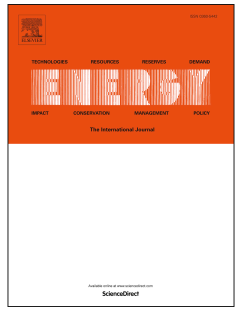

The future of coal supply in China based on non-fossil energy development and carbon price strategies

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PII: S0360-5442(20)32751-1

DOI: https://doi.org/10.1016/j.energy.2020.119644

Reference: EGY 119644

To appear in: *Energy*

Received Date: 25 March 2020

Revised Date: 24 November 2020

Accepted Date: 15 December 2020

Dingfei Jie: Methodology, Software, Validation, investigation, Writing - Original Draft
Xiangyang Xu: Conceptualization, Methodology, Project administration, Funding acquisition
Fei Guo: Methodology, Writing - Review & Editing, Supervision

The future of coal supply in China based on non-fossil energy development and carbon price strategies

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Abstract: To realize China's low-carbon development, coal needs to be produced and consumed in a clean and efficient way. In this paper, a multi-regional coal supply model is developed to gain insights into China's coal supply system up to 2050. Regional disparity, coal classification, and the development of clean coal technologies are specified in the model. Based on MESSAGEix, this model takes full consideration of coal mining, preparation, transformation, and transportation processes. Moreover, the effects of non-fossil energy development and carbon price are discussed. With the above framework, the future of China's coal supply system is optimized. Results indicate that: 1) China's national raw coal production will peak in 2030 under the business-as-usual scenario, while it has already peaked under the GREEN and carbon price scenarios, 2) The amount of coal used in final consumption and transformed into coke decreases, while coal transformed into liquids and SNG increases from 11 Mt in 2015 to 221 Mt in 2050 under the business-as-usual scenario, 3) both non-fossil fuel development and carbon price strategies have a positive effect on coal supply regulation and coal-related GHG emission reduction, 4) carbon price could facilitate the adoption of CCS technology and can effectively reduce coal-related GHG emissions.

Keywords: coal supply model, multi-regional, non-fossil energy development, carbon price

1. Introduction

China's energy system is coal-dominated, with about 69% of primary energy supply and 59% of energy consumption covered by coal in 2018 [1]. Coal has supported China's economic and social development for a long period. Although the share of coal in China's energy system has declined in recent years, about 66% of power generation [2] and 70% of energy consumed in the iron and steel industry [3] are still supplied by coal in 2016. Furthermore, the new coal chemical industry (including coal-to-oil, synthetic natural gas, olefins, and ethylene glycol, etc.) has been accelerated by the Chinese government [4]. China is rich in coal resources and poor in oil and gas resources. Coal will still be the main energy source for the coming decades [5]. Therefore, research on future coal supply in China is not only important to the development of coal industry but also could have a great significance for China's energy supply and energy security.

However, coal, as a traditional fossil fuel, is a high-carbon energy. For the same amount of energy produced, coal emits about 30% more carbon dioxide than crude oil [6]. In 2017, coal accounted for about 44% of global CO_2 emission from fuel combustion [7]. Under the low-carbon development, the

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future of coal industry has been discussed worldwide. In Germany, coal used to be the primary energy source for power generation. However, environmental concerns and climate change has affected its coal utilization. Recently, Germany has announced to phase out its coal-fired power plants by 2038 [8]. The share of coal for power generation has witnessed a downtrend. An EIA research shows that coal production in U.S. will decrease to 521 million short tons in 2020, followed by an increase to 677 million short tons in 2021[9]. The increase in coal production in 2021 could be explained by the increased natural gas price and the increased power demand. Wierzbowski et al. suggest that Poland’s coal-based power generation system should transform into a more sustainable and diversified energy mix towards 2050 [10]. The development of renewable energy and the improvement of energy efficiency are two measures to promote energy transition in India. Coal seems to be its main energy source until 2050 [11].

As the world’s largest CO_2 emitter, China plays an active role in carbon emission reduction. In 2015, it officially announced to peak its carbon dioxide emission around 2030 and lower its 2030 carbon dioxide emissions per unit of GDP by 60% -65% compared with 2005 [12]. Under the context of low-carbon development, China’s coal industry is facing significant challenges from both internal and external perspectives. Firstly, China has attached great importance to the development of non-fossil energy, which has been an inevitable choice to realize sustainable development. The installed capacity of hydro, wind, and solar power in China has increased to 352GW, 185 GW, and 175 GW respectively in 2018 [13]. In the 13th Five-Year Plan for energy development, non-fossil energy is projected to achieve 15% of primary energy consumption and 31% of power generation in China in 2020. Secondly, the emissions trading scheme is regarded as an effective strategy for carbon emissions reduction. China has set up seven carbon trading pilots since 2011 [14]. Based on the experience gained from these pilot markets, China officially launched the national carbon trading market for the year 2017 [15]. Thirdly, it is necessary to achieve clean production and efficient utilization of coal. In order to promote clean coal production, an official evaluation index system for clean production in coal mining and preparation industry was released in 2019. In addition, the target of coal preparation ratio is projected to be above 75% in 2020 by the Chinese government [16]. While for coal utilization, improving utilization efficiency has become the main target [17]. Besides being used as a fuel, coal is also used as chemical material. The capacity of coal liquefaction and coal-based synthetic natural gas (SNG) is projected to reach 13 million tons and 17 billion cubic meters per year respectively in 2020 [18]. Based on these contexts, the future of coal supply is closely related to the policies and transformations of coal industry and energy system. Therefore, it is essential to consider these trends while projection the future coal supply in China.

Many existing studies have analyzed different aspects of the coal industry in China, including the structure of coal industry chain and coal material flow. Li et al. [19] analyzed the evolution of coal industry chain with a combination of input-output analysis and an Average Propagation Length model. Zhang et al. [20] described coal flow with a physical input-output table. Bai et al. [21] discussed historical information about coal production, processing, and quality management of coal. Liu et al. [22] matched coal classification and gradation with utilization and formed an index system to optimize coal material flow. The above-mentioned studies are mainly concentrated on the historical changes or status quo of China’s coal industry, which are insufficient in the projection of the future coal supply system.

There are also many studies discussing future coal production in China [23-27] with trend extrapolation model. Normally, these studies ignore the impacts of energy system transition and technology changes. Furthermore, Wang et al. [28] analyzed the future layout of coal development based on the concept of “green resource”. They only analyzed the regional capacity for mining according to resource and mining conditions. Liu et al. [29] optimized provincial coal production and transportation pattern from a medium perspective (from 2015 to 2030). However, the attractiveness of a resource is not only determined by its production cost, but also determined by its utilization cost to provide energy service [30]. Therefore, a more comprehensive system is needed to project China’s coal supply. Except for the above-mentioned papers, some previous studies have optimized China’s energy transition through system analysis [31, 32]. Wang et al. [33] built a hybrid optimization model, which shows the decline of coal supply in total energy. These studies usually analyze the development trends of the whole energy system, which also include the projection of coal supply. However, these studies are generally at the national level without detailed information about coal industry. Therefore, the regional layout of coal industry is neglected. Furthermore, to our knowledge, there is no study considering coal types while projecting the future of coal supply in China.

Besides, many researchers focus on the utilization of coal. Power sector is the largest coal consumer. Many studies focus on power system optimization to estimate future power generation structure. Zhang et al. adopted the MESSAGE model to optimize China’s power system considering coal resource constraints and coal transportation [34]. Other power optimization models also include the development trend of coal-power generation technologies [35, 36]. Some researchers focus on the iron and steel industry. Zhang et al. use the MESSAGEix model to analyze future coal consumption in the iron and steel industry [37]. An et al. assessed the energy saving and emission reduction potential in the iron and steel industry [38]. With the development of the new coal chemical industry, some papers focus on the techno-economic analysis of CTL technology [39] and coal-to-SNG technology [40]. Although these papers focus on one specific coal utilization sector, they help well understand the development of China’s coal transformation process.

Different from previous studies, our study aims at building an integrated assessment of China’s coal industry towards 2050. A detailed multi-regional coal supply system model (with coal classification and detailed process of the coal supply chain) associating with low-carbon transition in China’s energy system is adopted to analyze the long-term national and regional coal supply and resource allocation. The rest of this paper is organized as follows. Section 2 depicts the multi-regional coal supply model and model scenarios. Section 3 shows the model results of coal supply in China through raw coal production and regional layout. Section 4 discusses the effects of strategies considered in the four scenarios and the trajectory of coal-related greenhouse gas (GHG) emissions. Section 5 concludes the results.

2. Methodology

2.1 Model approach and basic principles of coal supply model for China

In this study, MESSAGEix developed by the International Institute for Applied Systems Analysis (IIASA) is used to optimize the regional coal supply in China. MESSAGE (Model for Energy Supply Systems And their General Environmental Impact) provides a bottom-up model framework for users to describe the processes and relations defined in their energy systems. It is now wildly used for energy system planning and policy analysis [34, 37, 41]. With detailed technology options, the target of this model is to find the least-cost technology portfolio that satisfies the given demand. MESSAGEix is the latest version of MESSAGE, which is a linear optimization model implemented in GAMS. The CPLEX solver is used for model optimization. More detailed information and formula about MESSAGEix are displayed in the tutorial document of MESSAGEix [42] and an article from

Huppmann et al. [43].

Therefore, the coal supply model is built to optimize China's coal supply with the minimum cost of the whole system under a series of constraints. With a five-year interval, this paper optimized the coal supply system from 2015 to 2050. In the process of model construction, several factors are taken into consideration as basic principles in this model.

First is the regional division. As a country with a vast territory, China has prominent differences among regions in coal resources, geological conditions, economic development, coal production, and coal consumption. Therefore, China is divided into seven regions in this paper according to the previous study [44], as shown in Fig. 1. The seven regions are the NE (Liaoning, Jilin, and Heilongjiang), the HHH (Beijing, Tianjin, Hebei, Henan, Shandong, Jiangsu, and Anhui), the SOUTH (Shanghai, Hunan, Hubei, Guangdong, Guangxi, Zhejiang, Jiangxi, Fujian, and Hainan), the JSMN (Shanxi, Shaanxi, Inner Mongolia, and Ningxia), the GQ (Gansu and Qinghai), the SW (Sichuan, Chongqing, Yunnan, and Guizhou) and the XJ (Xinjiang). NE region has a relatively good resource condition. However, with the high intensity and long history of exploitation, coal resources in some areas of this region are almost exhausted [45]. HHH region is a densely-populated area with a developed economy. It is also the largest coal consumption region in China. SOUTH region is poor in coal resources. Coal demand in this region is highly dependent on other regions. Coal resource in South China is mainly located in SW region. JSMN is characterized by abundant coal resources, which is also the main coal producing region in China. GQ region and XJ region are in the west of China. The coal industry in these two regions is less developed, although they are rich in coal resources. Therefore, coal resource has great potential development, especially for XJ region.

Second is the coal classification. According to the Chinese national standard of coal classification, raw coal is divided into three kinds: anthracite, bituminous coal, and lignite. Bituminous coal can be further divided into 12 types [21]. Some types of bituminous coal that can be used as material for the coking process are classified as coking bituminous coal (Meager Lean coal, Lean coal, coking coal, Fat coal, 1/3 coking coal, Gas fat coal, and Gas coal) [22]. The other types of bituminous coal are classified as general bituminous coal (Meager coal, 1/2 stick coal, Weakly caking coal, Non-caking coal, and Long flame coal). Therefore, four kinds of raw coal are specified in our coal supply model, anthracite, coking bituminous coal, general bituminous coal, and lignite. The variation of characteristics among raw coal types leads to differences in coal processing and utilization methods, which is highlighted in the model.

Thirdly, the effects of the implementation of clean coal technology are considered in this model. Clean coal technology is a significant way to realize the efficient and environmental utilization of coal [46]. However, different clean coal technology could play an opposite role for coal supply. For example, advanced coal power generation technology, like ultra-supercritical (USC) and integrated gasification combined cycle (IGCC) power generation technology with high efficiency will decrease the coal consumption per unit of power generated. However, coal-to-liquids (CTL) and coal-to-SNG technology are possible to provide a new growth point for coal demand. Therefore, in order to provide a scientific projection for coal supply, these advanced technologies, including USC power generation technology, IGCC technology, pressurized fluidized bed combustion (PFBC) technology, carbon capture and storage (CCS) technology, CTL, and coal-to-SNG technology are contained in the coal transformation process of the proposed coal supply model.

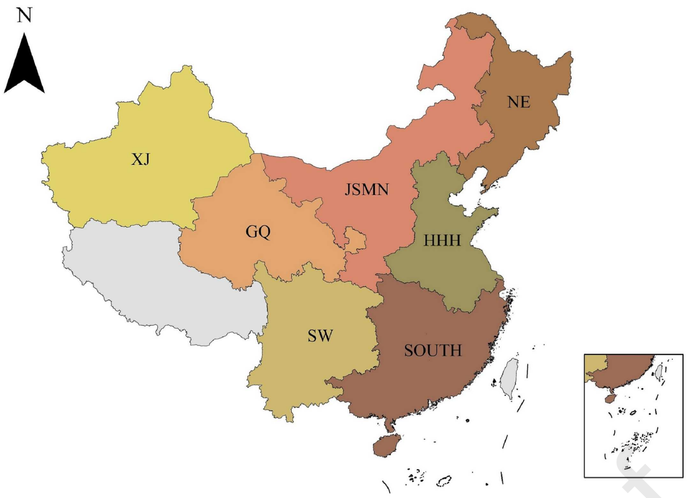

Fig. 1 Regional division of the model. The grey part of the picture includes Tibet, Hongkong, Macau, and Taiwan, which are not included in the model.

2.2 Model structure

The model structure is shown in Fig. 2. Different types of coal resources in each region are the basis of the model. The coal flow is the main part of this model, which is characterized by detailed technologies. Natural gas and non-fossil energy (nuclear, wind, solar, hydro, biomass, and geothermal) are considered as the substitution energy in power and heat supply. Regional transportation links the seven regions as a whole to meet the specific energy demand in each region. The main input data in this model includes resource volume, resource cost, technology parameters (historical capacity, investment cost, fixed cost, variable cost, emission factor, etc.), and demand data. The overall system cost includes resource cost, technology cost, and emission cost (when the carbon price is considered in the system). Through optimization of the model, the results show the coal material flow, coal transportation, power transmission, and coal-related GHG emissions.

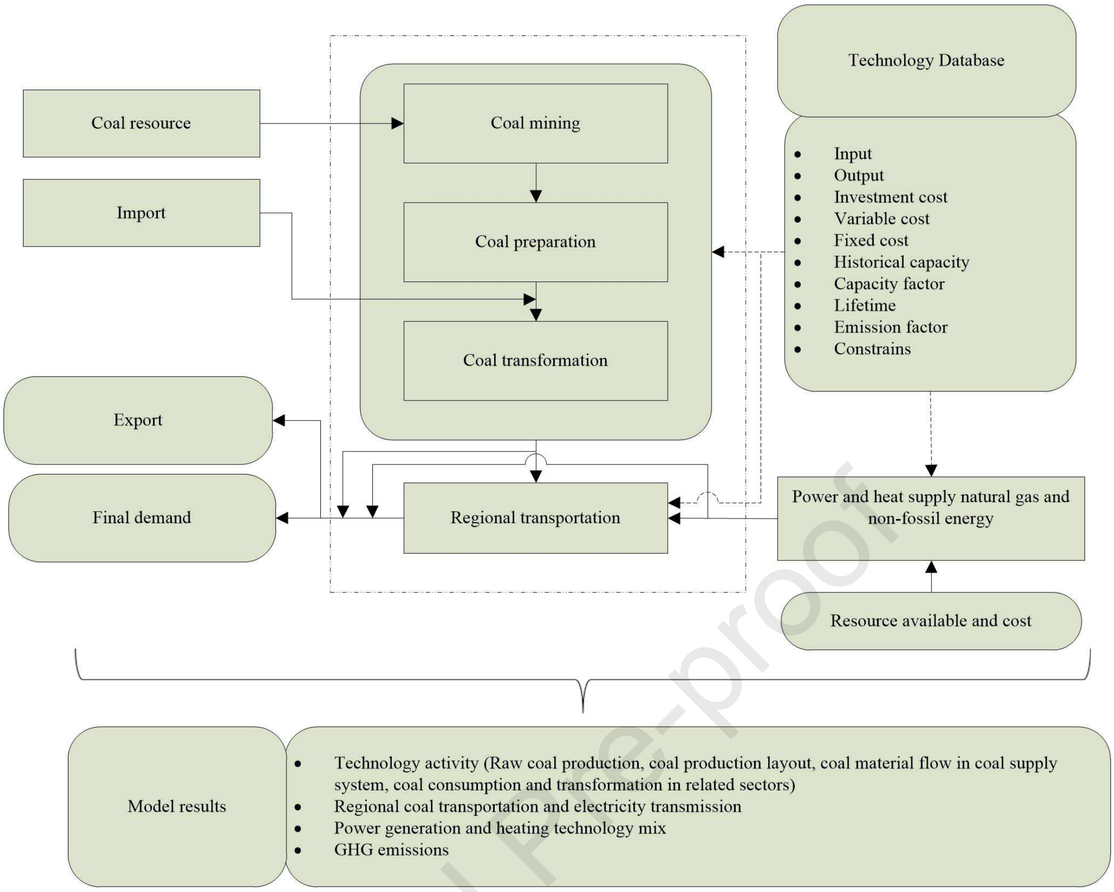

Fig. 2. The structure of the coal supply model.

Furthermore, a detailed energy flow chart in one region is shown in Fig. 3. For each sub-module, the network of the regional coal supply system is constructed by four energy levels, namely resource, primary, secondary, and demand. Energy carriers contained in these levels are connected by corresponding technologies. According to the coal classification mentioned above, four kinds of coal resources are encompassed in the resource level (anthracite, general bituminous coal, coking bituminous coal, and lignite). Different types of coal resources are mined in order to get the corresponding raw coal. As part of coking bituminous coal is used as steam coal in China [47], here we assume that this part of coking bituminous coal could be used in the same technologies in the preparation and transformation process as general bituminous coal. Therefore, the primary level includes four types of raw coal. Then, part of raw coal is prepared through coal preparation technology. Five outputs from the coal preparation process are contained in the secondary level, including four kinds of cleaned coal and other washed coal (byproducts of coal preparation process). As for the demand level, it includes the final consumption of coal and five related energy carriers (electricity, heat, CTL, SNG, and coke), which will be used by the end-users directly. All energy carriers in the primary level and secondary level are linked with energy carriers in the demand level through technologies such as coking technology, power generation technologies. Import, export, and transportation technologies are considered to reflect the energy flows between regions and countries. In addition, electricity and heat generated from natural gas and non-fossil energy are integrated into the model.

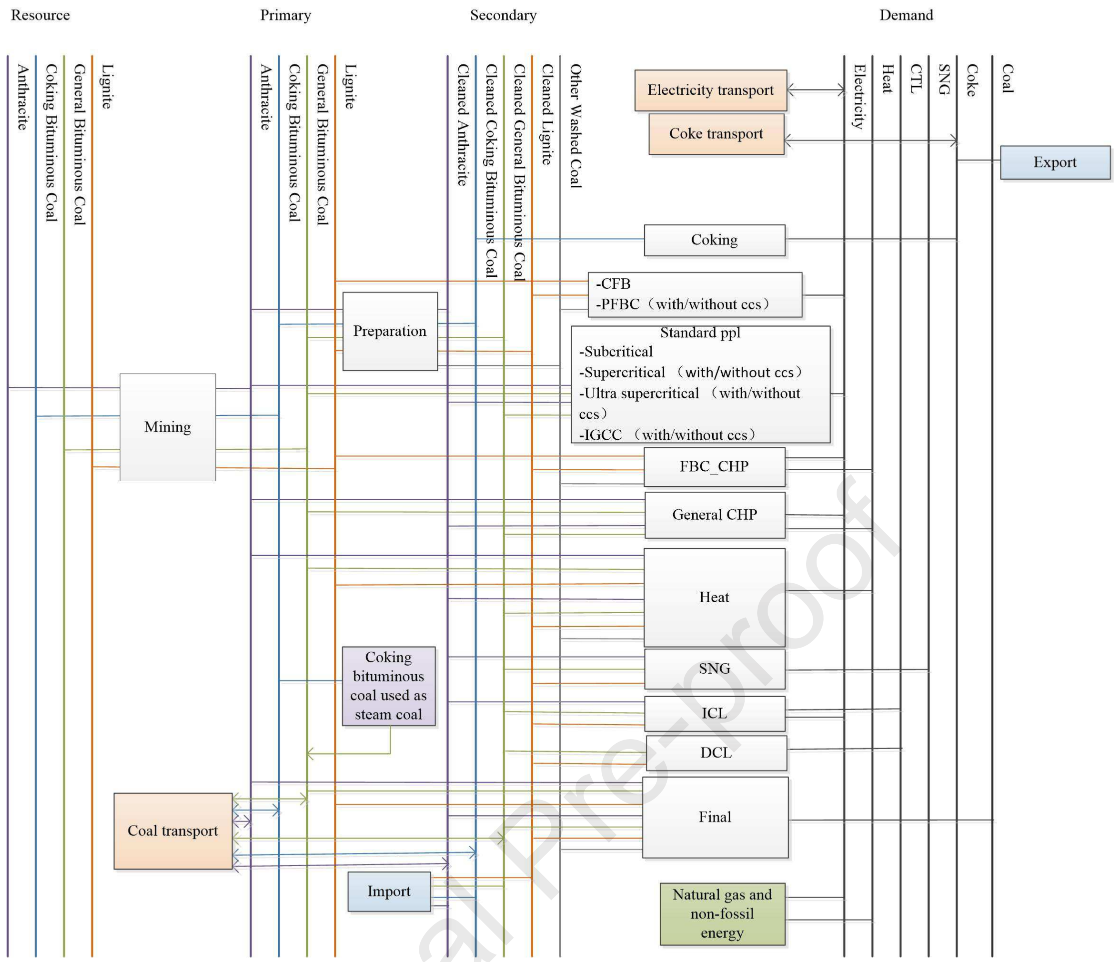

Fig. 3. The energy flow chart in one region.

2.3 Key assumptions and data

2.3.1 Coal mining

Two mining methods are adopted for coal mines in China, underground mining and surface mining. In this paper, we adopted specific underground mining technologies for each region to reflect the regional difference for coal production. Since surface mining only comprises less than 5% of national raw coal exploitation in China [48], we assume that the cost of surface mining technology all over the country is the same. Detailed technology parameters for coal mining technologies in 2015 are shown in Table 1. The coal resource output coefficients represent the percentage of exploited coal to the coal resources [49], which are related to the occurrence condition of coal resources. Therefore, they are assumed to remain constant. Cost parameters for underground mining technologies are estimated according to the average provincial mining cost in Ref. [50]and cost structure in Ref.[51]. For surface mining, the investment cost, fixed cost, and variable cost come from one specific surface coal mine in Xinjiang [52]. All mining costs are assumed to change over time according to Ref. [53]. The historical production data of raw coal is captured by national [54] and industry statistics [55]. Coal resources data are industry consulting data from China Coal Big Data Center Company [56].

Under the constraints of resources and environment, coal production in China faces a significant irrational layout. It has been a key objective to adjust the layout of coal mining industry during the 13th Five-Year period. The basic principle for layout adjustment is to comprise coal mining in the eastern area, restrict coal mining in the central and northeast region, and optimize coal mining in the western area, according to the 13th Five-Year Plan for coal industry [57]. Based on this principle, the shutdown of coal mines in SOUTH region is planned to be accelerated. Therefore, new coal mines are not allowed to build in this region. In addition, coal production capacity in SW region, HHH region, and NE region is projected to decline by the government.

Table 1. Parameters of mining technologies

	Region	Coal resource output coefficients (%)	Investment cost (yuan/t)	Fixed cost (yuan/t)	Variable cost (yuan/t)	Lifetime (year) [a]
Underground mining	JSMN	35	1285	88	86	60
	XJ	30	611	50	49	50
	SW	30	1421	145	142	40
	GQ	30	1803	123	120	60
	HHH	35	2451	167	163	60
	NE	35	2325	190	186	50
	SOUTH	30	2319	237	232	40
Surface mining		35	272	24	23	60

[a] The lifetime of mining technology is estimated according to regional average mine capacity [28].

2.3.2 Coal preparation

Coal preparation is a part of clean coal production, which is also regarded as an essential way by the Chinese government to promote clean and efficient coal use. It could effectively diminish the inorganic minerals and ash and sulfur content in raw coal [58]. Thus, an improvement in heating value and transformation efficiency could be obtained from the preparation process [59]. The choice of coal preparation technology could be determined by raw coal types, specific requirements for products, etc. [60]. Given all that, lignite with high moisture is prepared by dry preparation technology. The other three types of raw coal are washed in steam or coking coal preparation plants according to their utilization methods.

The lower heating value (LHV) and CO_2 emission factor of raw coal, cleaned coal, and other washed coal are shown in Table 2. The technology cost for coking coal and steam coal washing is taken from [61], while the cleaned coal washed and other washed coal output are taken from China Energy Statistic Yearbook [62] and relevant literature [63, 64]. The technology cost for lignite coal preparation is from Ref. [65] and the output of cleaned lignite is taken from [66]. The output for different coal preparation technologies is shown in Supplemental material (Table B1). The historical data of coal preparation capacity is obtained from China Coal Industry Statistic Yearbook [54].

Table 2. Unit LHV and CO_2 emission factor of cleaned coal and other washed coal

	Coal types	LHV (GJ/t)[a]	Emission factor (tCO2/t)[b]
Raw coal	Anthracite	23.39	2.21
	Coking bituminous coal	22.05	2.02
	General bituminous coal	22.05	2.02
	Lignite	13.40	1.32
Cleaned	Cleaned anthracite	28.54	2.69

coal	Cleaned coking bituminous coal	27.78	2.56
	Cleaned general bituminous coal	26.90	2.42
	Cleaned lignite	15.28	1.41
	Other washed coal[a]	11.20	1.27

[a] The LHV of raw coal, cleaned anthracite, cleaned other bituminous coal, and other washed coal is calculated from Ref. [67]. A 26% increase in LHV of coking bituminous coal will be achieved after the coking preparation process according to Ref. [68]. The LHV of lignite is assumed to increase by 14% after dry preparation [66].

[b] The emission factors for raw coal and other washed coal are calculated according to Ref. [67]. The emission factors for cleaned coal are calculated based on the carbon balance between inputs and outputs of coal preparation technologies, using data from Ref. [67] and Ref. [63]

Due to the government policy to enhance the coal preparation ratio, the share of national coal prepared is assumed to increase to no less than 75% in 2020 and 90% in 2030. Moreover, the lowest coal preparation ratio is assumed to remain constant from 2030 to 2050.

2.3.3 Coal transformation

In this analysis, main coal transformation processes, including coal-fired power generation, coal-fired heat supply, coking, CTL, and coal-to-SNG, are taken into consideration.

2.3.3.1 Coal-fired power generation and heating

Power generation is the dominant coal transformation sector, which consumed about 61% of total transformed coal in 2015 [68]. Coal used for power generation is classified into two categories in this paper. Lignite, cleaned lignite, and other washed coal are generally characterized by high moisture and low heat value. Thus, power plants for this type of coal use circulating fluidized bed combustion (CFB) and pressurized fluidized bed combustion (PFBC) technology, as well as fluidized-bed combustion CHP (FBC_CHP). Power plants for other coals are classified into subcritical (SBC), supercritical (SPC), USC, and IGCC. Meanwhile, a general CHP [69] is also adopted for combined heat and power supply. However, all types of coal in heat supply are regarded as substitutes for each other. Therefore, coal-fired boiler in heat supply could be fueled by all types of coal. Besides, the benefit of the coal preparation process leads to a 5% increase in the transformation efficiency of cleaned coal in power generation and heat supply [70]. In addition, CCS technology is assumed available in power generation technologies, and could be implemented with SPC, USC, IGCC, and PFBC.

The cost parameters of PFBC are estimated according to Ref. [71], while its efficiency and lifetime are obtained from Ref. [72]. For other coal-fired power plants, the cost and lifetime parameters are based on Ref. [36] and the investment cost of coal-fired power generation plants in China [73]. Their efficiency parameters in 2015 are estimated according to Ref. [34, 36]. The efficiency of USC, IGCC, and PFBC is assumed to increase during the model period [74, 75] considering technological progress. The efficiency parameters of other coal-fired power generation technologies are assumed to remain at the 2015 level. For coal-fired power plants with CCS, the increase of investment cost and energy penalty by the implementation of CCS is estimated according to Ref. [76]. The increase of variable and fixed O&M (operating and management) cost is estimated based on Ref. [75]. The capacity factors of coal-fired power plants are estimated according to the China Electric Power Yearbook [77].

For the coal-fired co-generation technologies and heating technology, the efficiency parameters are estimated according to Ref. [69, 78]. Cost parameters of co-generation technologies are collected from Ref. [34, 79], while cost parameters of heating technologies are estimated based on Ref. [80]. The main parameters for coal-fired power generation and heating technologies are shown in the supplementary material (Table B2-B5).

2.3.3.2 Coal coking, CTL and coal-based SNG

Cleaned coking bituminous coal is used as the material for coke production. The technological parameters for coking technology are estimated according to Ref. [37] and China Energy Statistic Yearbook [62].

Since air pollution has been a key issue for China, policies like the Three-Year Action Plan to Win the Blue-Sky Defense War (2018) has issued to prevent and control air pollution, especially in some key areas including Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Anhui, and parts of Hebei, Shanxi, Shandong, Henan, and Shaanxi province. Coking capacity is constrained in these key areas due to its high energy consumption and high pollution. HHH region and JSMN region are the main coke producing regions, which also include most of the key areas for the prevention and control of air pollution. Therefore, an upper bound is set for coking capacity in these two regions according to related national and provincial policies.

Considering the special requirement for coal used in the coal chemical industry, only cleaned coal can be used in the CTL process and coal-to-SNG process in this model. Except for cleaned coking bituminous coal, the other three types of cleaned coal are used evenly in indirect coal liquefaction (ICL) and coal-to-SNG process, while cleaned anthracite is not suitable for direct coal liquefaction (DCL) technology, as shown in Fig. 3.

The cost parameters for coal-to-SNG, ICL, and DCL technologies in 2015 are from relevant studies [81-83]. The annual decreasing rates of cost for these three technologies are obtained from IEA's Energy Technology Systems Analysis Program [84]. The material coal consumption in coal-to-SNG, ICL, and DCL process is assumed to decrease, and will reach the advanced level announced in the 13th Five-Year Plan for the Development of Coal Deep Process in 2050. Material consumption for coal coking, DCL, ICL, and Coal-based SNG technologies are shown in the supplemental material (Table B6).

2.3.4 Power generation and heating from non-fossil fuel energy and natural gas

As mentioned before, non-fossil energy and natural gas have played a vital role under the low-carbon development, which could substitute coal in power generation and heat supply. Therefore, six alternative power generation technologies and four alternative heat supply technologies: natural gas-fired power (NG), wind power, solar power, hydropower, biomass power, nuclear power, gas boiler heating, solar heating, biomass heating, and geothermal heating are integrated into the model, as shown in Fig. 3.

For these technologies, cost and lifetime parameters are collected from related studies [34, 36] and the Center for Renewable Energy Development [85]. The efficiency of biomass power generation [85] and natural gas-fired power generation [86] is assumed to increase considering the technical progress. Capacity factors of hydropower, nuclear power, and wind power are estimated based on the China Electric Power Yearbook [77]. The capacity factor is assumed to be 50.4% for biomass power plants and 45.7% for gas-fired power plants [87]. The capacity factor for solar power generation is calculated according to Ref. [88], as shown in the supplementary material (Table B7). For solar heating, the capacity factor is estimated according to the annual sunshine hours in each province [89]. The regional cost of natural gas is assumed to increase over time according to [53, 90]. Uranium price is set at 574 yuan/kg in 2015 [34], with annual increasing rate of 1.1% [71]. Biomass price is set as 24 yuan/GJ during the model period according to Ref. [69]. The main parameters for non-fossil fuel based power generation and heating technologies are shown in the supplementary material (Table B2-B5).

Considering the resource distribution of renewable energy and the technology development level, the regional upper limits for installed capacity of non-fossil fuel based power plants are estimated according to relevant studies [91, 92] and Renewable Energy Data Manual [93]. The regional availability of renewable resource for heating is assessed according to Ref. [93-95]. Besides, the upper limits of annual construction for non-fossil fuel based power generation technologies are calculated according to previous experiences [77, 96] and relevant studies [90, 92]. The limits for non-fossil fuel based power plants are shown in the supplemental material (Table B8-B9).

2.3.5 Transport

As mentioned before, the flows of energy among regions is reflected in this model through inter-regional transport technologies. For different energy carriers, two categories of transportation technologies are adopted. One is railway and waterway transport for raw coal, cleaned coal, and coke. The other one is electricity transmission technology.

By contrast with the resource’s distribution, a large proportion of coal is consumed in the south and east of China. The geological distribution conflict between coal resources and coal consumption has resulted in coal transport in China. Railway and waterway are two mature long-distance transportation methods, which are considered as inter-regional transportation technologies for both coal and coke in this model. The characteristics of lignite make it unsuitable for long-distance transportation [97]. Other washed coal is promoted to be used for power generation near the preparation plants [98]. Furthermore, it is uneconomic for long-distance transport of low heat value coal. Therefore, we do not consider the regional transportation of lignite, cleaned lignite, and other washed coal. As a result, these three types of coal can only be consumed in their producing region. Besides, transportation routes of coal are only considered between adjacent areas in this model, and waterway transportation is only considered from SW to SOUTH and HHH to SOUTH according to the geographic features.

Different from coal transportation, electricity can be transmitted directly from one region to the other six regions. In this paper, two power transmission technologies (Ultra-high voltage power transmission technology and High voltage transmission technology), which enable the long-distance transmission of electricity, are taken into consideration [87].

2.3.6 Import and export

China has been a net coal importer since 2009 [21]. These patterns in international trades are likely to be continued in the future. Since coal could be transported among regions, only one importing route for each kind of coal is considered in this model. According to the historical data, anthracite, general bituminous coal, and lignite are imported to China through the SOUTH region, while coking bituminous coal is imported to China through the HHH region. The cost of coal imported is from Ref. [53]

Besides, China has been a net coke exporter according to official NBSC (National Bureau of Statistics of China) data [99]. The exported volume of coke could be influenced by many factors, including trade policy, world coke demand [100], resource protection, and economic performance [101]. As a result, the export volume of coke is volatile. However, the future export of coke could be limited by the weak coke demand growth in the international market[102], the policies to protect scarce resources of coking coal, and the pressure of air pollution in China. Furthermore, exported coke only accounts for a very small part compared with China's domestic coke demand since 2009. Since the prediction for coke export is not the focus of this study, we simply assumed that the exported coal is about 2% of final coke demand according to historical data in 2015 [68].

2.3.7 Demand

The final consumption for different energy carriers related to coal is used as the model demand in this study. We calculated the national final consumption of electricity, heat, coke, and coal according to historical data in 2015 [68] and the IEA report [103]. Then, the regional demand is achieved by a downscaling method (see supplementary material) [104, 105]. The national production for CTL and coal-based SNG is projected according to Ref. [103]. Then they are divided into regional production according to the previous studies [106, 107], representing the corresponding commodities produced in each region. The regional demand data are shown in the supplementary material.

2.4 Scenario analysis

Table 3. Scenario description in the coal supply model

Scenario		Scenario description
Non-fossil energy development [a]	BAU	Non-fossil energy continues to increase according to the current trend. In the power sector, the capacity targets for hydro, wind, solar, biomass, and nuclear are 431.61GW, 800GW, 1000GW, 50GW, and 150GW respectively in 2050. For the heat sector, the target share of non-fossil energy on total heat supply is set as its 2015 share (1%) during the model periods. Besides, the target for natural gas power generation is assumed not less than 34.8 GWyr from 2020. The target share of natural gas in total heating supply is assumed to keep its 2015 level.
	GREEN	The development of non-fossil energy is further promoted, which plays a more positive role in China's energy system. In the power sector, the capacity targets for hydro, wind, solar, biomass, and nuclear are 431.61GW, 1000GW, 1180GW, 59GW, and 200GW respectively in 2050. For the heat sector, the target share of non-fossil energy on the total heat supply is 36% in 2050. Besides, the target for natural gas power generation is assumed not less than 34.8 GWyr from 2020. The share of natural gas in the total heating supply is assumed to increase to 9% in 2030.
Carbon price	BAU_50	A carbon price of 50 yuan/t CO_2 is implemented in 2015 with an annual growth rate of 5% while the development of non-fossil energy at least reaches their targets in the BAU scenario.
	GREEN_50	A carbon price of 50 yuan/t CO_2 is implemented in 2015 with an annual growth rate of 5% while the development of non-fossil energy at least reaches their targets in the GREEN scenario.

a. More details about the non-fossil development target in the BAU and GREEN scenario are shown in the supplementary material. These targets are projected according to China's 13th Five-Year Plan and Ref. [92, 94, 108-110].

Under low-carbon development, China has made great efforts to promote the development of non-fossil energy, and this trend is likely to be continued in the future with a high probability. Thus, the

BAU (business-as-usual) scenario and GREEN scenario are developed to describe the possible development trend of non-fossil energy. Furthermore, the roles of carbon trading in the coal supply system are evaluated by introducing a carbon price into the model. According to the pilot carbon market in Beijing, the carbon price in 2015 is assumed to be 50 yuan/t CO_2, with an annual growth rate of 5% [111]. Consequently, four scenarios are constructed in this paper, as shown in Table 3.

3 Results and discussion

3.1 The future of the coal supply system under the BAU scenario

3.1.1 Raw coal production

Under the BAU scenario, raw coal production in China will peak in 2030 (as shown in Fig. 4). Although a slight increase appears in 2020, raw coal production will then increase to 3791 Mt in 2030. After peaked in 2030, the national raw coal production gradually decreases to 3526 Mt in 2050. JSMN region with abundant coal resources is the main raw coal producing region in China. The proportion of raw coal production in JSMN region to total grows to 81% in 2050. XJ region gradually becomes the second coal producing region in China. The raw coal production in XJ region reaches 385 Mt in 2050, which more than doubles its current level. Totally, these two regions will comprise about 92% of raw coal production in China. For all the other five regions, raw coal production all shows a declining tendency. The raw coal production in GQ region and SW region almost drops to 1/3 of its current level. Both HHH region and NE region show a dramatic decline in coal mining. They only account for about 5% of national raw coal production in 2050. Furthermore, SOUTH region is projected to exit coal mining in the last period of the model.

As the primary material for coke, the trajectory of coking bituminous coal (431 Mt in 2050) shows a downward tendency in accordance with the reduction of coke demand. General bituminous coal accounts for more than half of coal reserves in China and is the main kind of thermal coal. In 2050, the production of general bituminous coal accounts for 60.7% of the total raw coal produced in China. With the highest heat value, the production of anthracite increases to 815 Mt in 2050. Lignite has the lowest heat value and the largest capacity for surface mines among the four types of raw coal. Due to the lower cost of surface mining, surface-mined lignite is still competitive. Therefore, the production of lignite is quite stable from 2020.

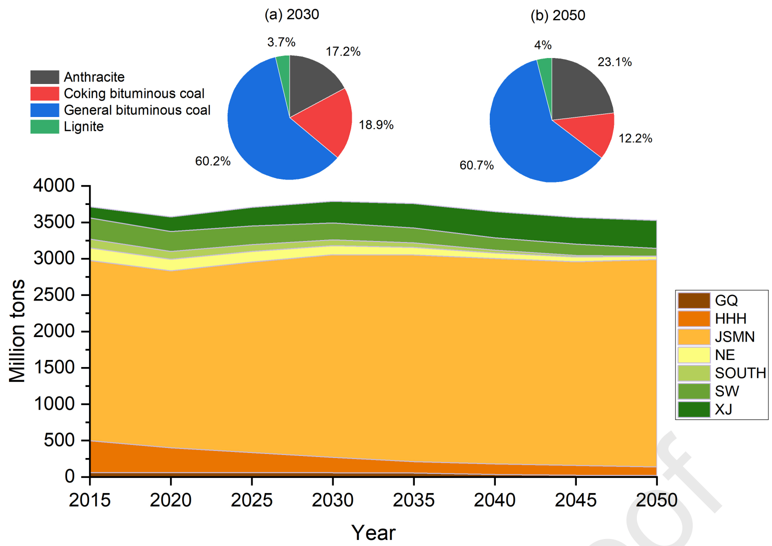

Fig. 4. China's regional raw coal production towards 2050 and the share of four types of raw coal in total raw coal production under the BAU scenario (pie chart).

3.1.2 National coal material flow

The national coal material flow under the BAU scenario for the year 2030 and 2050 are shown in Fig. 5. With the gradual changes in energy consumption structure, coal used for final consumption decrease to 602 Mt in 2050. Furthermore, the amount of coal transformed into coke also decreases significantly. On the contrary, the amount of coal transformed into liquids and SNG grows from 11 Mt in 2015 to 221Mt in 2050. In addition, coal consumed for power generation and heating shows an increasing tendency. Although power generation and heating from non-fossil energy increases, the growth in national electricity and heat demand lead to a higher demand for coal-fired power generation and heating. Besides, the amount of coal used in each sector is determined by the energy demand of the sector and the combination of coal types. For example, from 2030 to 2050, the demand for coal final consumption in heating value decreases by 31%. However, the amount of coal consumed in this sector decreasing by 38%.

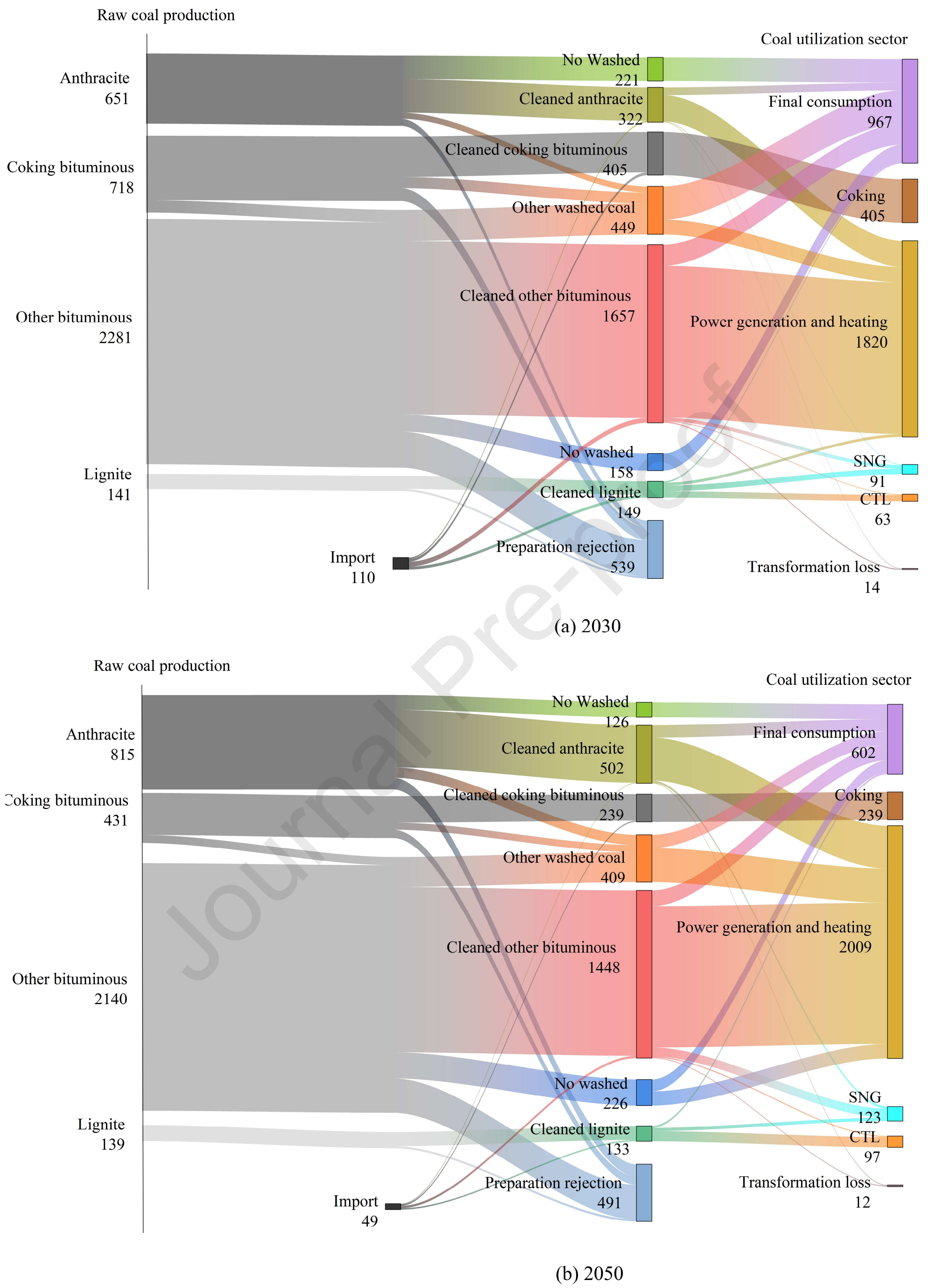

Fig. 5. The national coal material flow in 2030 and 2050 under the BAU scenario (Unit: Mt)

3.1.3 Inter-regional transportation

The total volume of coal transported among regions declines from 1303 Mt in 2015 to 1028 Mt in 2050 in a fluctuation way. JSMN region dominates regional coal export in China. SOUTH region, North region, and HHH region are the three main import regions of coal. Although XJ region has advantages in coal mining, coal transportation from this region is not observed during the modeling period. The long-distance from XJ region to the importing region limited its coal exports. Due to the higher heat value of cleaned coal, all the coal has been washed before transportation from 2020. This phenomenon reflects the advantages of cleaned coal in transportation.

In contrast, electricity transmission develops rapidly. This is mainly benefitting from the construction of UHV transmission lines. Several new UHV transmission lines will be built in the future. Totally, electricity is transmitted from JSMN region, SW region, XJ region, HHH region, and GQ region to SOUTH region, from JSMN region and XJ region to HHH region, from XJ region and GQ region to SW region, and from JSMN region to NE region in 2050.

3.2 Effects of non-fossil energy development

In the supply side, non-fossil energy is the main substitution energy for coal. A more positive target for non-fossil energy development is described in the GREEN scenario. In this scenario, raw coal production in China has already peaked in 2015, as shown in Fig. 6. The total raw coal production in 2050 under the GREEN scenario is 3191 Mt, which achieves a 9% reduction in total raw coal production in 2050 compared with the BAU scenario. Shifting more non-fossil energy to China's energy system will result in a reduction in coal demand. Under the GREEN scenario, the output of non-fossil energy grows up to 849 GWyr in 2050, about 140 GWyr higher than the BAU scenario. Moreover, the power generation and heating from natural gas are about 49 GWyr in 2050, only 6 GWyr higher than the BAU scenario. Consequently, coal used for power and heat supply in 2050 decreases by 287 Mt. The reduction of thermal coal in power and heat supply results in the reduction of national raw coal production in China.

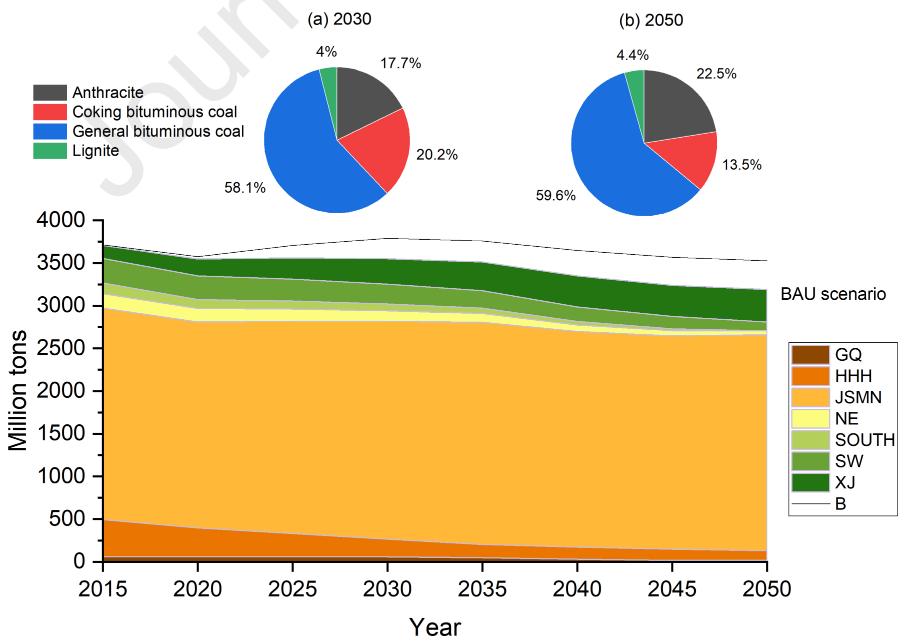

Fig. 6. China's regional raw coal production towards 2050 and the share of four types of raw coal in total raw coal production under the GREEN scenario (pie chart).

The distribution of coal production is similar to that under the BAU scenario. Raw coal production in

JSMN region reaches 2528 Mt, about 79% under the GREEN scenario for the year 2050. Moreover, raw coal production in XJ region increased to 327 MT in 2050, which comprises about 12% of national raw coal production in 2050. In terms of coal types, the proporation of different coal types is also similar to the BAU scenario. Under the GREEN scenario, the production of general bituminous coal accounts for 59.6% of the total raw coal produced in China, while anthracite account for 22.5% of China's total raw coal production in 2050.

3.3 The role of carbon price

The impacts of carbon price on the coal supply system are assessed in the BAU_50 scenario and the GREEN_50 scenario. China's national raw coal production has already peak in 2050 under these two scenarios. Under the BAU_50 scenario, the raw coal production in 2050 is 2859 Mt, about 19% lower than that under the BAU scenario. The GREEN_50 scenario could even decrease the national raw coal production to 2730 Mt, about 14% lower than the GREEN scenario (as shown in Fig. 7). Under the BAU_50 and GREEN_50 scenario, JSMN region accounts for 81% and 80% of national raw coal production in 2050 respectively. Furthermore, the production of anthracite reduces to 390 Mt under the GREEN_50 scenario, which comprises 14% of total raw coal production.

Under the carbon price scenarios, coal is not always the least expensive fuel. Thus, the development of non-fossil energy is further promoted. The electricity and heat supplied by non-fossil energy in 2050 is about 944 GWyr and 1035 GWyr under the BAU_50 scenario and the GREEN_50 scenario, respectively. Besides, the natural gas power generation and heating under BAU_50 and GREEN_50 reach 77 GWyr and 69 GWyr respectively. Under the carbon price scenarios, technology choice, especially for power generation (as shown in Fig. 8), is also profoundly affected. USC is currently a mature technology for power generation, and will (with and without CCS) dominates China's power system in the coming years. Power generation from CHP increases rapidly under the BAU scenario. However, under the GREEN scenario , non-fossil energy and natural gas heating is about 55 GWyr higher than the BAU scenario. Therefore, the heating demand for CHP is also decreased, which results in a slight decrease in power generation by CHP. Furthermore, new IGCC power plants will not be built in this analysis, except for the existing demonstration project in Tianjin, due to the high investment cost. Although CCS could reduce CO_2 emissions, the adoption of CCS in power plants causes an extra energy penalty and cost increases. Therefore, CCS is only adopted under carbon price scenarios.

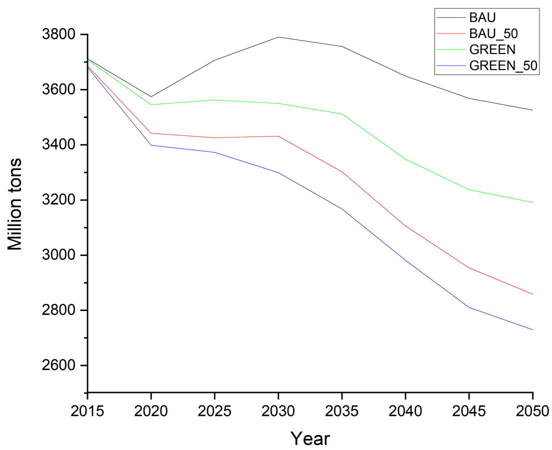

Fig. 7. Comparison of the national raw coal production under the carbon tax scenarios and non-fossil energy development scenarios.

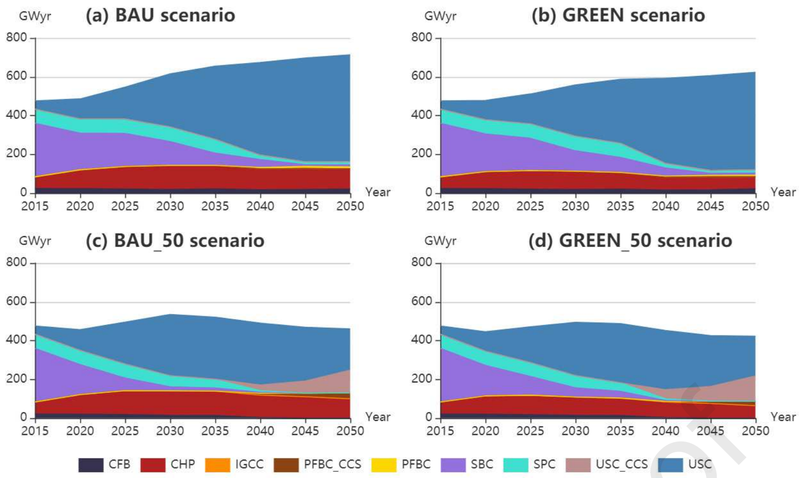

Fig. 8. Generation mix of coal-fired power plants under different scenarios

3.4 Comparison with other studies

As shown in Ref. [23-25], the raw coal production in China is projected to reach its peak between 2024 and 2030. However, some studies forecasting China's coal production peak arrive before 2020, which is similar to our study[26, 27]. In our analysis, China's national raw coal production will peak in 2030 under the BAU scenario. For the other three scenarios, it has already peaked in 2015.

As for regional raw coal production, we compared our results with Ref. [28, 29] and found that the developing trend of coal production industry layout is similar to existing studies. Here, raw coal production will be more concentrated in JSMN and XJ region. However, there are some differences. In Ref. [29], the coastal areas of Southeast China and Central China will exit coal mining around 2025. In our model, SOUTH region will exit coal mining from 2050 under all four scenarios. However, in Ref. [28], South China still produces coal in 2050 (with a small capacity). On the contrary, Northeast China will exit coal mining in 2050. Compared with these studies, our model considered a more integrated coal supply system, which may have a more reasonable result.

3.5 Coal-related GHG emission

In this model, the coal-related GHG emissions are calculated from a life-cycle perspective, which is constituted by CH_4 leakage in coal mining, CO_2 emissions caused by fuels consumed in coal and coke transport, and CO_2 and N_2O from coal utilization.

Coal-related GHG emissions in the four scenarios are present in Fig. 9. With the decreasing of coal demand, coal-related GHG emissions also show a downward trend under all four scenarios. In the BAU scenario, coal-related GHG emissions decrease to 7241 Mt in 2050. The GREEN scenario could decrease by 9% of coal-related GHG emissions compared with the BAU scenario in 2050. Carbon price has a significant effect on emission reduction. In the carbon price scenarios, coal-related GHG emission could be as low as 4735 Mt CO_2-equivalent in the BAU_50 scenario and 4381 Mt CO_2-equivalent in the GREEN_50 scenario for the year 2050. GHG emissions in the carbon price scenarios are significantly lower due to the utilization of CCS.

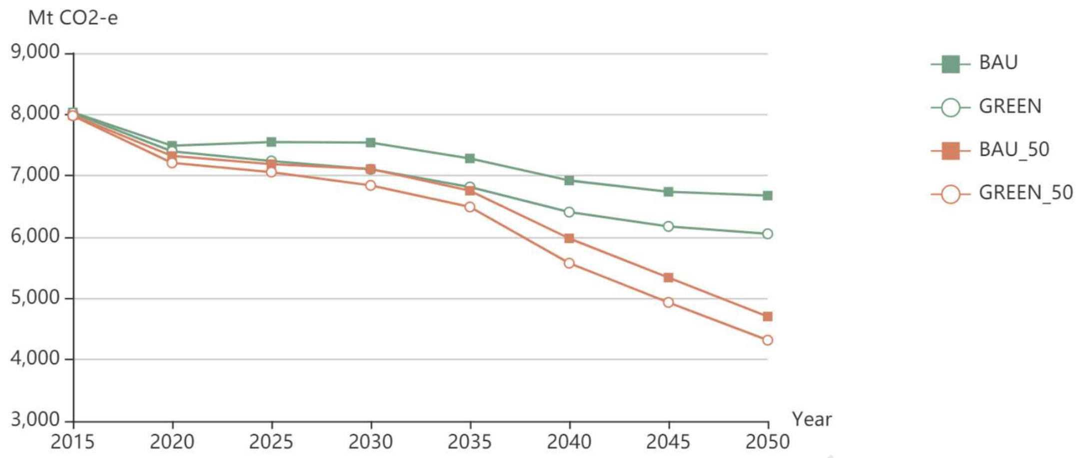

Fig. 9. Coal-related GHG emissions in four scenarios.

3.6 Sensitivity analysis

3.6.1 Sensitivity analysis of carbon price

The carbon price has a significant effect on coal supply, as shown in the model results. Here, we carry out a sensitivity analysis to assess the relationship between the carbon price and coal supply in China. We considered a 20% change in carbon price. This means the carbon price in 2015 is set as 40 yuan/ton (BAU_40 scenario) and 60 yuan/ton (BAU_60 scenario) with annual increasing rate of 5% based on the BAU scenario. National raw coal production under the BAU_40 scenario and the BAU_60 scenario are shown in Fig. 10. No surprisingly, all carbon price scenarios show a reduction in coal production comparing with the BAU scenario. However, even if the initial carbon price in 2015 increases or decreases by 20%, the national raw coal production is only slightly changed (about 3%) during the model period.

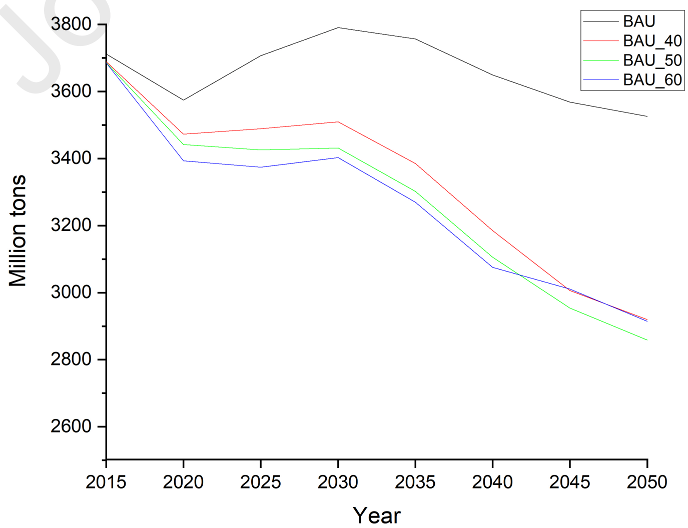

Fig. 10. Total raw coal production in different carbon price scenarios*.

* Compared with the BAU_40 and BAU_50 scenario, the decrease of raw coal production under the BAU_60 scenario is signitely slower from 2040. This is mainly caused by more CCS technology adopted under the

3.6.2 Sensitivity analysis of renewable energy cost

The development of non-fossil energy has a significant effect on the coal supply system, as analyzed above. However, the investment cost of renewable energy is still uncertain. Tang et al. assessed the low-carbon transition pathway of China’s power system, considering the cost uncertainty of solar and wind power generation technologies [112]. Although we have considered the cost decrease of wind and solar power generation technologies, their cost uncertainty on the coal supply system remains unclear. Therefore, a sensitivity analysis of solar and wind investment cost is carried out. We considered a high-speed decrease (HSD) for the investment cost of solar and wind power generation technologies according to Ref. [112], as shown in Fig. 11. The results are very similar before 2040. With the continuous decrease of the investment cost, raw coal production is significantly decreased after 2040. Finally, in 2050, the national raw coal production is about 6% lower than that under the BAU scenario.

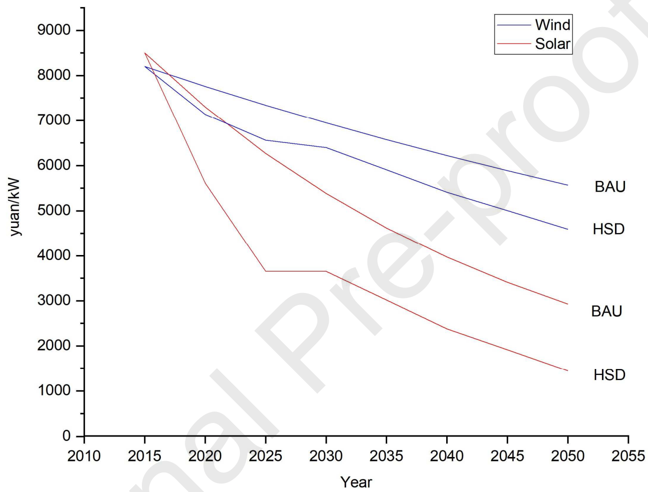

Fig. 11. Investment cost of wind and solar power generation technologies

4 Conclusion

This paper builds a multi-regional coal supply model through 2050, considering China’s coal classification. In the context of low-carbon development, requirements for clean production of coal and clean coal technologies are taken into consideration in the model. Moreover, two strategies of promoting the development of non-fossil energy and implementing carbon price are analyzed under four scenarios. The optimized results displayed China’s coal supply from different perspectives.

The results of the optimization model reveal that national raw coal production in China will peak in 2030 at 3791 Mt under the BAU scenario. Then, the national raw coal production will decreas to 3526 Mt in 2050. However, for the other three scenarios, it has probably peaked in 2015. This study also reveals the raw coal production layout in China through 2050. Coal mining will be more concentrated in JSMN and XJ regions in the future. The share of JSMN region and XJ region in total raw coal production is about 92% in 2050 under the BAU scenarios. What’s more, JSMN region will be the main coal export region in China. More UHV lines will be built to meet the electricity in HHH region and SOUTH region.

The amount of coal used in each sector is also analyzed in our model. Due to the structural changes in coal-related energy demand, the amount of coal used in final consumption and transformed into coke

BAU_60 scenario.

decreases, while coal transformed into liquids and synthetic natural gas grows to 221 Mt in 2050 under the BAU scenario. The economic competitiveness and environmental effects of the CTL and coal-to-SNG projects are still controversial. However, this is beyond the scope of this research. The development of CTL and coal-to-SNG technologies seem to provides a new increasing point for the coal industry. However, it still cannot hinder the coal production peak in China. The decrease of coal seems inevitable in China with the speeding up of electrification and technology development. Besides, both the energy demand and combination of coal types could influence the total amount of coal usage in one sector.

Through the scenario analysis, developing non-fossil energy and implementing carbon price would be effective ways to regulate China’s coal supply. In the GREEN and BAU_50 scenario, national raw coal production in 2050 is 9% and 19% lower than the BAU scenario respectively. Under the GREEN scenario, raw coal production in China could decrease to 2730 Mt in 2050.

Under carbon price scenarios, CCS is adopted, which leads to a significant reduction of coal-related GHG emission. Under the BAU scenario, coal-related GHG emissions in 2050 are about 7241 Mt. When a carbon tax is levied, coal-related GHG emissions in 2050 decrease to 4735 Mt under the BAU_50 scenario. In the GREEN_50 scenario, coal-related GHG emissions are further reduced, which could decrease to 4381 Mt in 2050.

Besides, there are also some limitations on our research. This study does not include specific sectors for coal final consumption. This may ignore the specific demand for coal quality and coal types. Besides, the alternative of other energy carriers for coal in these sectors is only reflected through the decline in coal final consumption, which is exogenous. Therefore, our further research will take these factors into consideration.

5 Acknowledgments

This work is supported by the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology (Beijing) opening foundation project [grant number SKLCRSM17KFB02] and Shanxi Province Joint Research Fund of Coalbed Methane [grant number 2015012017]. The authors appreciate Volker Krey for discussions during this research.

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Highlights

- A multi-regional coal supply model with four types of raw coal is developed.
- Raw coal production in China will peak in 2030 at 3791 Mt under the BAU scenario.
- Coal production will be more concentrated in JSMN region and XJ region.
- Raw coal output in the GREEN scenario is 9% lower than the BAU scenario in 2050.
- Carbon price scenarios have a significant effect on GHG emissions reduction.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: