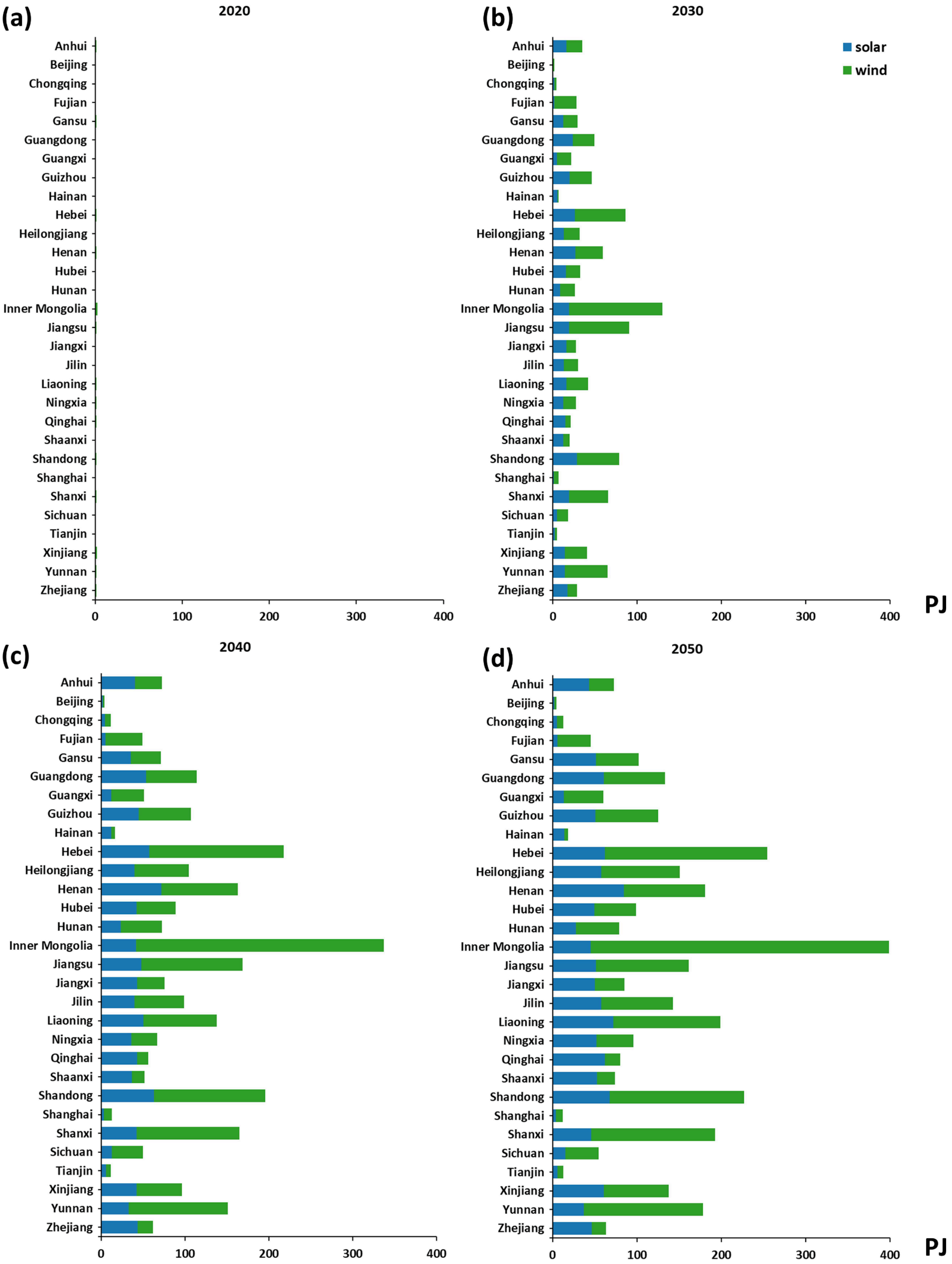


Fig. 8. Electricity consumption for PtG production in China during 2020–2050.

2.4.3. Supply chains of low-carbon gas

The low-carbon gas supply chains considered in this study include biomethane (anaerobic digestion and upgrading), bio-SNG (gasification and methanation), hydrogen (PtH), and low-carbon SNG (PtM) [41] ("process-based model" in Fig. 3). The biomethane supply chain includes biomass pretreatment, anaerobic digestion, biogas cleaning and upgrading, compression, transmission, and combustion by end-users. The bio-SNG supply chain includes pretreatment of biomass, gasification, gas cooling and particulate removal, gas cleaning, methanation, H_2O and CO_2 removal, compression, transportation, and combustion by end-users. The hydrogen supply chain includes electrolysis, compression, hydrogen blending into NG pipeline or transported by dedicated hydrogen pipeline, and combustion by end-users. The Low-carbon SNG supply chain includes electrolysis, methanation, compression, transportation, and combustion by end-users.

The CO_2 required for the methanation of low-carbon SNG comes from biomass (section 2.4.1) and is supplemented by air capture. The technical, economic, and emission data for low-carbon gas supply chains are derived from a synthesis of literature and practical information. As biomethane production is a mature technology [42], biomethane supply chain is mainly based on practical large-scale production data from Wang et al. [43] and Qyyum et al. [44]. As bio-SNG and low-carbon SNG production are less mature technologies and not commercially available, we used high quality engineering studies, which assume that they are mature and deployed at full scale, to project the techno-economic performance of those technologies. For bio-SNG production [42], the potential large-scale production data are based on Ardolino & Arena [45] and Batidzirai et al. 2019 [46]. For hydrogen and low-carbon SNG production, the median of predicted production data during 2020 to 2050 are based on Liu et al. [15] and Blanco et al. [47]. The main technical, economic, and emission data used for the low-carbon gas supply chains are summarized in Table 3 and the detailed data for each supply chain is provided in the Supplementary Material.

The energy efficiency η (%) per process was calculated as energy input E_{in} (MJ) divided the energy output energy output E_{out} (MJ) [60], as detailed in Eq. (6). The energy input E_{in} (MJ) is the process fuel consumption PF_i (MJ) plus the energy output in Eq. (7). The variable i is the type of process fuel used in this study including NG, diesel, and electricity. The GHG emissions of the process involved in the low-carbon gas supply chains were calculated based on Eq. (8). The GHG emission factors EF_u and EF_c (g CO_2-eq/MJ) refer to the upstream and combustion emissions for certain types of process fuel, respectively. GHG_v and GHG_f (g CO_2-eq/MJ) refer to venting and fugitive emissions for the process, respectively. The production cost C_p ($/MJ) was calculated based on Eq. (9) [61]. The biogenic CO_2 emissions were not considered as GHG emissions in this study, and we assumed that the carbon is entirely re-emitted in the environment based on Collet et al. [49]. The CO_2 source from biomass enables the integration of electrolysis plants with AD biogas plants and gasification plants to increase methane production [49]. The additional GHG emissions and costs (other than biomethane and bio-SNG) were allocated to low-carbon SNG supply chain. C_{ac} ($/year) refers to annualized capital cost, which was calculated using Eq. (10) with discount rate r and plant life n. C_{TCR} ($) refers to the total capital requirement [58]. C_{PF}($/year), $C_{O\&M}$ ($/year), and Y (MJ/year) are the annual costs of process fuel, operation and maintenance (O&M), and annual yield, respectively.

Table 3
Main techno-economic data for low-carbon gases supply chain.

Main data	Unit	Value	Reference
Efficiency of biomethane production (electricity from grid)	–	28.54%	[43,44,48,49,50,51]
Efficiency of bio-SNG production (electricity from grid)	–	53.48%	[41,45,46,52,53,54]
Efficiency of hydrogen production (electricity from renewable)	–	73.53%	[15,47,49,55,56]
Efficiency of hydrogen methanation (electricity from renewable)	–	80.86%	[45,47,49]
Emission factor for electricity from grid	g CO_2-e/MJ	206.8	[57]
Discount rate	–	10%	[58]
Electricity price for industry	$/MJ	0.0364	[59]

$$\eta = \frac{E_{in}}{E_{out}} \times 100\%, \tag{6}$$

$$E_{in} = \sum PF_i + E_{out}, \tag{7}$$

$$GHG = \sum PF_i \times (EF_u + EF_c)_i + \mathrm{GHG}_v + GHG_f, \tag{8}$$

$$C_p = \frac{C_{ac} + C_{PF} + C_F + C_{O\&M}}{Y}, \tag{9}$$

$$C_{ac} = C_{TCR}{}^{*}\left(\frac{r^{*}(1+r)^n}{(1+r)^n - 1}\right) \tag{10}$$

The avoided GHG emissions GHG_a (g CO_2-eq/MJ) and GHG emissions avoidance cost C_a($/t CO_2-e) were calculated because low-carbon gases replace NG (Eqs. (11) and (12)). The subscription rc refers to the NG reference case. The average pipeline imported gas and LNG imports well-to-gate cost were estimated based on Wang and Zhu [62], O'Sullivan [63] by imported amount per country [19], which were 0.011 $/MJ and 0.016 $/MJ, respectively. The average GHG emissions of pipeline imported gas and LNG imports were estimated based on Gan et al. [19]. The well-to-gate GHG emissions of pipeline import, LNG import, and combustion GHG emissions are 35.92 g CO_2-eq/MJ, 19.73 g CO_2-eq/MJ, and 51.26 g CO_2-eq/MJ, respectively.

$$GHG_a = (GHG - GHG_{rc}), \tag{11}$$

$$C_a = \frac{C_p - C_{p,rc}}{GHG - GHG_{rc}} \times 1,000,000. \tag{12}$$

2.5. Potential of gas supply in China during 2020–2050

The total gas demand in China, domestic NG production, pipeline NG import, LNG import, and low-carbon gas production in 2020–2050 are shown in Fig. 9. The provincial breakdown is provided in the Supplementary Material. The potential of PtH (H_2) and PtM (low-carbon SNG) are shown in Fig. 9 (a) and (b), respectively. It can be seen that there is sufficient gas supply during 2020–2050 to meet the gas demand in China. However, the low-carbon gas supply is not sufficient to replace all imported NG, but it can replace all the imported LNG and half of the imported pipeline NG in 2050.

2.6. Scenario proposal

As the gas market in China is developing rapidly and has various possible outcomes, we proposed 7 scenarios to balance the gas demand and supply in China during 2020–2050. To establish a scenario analysis, several parameters remained unchanged for each scenario, including the total gas demand of China and the transportation routes between provinces. The total gas demand of China during 2020–2050 for the different scenarios remain the same based on CREO Below 2 scenario. The gas transportation routes between provinces remain the same with possibility for expansion as assumed in Section 2.3. The base case scenario was set such that all the gas demand was met with NG. NG was supplied first by domestic production, then pipeline imports, and lastly LNG imports. The high proportion of NG import dependence in China increases the energy security risk of the NG supply [35,37]. Therefore, the proposed scenarios, with the exception of the base case, use the domestic production of low-carbon gases to replace pipeline imported NG and imported LNG. By replacing the imported NG with domestically

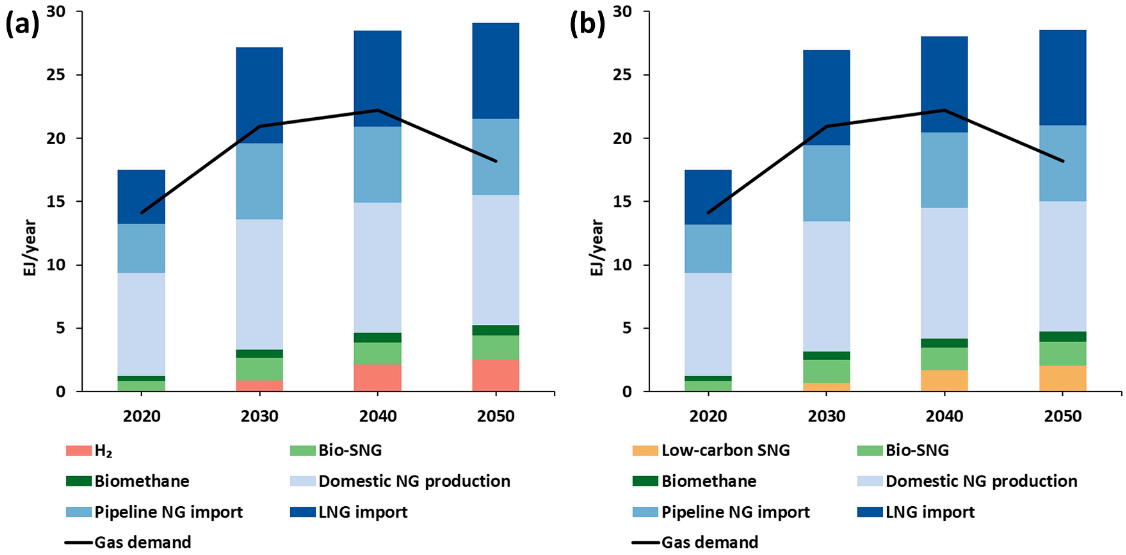


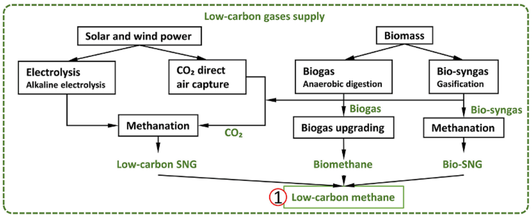
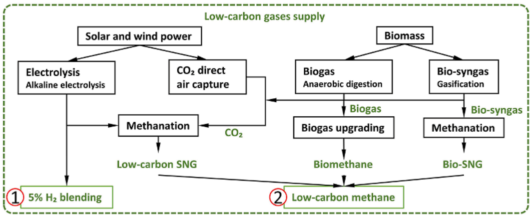
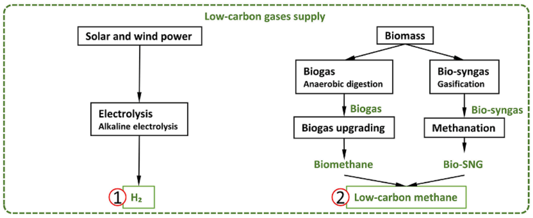
Fig. 9. Gas demand and supply in China during 2020–2050.

produced low-carbon gases, both GHG emissions and the security risk of China's gas supply are reduced. Therefore, the primary gas supply orders are: low-carbon gas, domestic NG, and international NG import. The scenarios considered with their detailed gas supply orders are listed in Table 4. In scenarios 1 and 2 (S1 and S2), all the hydrogen produced from solar and wind is converted to low-carbon SNG. Meanwhile, in scenarios 3 and 4 (S3 and S4), hydrogen is blended into the NG infrastructure by 5%, while the rest of the hydrogen is converted to low-carbon SNG. Finally, in scenarios 5 and 6 (S5 and S6), the hydrogen produced from solar and wind is supplied by a dedicated newly built hydrogen pipeline. As the hydrogen produced cannot meet the provincial gas demand, a dedicated hydrogen pipeline is built inside a province to supply hydrogen within the province. The NG pipeline infrastructure in 2030–2050 expands once from 2020 level as the minimum expansion to supply peak gas demand in China for the base case and each scenario.

3. GHG emissions, cost, and provincial potential of low-carbon gas supply

As shown in Fig. 10, the life-cycle GHG emissions of low-carbon gas supply chains include gas production, upgrading/methanation, and transportation (combustion in the end-user is carbon neutral). The transportation GHG emissions were constant for all the low-carbon methane supply chains as they all utilize the same NG infrastructure

Table 4
Proposed scenarios to balance the gas demand (derived from China Renewable Energy Outlook 2019 below 2 scenario) and supply.

Base Case	Natural gas supply: ① Domestic production ② Pipeline import ③ LNG import	
Scenario 1		Natural gas supply: ② Domestic production ③ LNG import ④ Pipeline import
Scenario 2		Natural gas supply: ② Domestic production ③ Pipeline import ④ LNG import
Scenario 3		Natural gas supply: ③ Domestic production ④ LNG import ⑤ Pipeline import
Scenario 4		Natural gas supply: ③ Domestic production ④ Pipeline import ⑤ LNG import
Scenario 5		Natural gas supply: ③ Domestic production ④ LNG import ⑤ Pipeline import
Scenario 6		Natural gas supply: ③ Domestic production ④ Pipeline import ⑤ LNG import

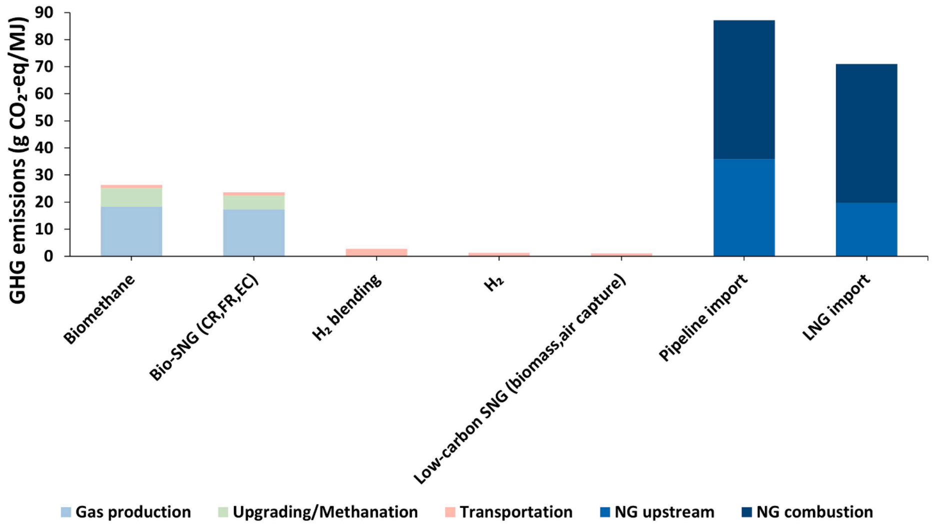


Fig. 10. Life cycle GHG emissions of low-carbon gas supply chains compared with pipeline and LNG imports in China (transportation for 1000 km).

for transportation. The biomethane supply chain had a higher GHG emissions value than the bio-SNG supply chain because of its low energy efficiency, as compared with the bio-SNG supply chain. H_2 blending had higher GHG emissions than H_2 due to the higher efficiency of electric motors used in hydrogen pipeline transportation. The low-carbon SNG (biomass, air capture) had the lowest GHG emissions among the low-carbon methane supply chains because electrolysis, methanation, and its CO_2 source are carbon neutral. Low-carbon SNG had comparable GHG emissions with those of H_2 as its emissions were only from pipeline transportation. The production costs of low-carbon gas supply chains, which include the costs of feed, gas production, upgrading/methanation, and transportation, are shown in Fig. 11. The transportation cost remained the same for low-carbon methane supply. The transportation costs for H_2 blending and H_2 were much higher than that of low-carbon methane because of the low energy content of H_2 and the high cost of the dedicated H_2 pipeline. The biomethane supply chain had the lowest production cost because of the zero cost of AM and the low-costs of the AD and upgrading processes. The production cost of the bio-SNG supply chain varied according to the cost of feed (CR, FR, and EC). The production costs of H_2 blending and H2 were comparable, with the exception of transportation cost. The production cost of low-carbon SNG with air capture was the highest because of the high cost of CO_2 capture from air.

Fig. 12 depicts the avoided GHG emissions and the GHG emissions avoidance cost of the low-carbon gas supply chains by replacing pipeline imported NG (a) and imported LNG (b). The biomethane supply chain had the lowest avoided GHG emissions and avoidance cost. The avoidance cost of biomethane replacing LNG reached negative value because the production cost of biomethane is lower than the well-to-gate cost of LNG. The variation in avoidance cost among the bio-SNG (CR, FR, and EC) supply chains was caused by the different feed costs of CR, FR, and EC. The low-carbon SNG (biomass and air capture) had the highest avoided GHG emissions and avoidance costs. Meanwhile, H_2 blending and H_2 had comparable GHG avoidance costs with bio-SNG (FR), but much higher avoided GHG emissions for both replacing pipeline and LNG imports. By comparing (a) and (b) in Fig. 12, it is clear that for biomethane, bio-SNG (CR, FR, and EC), H_2 blending, and H_2, replacing pipeline imported NG with low-carbon methane will achieve higher avoided GHG emissions with higher avoidance costs compared with replacing imported LNG. However, for low-carbon SNG (biomass and air capture), replacing pipeline imported NG will achieve higher avoided GHG emissions with lower avoidance costs than replacing imported LNG.

The low-carbon gases and NG consumption distribution for each province in China from 2020 to 2050, with two supply strategies for converting solar and wind electricity to low-carbon SNG and hydrogen,

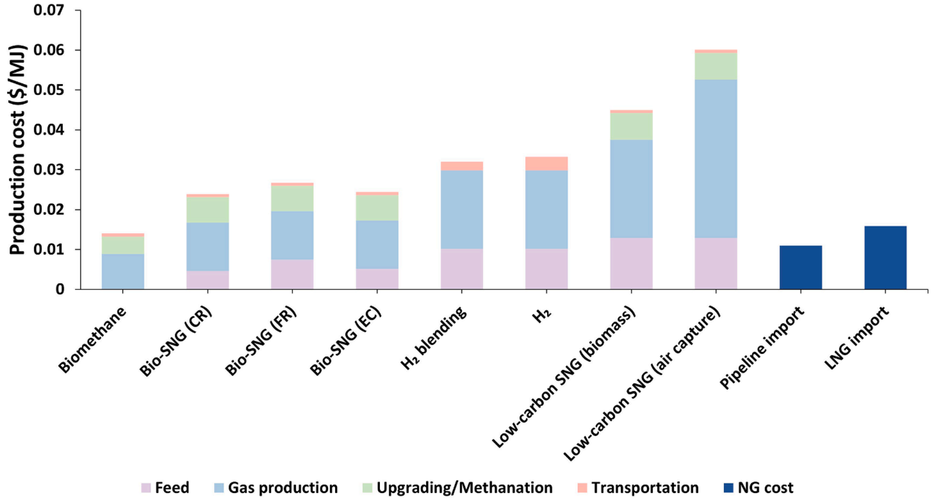


Fig. 11. Production costs of low-carbon gas supply chains compared with pipeline and LNG imports in China (transportation for 1000 km).

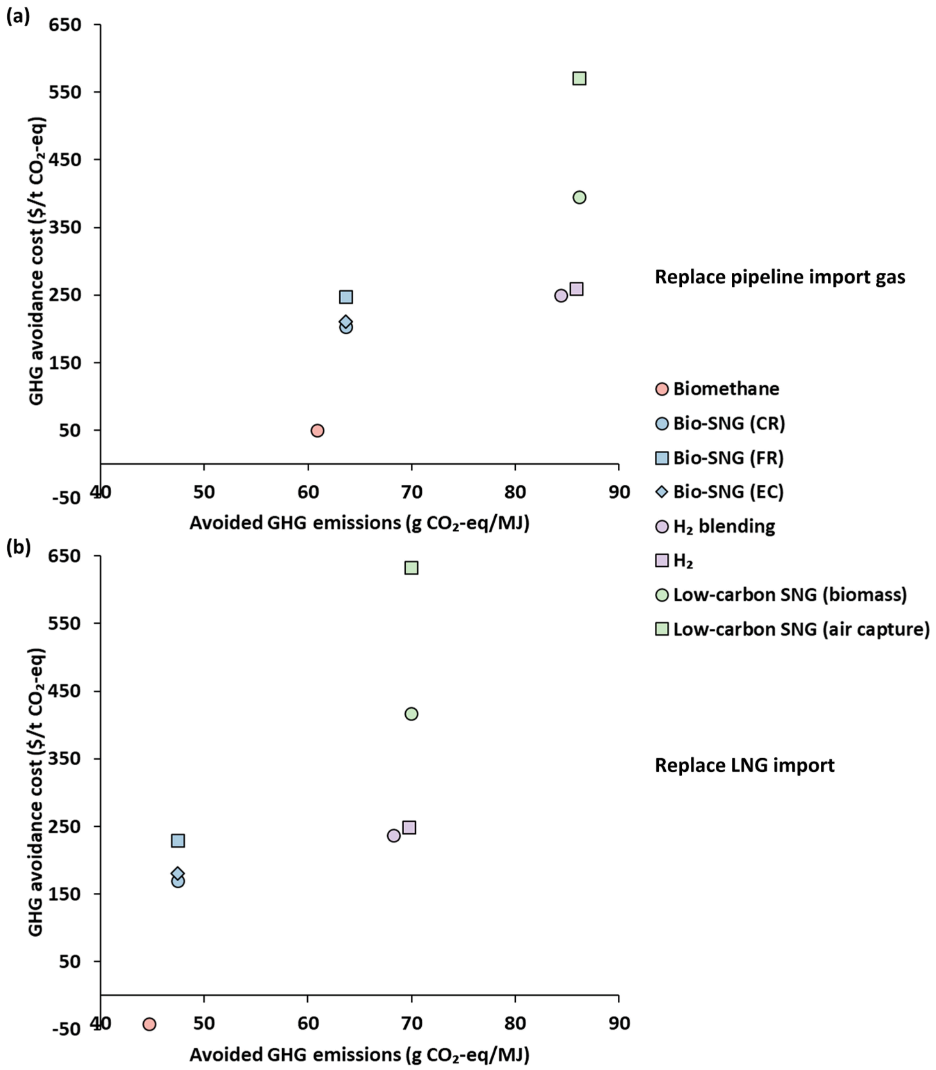


Fig. 12. Avoided GHG emissions and GHG emissions avoidance costs of low-carbon gas supply chains in China (based on pipeline gas import price of 0.011 $/MJ and LNG import price of 0.016 $/MJ).

are shown in Fig. 13 and Fig. 14, respectively. The total amount of low-carbon gas production increased significantly during 2020–2050, wherein the total amount of biomethane, bio-SNG, and low-carbon SNG was 1212 PJ, 3229 PJ, 4346 PJ, and 4887 PJ for 2020, 2030, 2040, and 2050, respectively. The total amount of biomethane, bio-SNG, and hydrogen was 1213 PJ, 3331 PJ, 4638 PJ, and 5249 PJ for 2020, 2030, 2040, and 2050, respectively. Because of the energy loss in the conversion from hydrogen to low-carbon SNG, the total amount of hydrogen potential was higher than that of low-carbon SNG. Moreover, the period 2020–2030 had the most significant low-carbon gas production increase.

As shown in Fig. 13, biomethane, bio-SNG, and low-carbon SNG are injected into the NG pipelines as a mixture for transport. Meanwhile, as shown in Fig. 14, hydrogen is first supplied in the production province, then the biomethane and bio-SNG mixture. In 2020, biomethane and bio-SNG production were comparable for most provinces. Ningxia is the only province with a relatively high proportion of low-carbon SNG and hydrogen, which is approximately 12%. Yunnan is the only province that exceeds 100 PJ of low-carbon gas production and exports low-carbon gas. In 2030, bio-SNG, low-carbon SNG, or hydrogen production surged in most provinces. Biomethane production also increased, but at a lower rate than that of bio-SNG, low-carbon SNG, or hydrogen. The low-carbon gas production of Inner Mongolia and Yunnan province exceeded 200 PJ and 300 PJ, respectively. Further, Yunnan and Guangxi provinces exported the low-carbon gas. In 2040, low-carbon SNG or hydrogen surged again, dominating in several provinces. In 2040–2050, the increasing rate of low-carbon gas production was only 1.2% per year, which means the implementation of low-carbon gas production in China was most accomplished in 2040. During this period, Yunnan, Guangxi, Guizhou, and Inner Mongolia provinces exported the low-carbon gas. Total gas consumption increased from 2020 to 2040, and then declined from 2040 to 2050. Yunnan is the only province that exported hydrogen, and its gas demand can be met by hydrogen in 2040–2050. In 2020, NG consumption was dominated in most provinces, with the exception of Yunnan, Guizhou, and Guangxi. Except for Yunnan, the low-carbon gas produced was consumed within the production province. In 2030, the proportion of low-carbon gas consumption increased significantly in most provinces. The gas demand of Yunnan and Guangxi provinces can be met by low-carbon gases. In 2040, the proportion of low-carbon gas consumption continues to increase, and the gas demand of three south-west provinces (Yunnan, Guangxi, and Guizhou) can be met by low-carbon gases. In 2050, low-carbon gas consumption was dominant in 10 provinces because of the increase in low-carbon gas production, export of low-carbon gas, and decrease of gas demand. Yunnan is the only province in which the gas demand can be met by low-carbon gases in 2020–2050, and by pure hydrogen in 2040 and 2050.

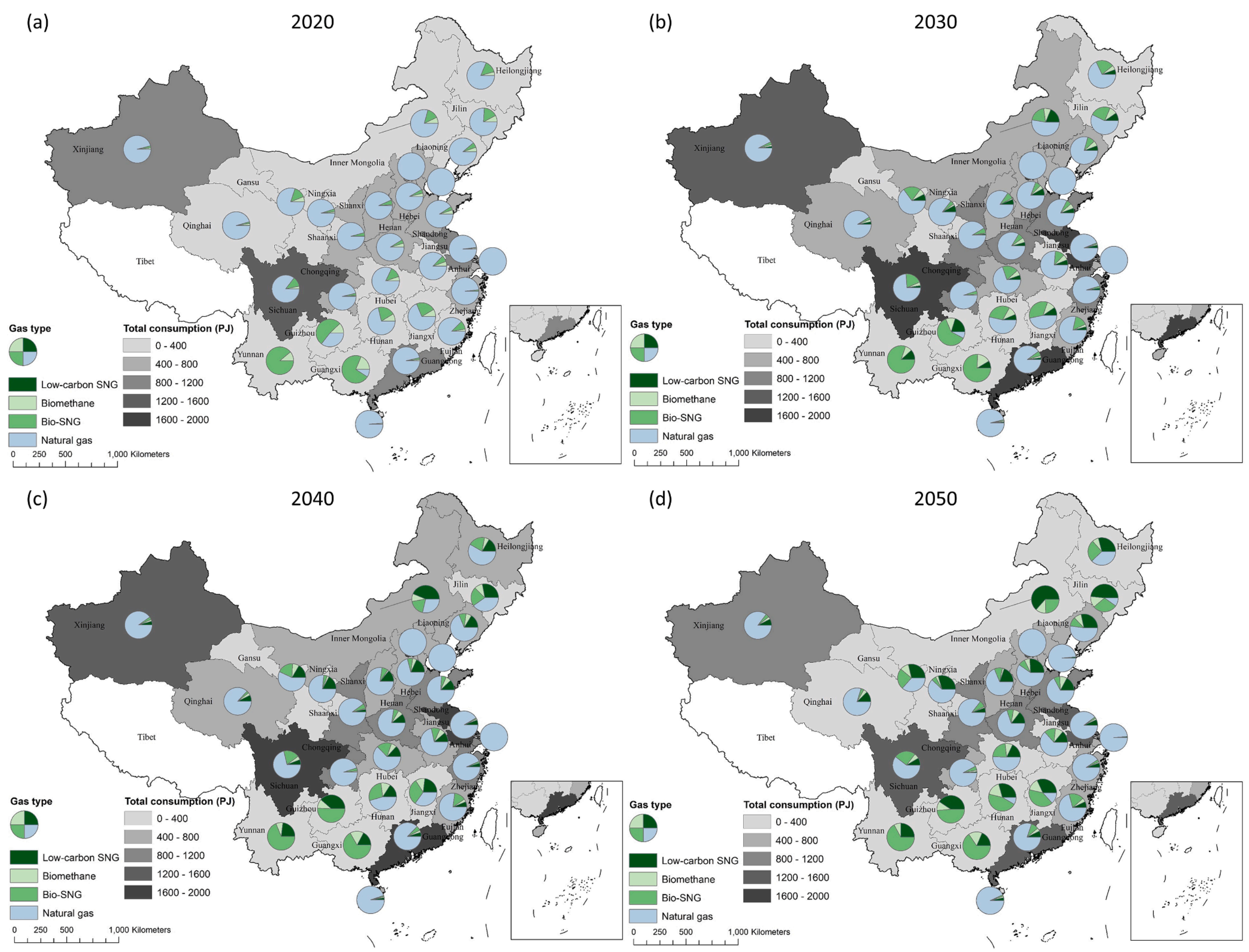


Fig. 13. Low-carbon SNG, biomethane, bio-SNG, and NG consumption for each province in China for 2020–2050.

4. Spatial-temporal variation of NG infrastructure and GHG avoidance potentials

The results of the gas transportation infrastructure with spatial distribution are shown in Fig. 15. In 2020, all the proposed scenarios are able to utilize the existing infrastructure capacity (Fig. 15 (a)) to supply gas to meet provincial gas demands. From 2030 to 2050, the NG infrastructure expanded at 2030 to supply peak gas demand in China for each scenario. The expansions for the base case and 6 scenarios are shown in Fig. 15 (b)–(h). The expanded capacities of the base case and six scenarios are 31%, 19%, 41%, 20%, 48%, 18%, and 41% greater than the 2020 level, respectively. The comparisons of S1 vs. S2, S3 vs. S4, and S5 vs. S6 show that replacing pipeline import gas with domestically produced low-carbon gas will reduce the need for gas transportation infrastructure expansion, whereas replacing imported LNG will increase the need for gas transportation infrastructure, especially in the southeastern coast provinces. By replacing the imported LNG with low-carbon gases in S2, S4, and S6, the gas infrastructures, especially in the NG production provinces of Shaanxi, Sichuan, and Chongqing to Guizhou, Guangxi, and Guangdong, expanded 120% to 138% compared with those of S1, S3, and S5, respectively. The H_2 blending option in S3 and S4 increased the need for pipeline capacity, as compared with S1 and S2 because of the low volumetric energy content of H_2. As there is a higher total energy amount of H_2 in S5 and S6 compared with the low-carbon SNG in S1 and S2, the expansion capacities for S5 and S6 were lower than those in S1 and S2, respectively. Note that S5 had the lowest expansion capacity.

The pipeline utilization rate of S5 is shown in Fig. 16 as a representative for the other scenario studies as its expanded pipeline capacity during 2030–2050 is the lowest among the 6 scenarios. The utilization rates for the other scenarios are provided in the Supplementary Material. As shown in Fig. 16(a), several pipelines in central China already exceed 90% of utilization rate. Therefore, an expansion of the pipeline network for 2030–2050 was necessary to meet the increasing gas demand. In 2030, the overall pipeline utilization rate increased especially around Beijing and Guangdong. Although the gas demand increased from 2030 to 2040, the overall pipeline utilization rate remained almost constant. This is because low-carbon gas production surged during 2030–2040 and most of the produced low-carbon gases were consumed locally without entering the pipeline network. During 2040–2050, the overall utilization rate of the pipeline network decreased as the gas demand dropped and low-carbon gas production continued increasing. Note that the pipeline utilization rate for coast provinces (Guangdong, Fujian, and Zhejiang) increased from 2040 to 2050 because LNG imports declined from 2040 to 2050 as they were replaced by domestic NG and low-carbon gas production. Thus, using low-carbon gases to replace pipeline NG imports will cause pipeline under-utilization in Xinjiang and Heilongjiang, where most of the pipeline NG imports come from.

The avoided GHG emissions and associated avoidance costs with the contribution of each low-carbon gas in China from 2020 to 2050 for all 6 scenarios are illustrated in Fig. 17. The total GHG avoidance costs and total avoided GHG emissions of the scenarios replacing pipeline imported NG (S1, S3, and S5) were higher than those of the scenarios replacing imported LNG (S2, S4, and S6). This is because the imported

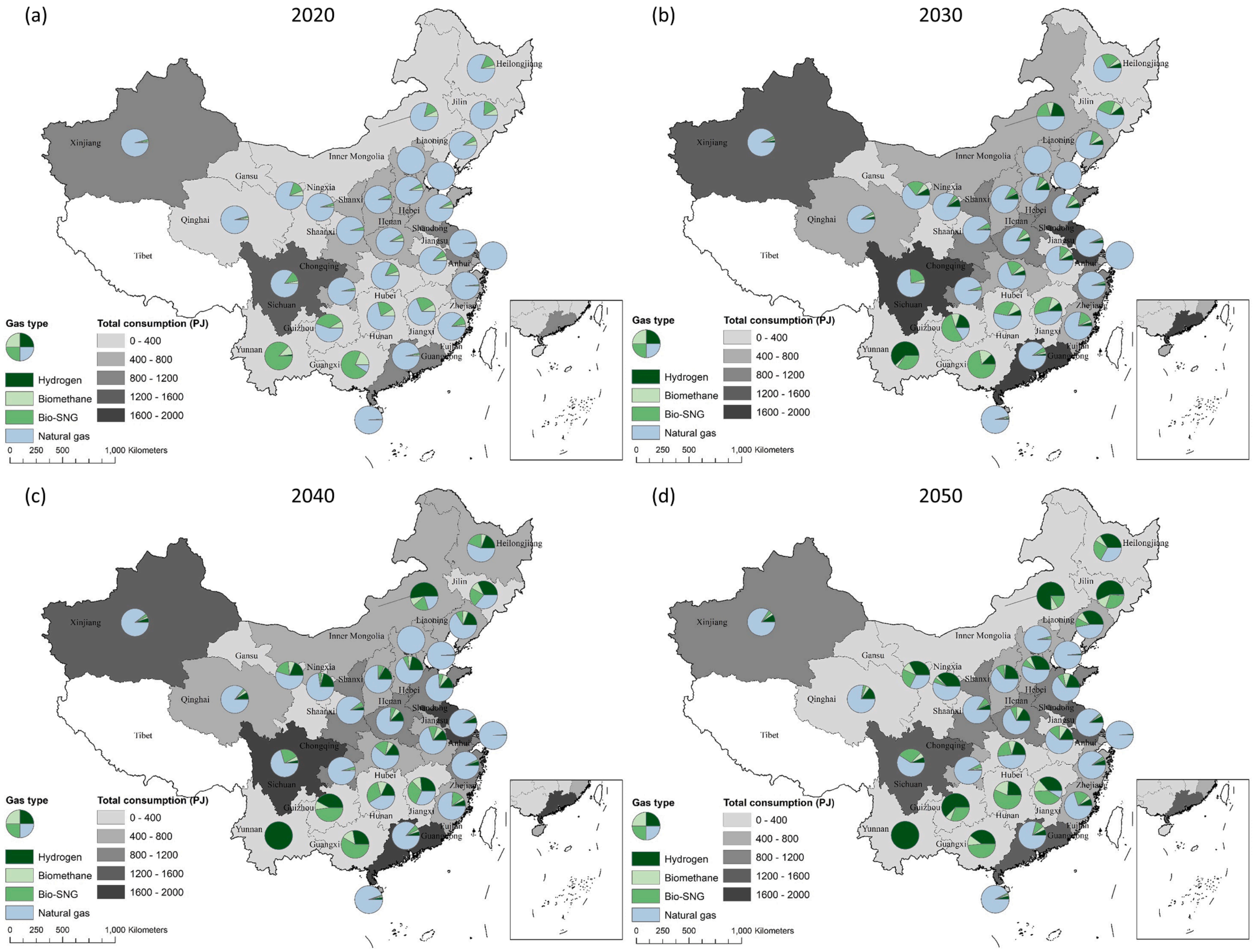
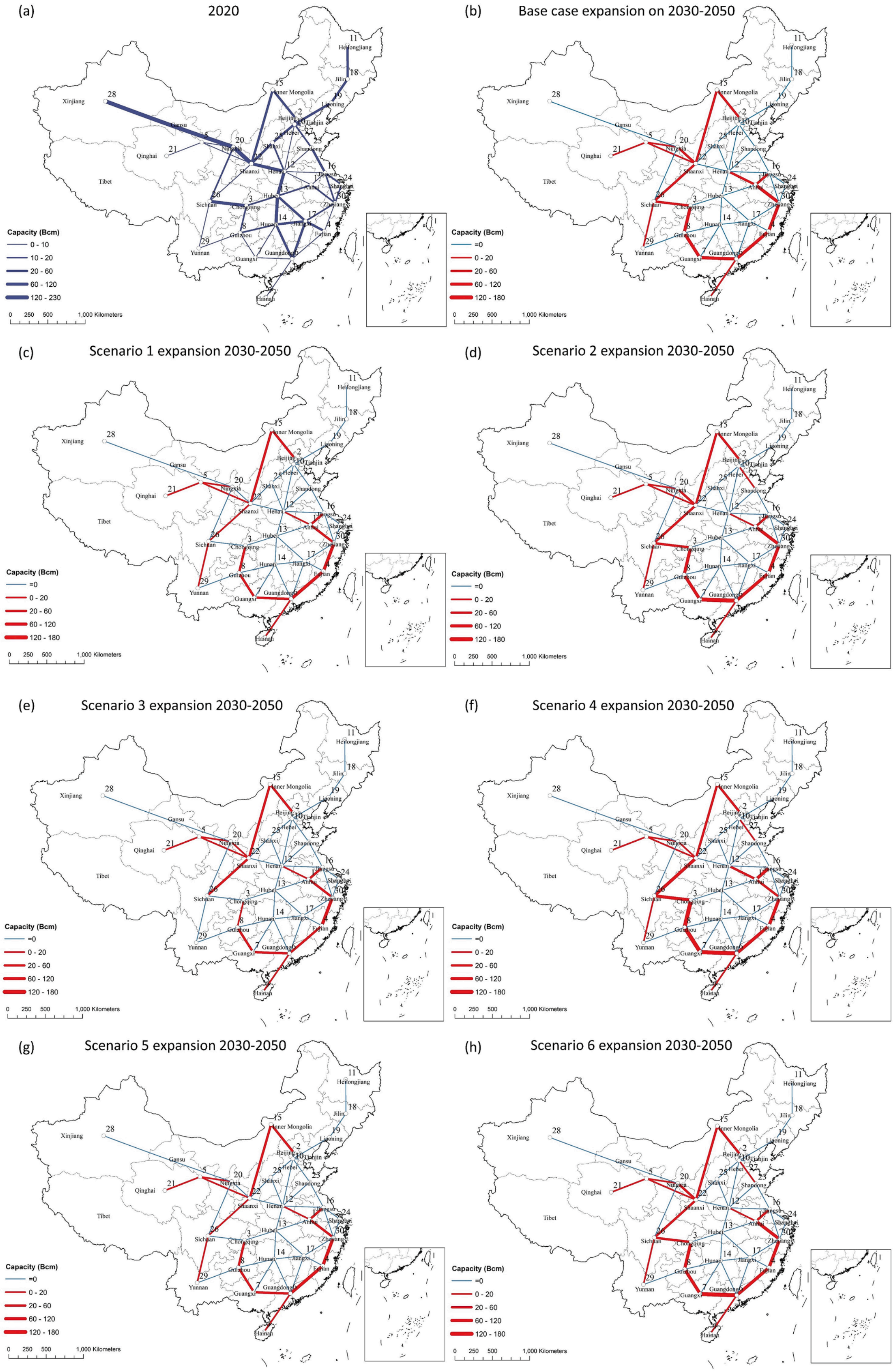


Fig. 14. Hydrogen, biomethane, bio-SNG, and NG consumption for each province in China for 2020–2050.

LNG has a higher well-to-gate cost and lower life-cycle GHG emissions compared with pipeline imported NG. As shown in Fig. 17(a), bio-SNG accounted for 41%–68% of the total avoided GHG emissions for all 6 scenarios in 2020 and 2030, whereas the H_2 and/or low-carbon SNG accounted for 47%–57% in 2040 and 2050. S5 and S6 had the highest avoided GHG emissions among the scenarios that replaced pipeline imported NG and those replacing imported LNG, respectively. In 2030, the CO_2 from biomass was not sufficient for low-carbon SNG production and the remaining required CO_2 comes was collected via air capture. In 2030, 2040, and 2050, 2%, 16%, and 20% of the low-carbon SNG were low-carbon SNG (air capture), respectively. As illustrated in Fig. 17(b), bio-SNG accounted for 7–11 billion dollars (B$) of the GHG emissions avoidance cost for the 6 scenarios in 2020. In 2030, bio-SNG still had the highest GHG emissions avoidance cost for S5 and S6, whereas H_2 and/or low-carbon SNG were the highest for S1, S2, S3, and S4. In 2040 and 2050, the H_2 and/or low-carbon SNG accounted for 32–88B$ of GHG emissions avoidance cost for all 6 scenarios. From 2040 to 2050, 22% and 27% of the avoidance costs of low-carbon SNG are from low-carbon SNG (air capture), respectively. S5 and S6 had the lowest avoided GHG emissions among the scenarios replacing pipeline imported NG and those replacing imported LNG, respectively. Therefore, S5 and S6 are ideal scenarios as they had the highest avoided GHG emissions and lowest GHG emissions avoidance cost among the studied scenarios. In the short-term (2020–2030), S6 had lower avoidance cost with slightly lower avoided GHG emissions compared with S1. In long-term (2040–2050), S5 had higher avoided GHG emissions with a slightly higher avoidance cost. In addition to the benefit of high avoided GHG emissions, S5 also reduced NG infrastructure expansion by 56% as compared with S6.

Fig. 18 and Fig. 19 show the cumulative avoided GHG emissions and GHG emission avoidance costs for 6 scenarios on a provincial level based on low-carbon gas production in China during 2020–2050. The overall distribution is consistent with the total results shown in Fig. 17. The cumulative avoided GHG emissions for the 6 scenarios are 7513 million tonne (Mt), 5983 Mt, 7663 Mt, 6125 Mt, 8338 Mt, and 6733 Mt, respectively. The cumulative GHG avoidance costs for 6 scenarios are 2227B$, 1764B$, 2102B$, 1633B$, 1575B$, and 1090B$, respectively. The specific GHG avoidance cost for the 6 scenarios are 296 $/t CO_2, 295 $/t CO_2, 274 $/t CO_2, 267 $/t CO_2, 189 $/t CO_2, 162 $/t CO_2, respectively. As shown in Fig. 18, Yunnan and Inner Mongolia were the top two provinces with the highest avoided GHG emissions in each scenario. The scenarios (S1, S3, and S5) replacing pipeline imported NG had higher cumulative avoided GHG emissions compared with those replacing imported LNG (S2, S4, and S6). S5 and S6 had the highest cumulative avoided GHG emissions, especially in Inner Mongolia, Shaanxi, Hebei, Henan, Jiangsu, and Guangdong. As shown in Fig. 19, Yunnan and Inner Mongolia were also the top two provinces with highest GHG emissions avoidance cost for each scenario. S1, S3, and S5 had higher GHG avoidance costs compared with S2, S3, and S6, respectively. Moreover, S5 and S6 had the lowest cumulative GHG emission avoidance cost in each province. The overall provincial results of the cumulative avoided GHG emissions and GHG emission avoidances cost show that Yunnan, Inner Mongolia, and middle-eastern part of China are critical for suppling low-carbon gases.



(a) 2020

(b) Base case expansion on 2030-2050

(c) Scenario 1 expansion 2030-2050

(d) Scenario 2 expansion 2030-2050

(e) Scenario 3 expansion 2030-2050

(f) Scenario 4 expansion 2030-2050

(g) Scenario 5 expansion 2030-2050

(h) Scenario 6 expansion 2030-2050

Fig. 15. Pipeline network capacity for 2020 and its expansion (in red) for base case and six scenarios.

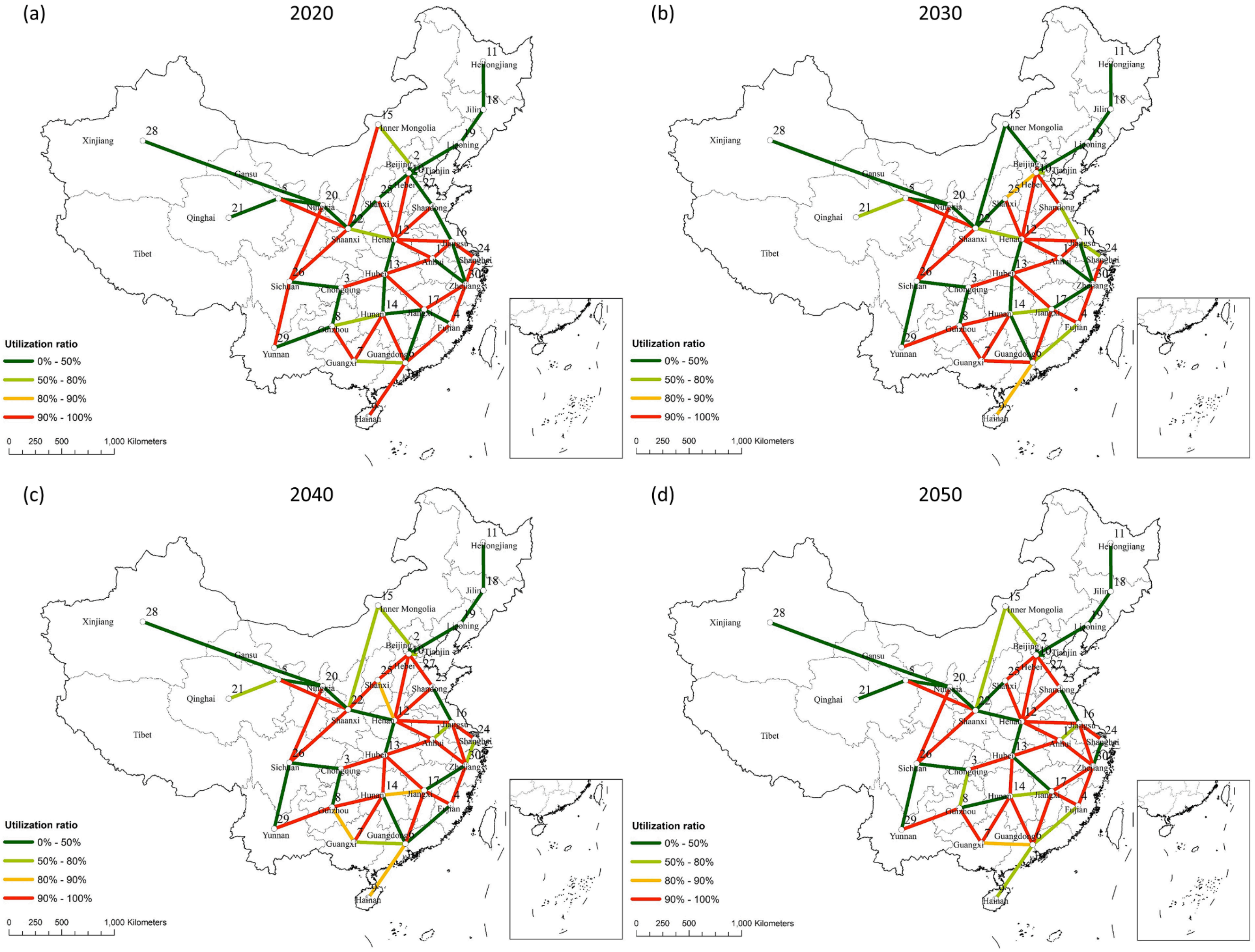


Fig. 16. Pipeline utilization rate for scenario 5 during 2020–2050.

5. Discussion

The biomass potentials for AM, CR, and FR were estimated based on Kang et al. [20], which were 20% higher than the estimations of Liu et al. [64] and 28% lower than those of Yang et al. [65]. Due to the limited data available for the EC actual yield, we estimated the EC potential based on a recent study by Zhang et al. [21], which is much higher than the previous estimation by Zhang [66] because the former study identified the best suited EC for specific marginal land based on land suitability and highest energy yield. Therefore, the uncertainty of the EC potential should be addressed in future studies by providing reliable actual EC yield data for different marginal lands. As the main GHG emissions for biomethane and bio-SNG production are from biogenic methane leakage, fuel usage, and electricity from the grid, the total GHG emissions have the potential to be reduced by over 50% with advanced waste management [67,68] and lowered grid GHG emissions in China [69,70].

There is variation in the projection of the future solar and wind capacities from different low-carbon energy scenarios. Also, the potential of PtG could be much higher than that estimated in this study because the technical potential for solar and wind capacities could be much higher than the estimation in CREO 2019, as in the China high renewable penetration scenario [30] and the Energy transitions Commission (ETC) Zero-Carbon scenario [31]. In this study, the estimation of solar and wind capacities only has the resolution of a multi-provincial level. Accurate province levels or even city levels solar and wind capacity estimation are necessary for local governments to build an adequate PtG supply chain and thus warrant further study.

The gas flow considered in this study is the average flow per year, wherein the demand variation from peak season to offseason was not considered. The NG import price, including pipeline imported gas and imported LNG prices, was estimated as a mean value in this study. However, import prices vary significantly based on import source and time. According to the IEA [71], the Asian spot gas price increased from 2016 to 2018 by 43% and then dropped by 44% in 2019. With a 40% price increase for pipeline NG imports, the GHG avoidance cost of low-carbon gases would drop by 20%–32% for S1, S3, and S5. Meanwhile, with a 40% price increase for LNG imports, the GHG avoidance cost of low-carbon gases would drop by 32%–70% for S2, S4, and S6. As there is a large fluctuation in import prices, the high proportion of import dependence in China increases the energy security risk of gas supply [35,37], which can be mitigated by increasing low-carbon gas supply. Any necessary hydrogen end-user modifications were not considered in this study, which might increase the avoidance costs for S5 and S6. However, with an increase in hydrogen end-users, the cost will decrease in the future [72].

Herein, the CO_2 source for PtM is from biomass or air capture. As carbon dioxide capture and storage (CCS) from industry is considered an important strategy to reduce CO_2 emissions, the captured CO_2 could be possibly used for PtM, which is beneficial as it has lower cost than air-captured CO_2. However, in this case, fossil-based CO_2 would still be emitted to the atmosphere. The low-carbon methane supply chain can also apply CCS at industrial end-users to become a negative GHG emissions supply chain. The possibility of applying industrial CCS is

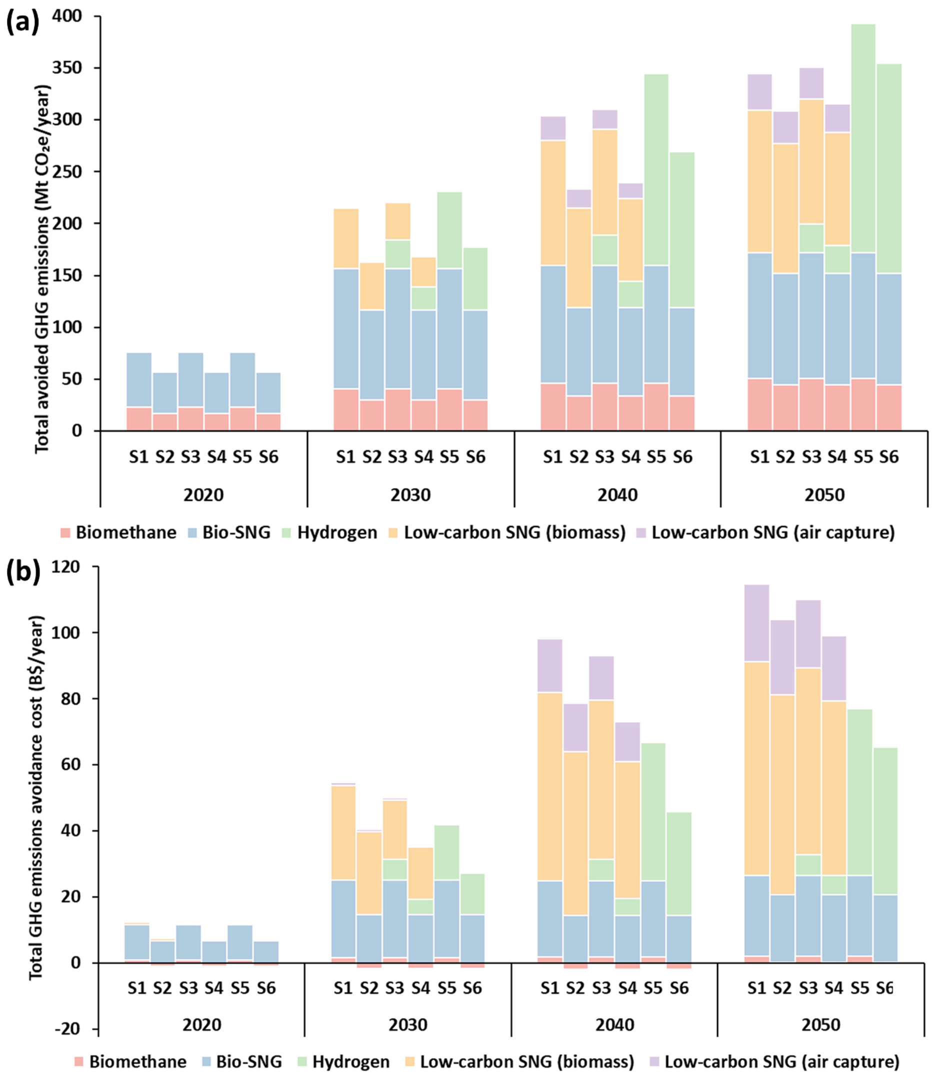


Fig. 17. Avoided GHG emissions and GHG emissions avoidance cost and of low-carbon gases in China for 2020–2050.

recommended for future investigations, as it would significantly influence GHG emissions and the cost of a low-carbon methane supply chain.

The findings of this study have to be seen in light of the limitation that we use a constant value for the emission factor of grid electricity and the technical, economic and environmental performance of low-carbon gas supply chains in our analysis during 2020 to 2050.

By using a constant value for the emission factor of grid electricity we ignore that decarbonization of the Chinese energy system will decrease this value over time. Therefore, we set the emission factor as 0 g CO$_2$-e/MJ to identify its maximum impact on low-carbon gas supply chains. The change results in: The GHG emissions of biomethane supply chain reduce from 26.3 to 19.5 g CO$_2$-e/MJ. The GHG emissions of bio-SNG supply chain reduce from 23.6 to 16.2 g CO$_2$-e/MJ. The GHG emissions of H$_2$ supply chain reduce from 1.3 to 0 g CO$_2$-e/MJ, because the GHG emissions of H$_2$ come only from electricity consumption at transportation. The GHG emissions of H$_2$ blending and low-carbon SNG supply chains remain unchanged as no grid electricity is consumed.

Because of the energy transition, scaling effects, and technological learning, the future low-carbon gas supply chains will have higher energy efficiency, lower costs, and lower GHG emissions. However, due to the high uncertainty of the development of low-carbon gas supply chains, the change of performance over time has not been considered in this study. We assume the mature and commercial scale deployment of low-carbon gas production technology to represent the future performance of low-carbon gas supply chains, as we synthesis large-scale production data and the median of future production data during 2020 to 2050. The inclusion of change of technical, economic and environmental performance over time for low-carbon gas supply chains would enhance the findings of this study and warrant further study.

6. Conclusions

Our analysis provided quantitative information regarding GHG emissions and the cost of low-carbon gas supply chains in China during 2020–2050. The methodology and models established in this study enabled the analysis of the potential of NG infrastructures to supply low-carbon gases at a provincial level. In this study, six scenarios were analyzed to evaluate the avoided GHG emissions, GHG emissions avoidance cost, and the capability of the NG infrastructure to supply low-carbon gases in China from 2020 to 2050. The results show that the existing NG infrastructure in 2020 is sufficient to meet the gas demand in 2020 for all scenarios. However, an expansion of the NG infrastructure is necessary from 2030 to 2050. The expanded capacities of the NG infrastructure of the base case and S1–S6 were found to be 18%–48%, compared with 2020 levels. Therefore, more attention should be paid to the deployment of NG infrastructure during 2030–2050 as the necessary expansion varies among the proposed scenarios. Although gas demand declines from 2040 to 2050, the pipeline network can still be used to

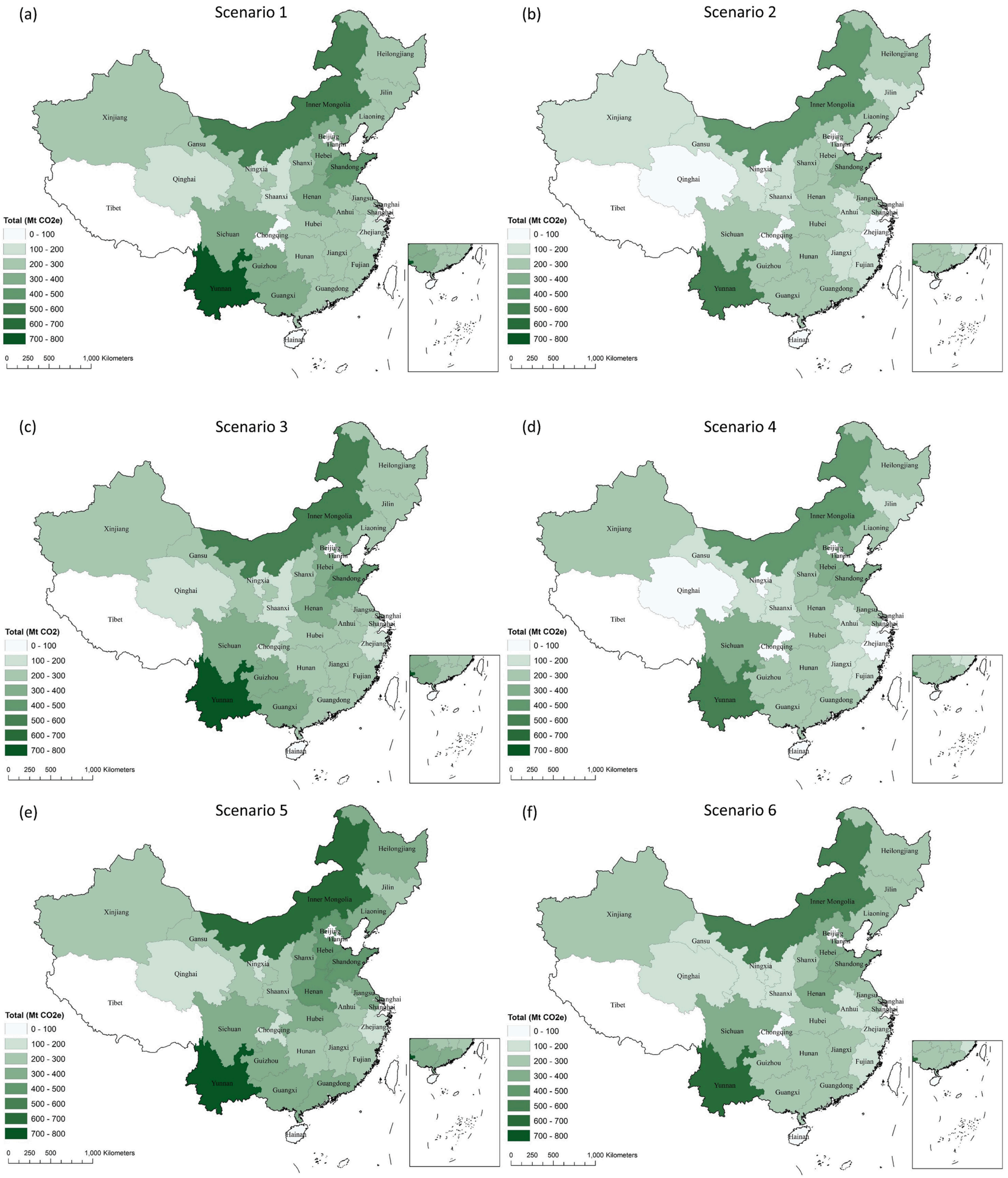


Fig. 18. Cumulative avoided GHG emissions of low-carbon gases during 2020–2050 for China in proposed scenarios.

supply the produced low-carbon gases. S5, which replaces pipeline imported NG with hydrogen, has the highest cumulative avoided GHG emissions of 8338 Mt. S6, which replaces imported LNG with hydrogen, has lowest GHG avoidance cost and specific GHG avoidance cost of 1090B$ and 162 $/t CO_2.

Herein, the results show that the biomethane supply chain has the highest GHG emissions and lowest production cost. Meanwhile, hydrogen and low-carbon SNG have the lowest GHG emissions and highest production costs. It is estimated that the total potential of low-carbon gas production will increase from 1.21 EJ in 2020 to 5.25 EJ in 2050, with hydrogen and low-carbon SNG being the fastest-growing low-carbon gases. The total gas demand will be 14.11 EJ in 2020 and 18.18 EJ in 2050. In 2020, low-carbon gas production is composed of biomethane (30%), bio-SNG (68%) and low-carbon SNG or hydrogen

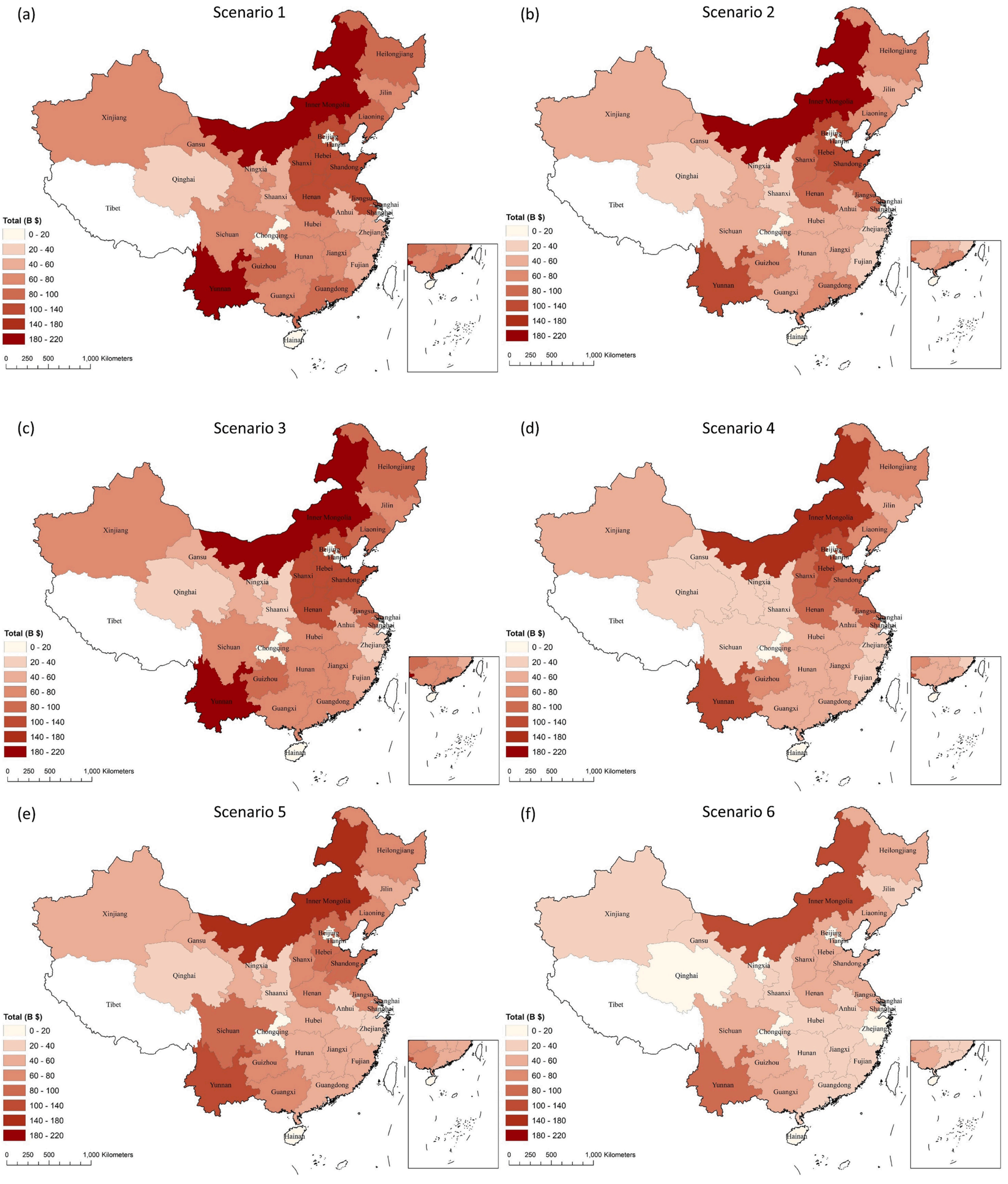


Fig. 19. Cumulative GHG avoidance cost of low-carbon gases during 2020–2050 for China in proposed scenarios.

(2%). These ratios change to 17%, 39%, and 44%, respectively, in 2050. At the provincial level, Yunnan and Inner Mongolia contributed approximately 17% of China's total low-carbon gas production during 2020–2050. The provinces of Yunnan, Guangxi, Guizhou, Hunan, Inner Mongolia, and Jilin have the potential to self-sufficient on gas demand with low-carbon gas supply.

Our results show that domestic low-carbon gas production cannot replace all the gas imports required for China. However, low-carbon gas production narrows the gap by 20%–67% between domestic supply and demand, thereby increasing the gas supply independence of China. As China's gas demand is mostly concentrated in eastern coastal provinces, replacing pipeline import gas (mostly from the west) with domestically produced low-carbon gases will shorten the gas transmission distance and consequently reduce the necessary NG infrastructure. Conversely, replacing imported LNG with low-carbon gases will increase the need for infrastructure. Therefore, replacing pipeline imported gas will result in relatively high avoided GHG emissions (due to relatively high GHG emissions of pipeline imported NG compared to imported LNG) and high avoidance costs, while replacing imported LNG will result in comparably low avoided GHG emissions with low avoidance costs because LNG is more expensive. According to IEA reports [42,73], the future low-carbon gas costs would be less than one-half than the costs in this study due to the energy transition, scaling effects, and technological learning. Considering the large range of NG import prices, replacing NG imports with domestic production of low-carbon gas has the potential to offset the NG import costs with significantly avoided GHG emissions. Note that the detailed strategies necessary to balance GHG emissions and the costs of replacing imported NG with low-carbon gases, which are valuable for decision makers, were not examined in this study and must be investigated further in future work.

In this study, we combined inputs from energy scenario results for low carbon energy future and a network flow model to represent the future gas infrastructure capturing gas demand and diversified supply. The results of this study show that supplying low-carbon gases in the NG infrastructure in China will significantly reduce the GHG emissions and NG imports not only in the short-term but also in the long-term. This study also shows that less expansion of NG infrastructure can be achieved by supplying low-carbon gas. The methodology proposed in this study can also be applied to address the same question for other countries.

CRediT authorship contribution statement

Jinrui Zhang: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Hans Meerman:** Supervision, Writing – review & editing. **René Benders:** Supervision, Writing – review & editing. **André Faaij:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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