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The impact of inter-regional transmission grid expansion on China's power sector decarbonization

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HIGHLIGHTS

- We quantify the energy, economic and environmental implications of inter-regional transmission grid expansion for China by 2030.
- The expansion largely benefits China in reducing generation costs and in securing power supply across regions.
- The expansion has a limited impact on mitigating the curtailment of renewable generation by 2030.
- The expansion slightly increases CO_2 emissions of the power supply in 2030.

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ABSTRACT

This paper investigates the impact of the inter-regional transmission grid capacity expansion on China's power sector decarbonization from the energy portfolio, economic efficiency and environmental perspectives. The impact is quantified based on a cluster integer unit commitment model which renders it suitable for modeling large-scale power systems with a high computational performance. The results show that, first, the inter-regional transmission grid capacity expansion has obvious economic benefit in reducing the total variable generation costs, mainly due to the increased ability of transmitting coal power with low marginal generation costs and the reduction in non-served load. Second, the expansion has a very limited impact on reducing the curtailment of renewable generation by 2030, although the extent to which the expansion can mitigate the curtailment of renewable generation increases with the share of renewable power in the generation portfolio. Third, the expansion increases CO_2 emissions of the power supply in 2030 by around 2%, mainly because it facilitates more use of cheap yet low-efficiency coal generation in regions with low fuel prices. To better deliver the value of the inter-regional grid expansion for China's power decarbonization, this paper proposes that: (1) the planning of the inter-regional and intra-regional grid development should be coordinated with the renewable power development; and (2) effective dispatch mechanisms which account for CO_2 emissions or generation efficiency across regions should be established. Additionally, the government plan of the inter-regional transmission capacity in 2030 is basically sufficient in enabling bulk power delivery and promoting renewable generation across regions.

1. Introduction

Given the fact that the power sector today accounts for about 40% of China's energy-related CO_2 emissions, electricity decarbonization is critical for China to accomplish a low-carbon economy [1,2]. In addition to promoting various low-carbon generation technologies (e.g. carbon capture and storage technologies), building a nationwide super-grid by expanding the inter-regional transmission grid is also proposed as one of the potential strategies to facilitate China's electricity decarbonization [3].

First, the inter-regional transmission grid is critical for China's power supply in view of the geographical imbalances between energy resources and electricity demand across regions. Specifically, most energy resources are situated in the North, Northwest and Northeast regions (also known as the three North regions), while the load centers are clustered in the East and South [4]. However, since China has historically focused on investments in the generation side, investments in the grid have been relatively limited. Although investments in the grid have increased to 45% of the total investments in the power sector during 2001–2009, it is still much lower than the international standard of 50–60% [5]. As a result, while the basic framework of inter-regional grid interconnections was established in 2005 [6], the total capacity of the

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inter-regional transmission grid has been quite limited so far [7]. As shown in Fig. 1, the total inter-regional transmission capacity was 47.40 GW by 2012, which is less than 5% of the national installed generation capacity [8]. Accordingly, about 80% of energy delivery across regions still relies on primary coal transportation (e.g. through railways and ships) [3].

More importantly, the fast development of generation capacity based on renewable energy sources (RES) in the three North regions puts additional stress on the development of the inter-regional transmission grid. As shown in Fig. 2, more than 70% of the national wind power capacity was centralized in the three North regions by 2013. If the growth of RES power continues like this, an increasing amount of RES generation must be exported across regions. Also, the flexibility of power system operations in the three North regions will be challenged by the increasing amount of RES generation considering the coal dominating generation portfolio in these regions. This concern has already been evidenced by substantial curtailment of wind generation in these regions during 2010–2011, especially in winter when most coal-fired power plants must keep running to supply heat demand [9]. Under such circumstances, expanding the inter-regional transmission grid becomes critical to increase the flexibility of the power system operation by re-distributing intermittent wind generation and thus promote the use of wind energy [10]. Further, the development of solar power will call for more inter-regional transmission capacity, as solar resources are concentrated in the Northwest and the North, which partially overlaps with the distribution of wind resources.

This paper aims to investigate the implications of the inter-regional transmission grid capacity expansion for China's power sector decarbonization, considering uncertainties arising from the penetration levels of RES power, environmental policies (CO_2 price) and the growth of electricity demand in the future. Many studies on China's power sector decarbonization have concentrated on the impact of technologies and policy interventions at the generation side (e.g. [12–15]) and the demand side (e.g. [16–18]), while very few studies have worked on the role of the inter-regional transmission grid. In particular, Chen et al. concluded that the government planned inter-regional transmission grid expansion can reduce CO_2 emissions of the national power supply in 2030 by around 10% (about 0.49 Gt), based on a power dispatch model which aims to minimize the CO_2 emissions of power supply on a yearly basis [3]. The work of Chen et al. shows the best possible contribution of the inter-regional transmission grid to mitigating CO_2 emissions, as the objective of power dispatch in practice is normally to minimize the system cost rather than CO_2 emissions. Moreover, Chen et al. did not model the variability of RES generation nor capture the key technical constraints in the power system operation (e.g. ramping constraints of power plants).

Given this, our work better quantifies the impact of the grid expansion by integrating the curtailment of renewable generation, the ramping up and ramping down, start-up and shut-down constraints for different generation technologies on an hourly basis. Our model furthermore features a high computational performance by adopting the cluster integer approach in [19] to the conventional unit commitment mode, which enables its applicability to model large-scale power systems. Additionally, this paper distinguishes itself by evaluating the impact of the inter-regional transmission grid expansion in China from the multiple perspectives of the energy portfolio, economic efficiency and environmental sustainability. This allows us not only to provide a comprehensive evaluation of the impact of grid capacity expansion concerning different policy goals, but also to explore the trade-offs of grid capacity expansion in achieving these goals.

Beyond China, many similar studies have been carried out for other countries. For instance, Brancucci et al. investigated the mid-term need for investing in cross-border transmission capacity in Europe considering different RES generation targets and CO_2 emission prices [20]. Schaber et al. investigated the impact of transmission grid expansion on electricity market and concluded

Fig. 1. The inter-regional transmission grid in 2012. Note that the numbers close to the lines indicate transmission capacity (in GW), and the arrows reflect the main directions of power flows. The data are compiled by the authors with data in [3,8].

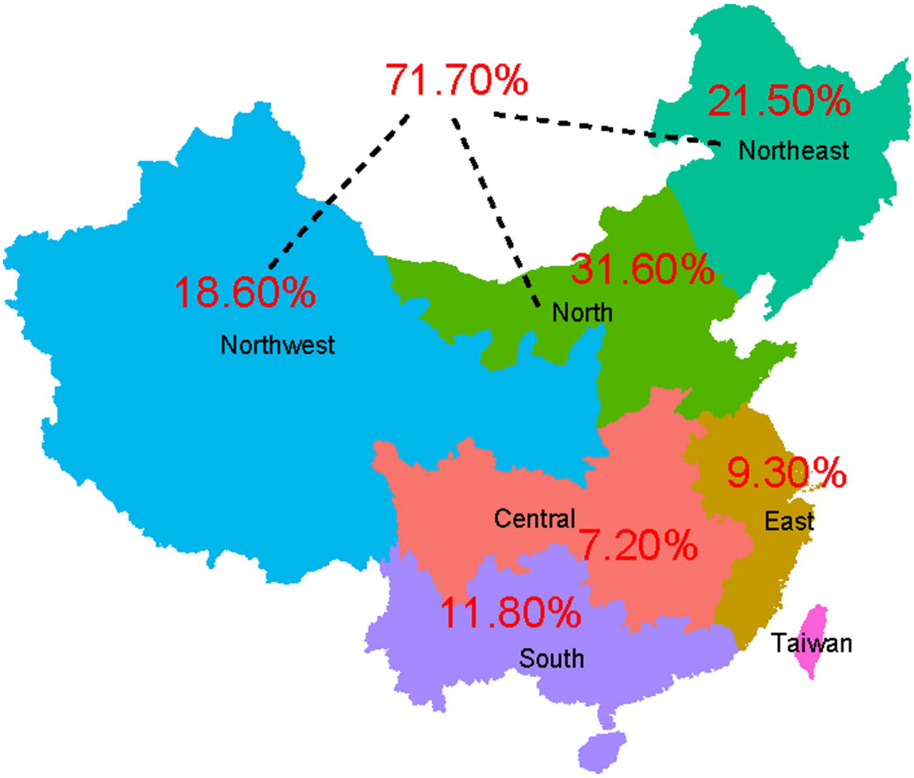

Fig. 2. The distribution of wind power capacity in China by 2013. The total capacity was 91.42 GW [11].

that the expansion helps alleviate the possible revenue losses for conventional fossil power suppliers arising from the competition with RES generation [21]. All these studies have provided useful insight for us in developing this work.

Specifically, this work answers two questions: (1) what is the impact of the inter-regional transmission grid capacity expansion on China's power sector decarbonization from the energy portfolio, economic efficiency and environmental perspectives? and (2) how are these implications affected by CO_2 price, electricity demand growth and RES penetration levels in the future? Based on answers to these questions, recommendations regarding the planning of the grid development are formulated for Chinese policy makers. This work quantifies the impact of the inter-regional transmission grid expansion with a multi-region power dispatch model. The model is applied to a set of scenarios of the 2030 power system which vary in the settings of: (1) inter-regional transmission capacity; (2) CO_2 prices; (3) electricity demand growth; and (4) RES power penetration levels.

The remainder of this paper is organized as follows. Section 2 explains the multi-regional power dispatch model. Section 3 introduces the scenario definitions and the key data for the scenarios. Section 4 analyzes the scenario results regarding the implications of expanding the inter-regional transmission capacity, and provides insight into the utilization of transmission lines. Section 5 analyzes the sensitivity of the results to CO_2 prices, electricity demand growth and RES power penetration levels. Section 6 discusses the policy implications for China regarding the planning of the grid expansion and final conclusions are given in Section 7.

2. Descriptions of the multi-region power dispatch model

2.1. Model structure and assumptions

The Chinese power system is modeled as a six-region power system reflecting the current division in network operation and power supply service across regions. The six regional power systems are the North, East, Central, Northeast, Northwest and the South, whose geographical distributions are shown in Fig. 1. More details about the spatial coverage of the six systems are shown in Table 1.

Table 1
The spatial coverage of the six regional power systems [22].

Regional power system	Spatial coverage (including provinces, municipalities and autonomous regions)
North	Beijing, Tianjin, Hebei, Shanxi, Shandong and West Inner Mongolia[a]
East	Shanghai, Jiangsu, Zhejiang, Anhui and Fujian
Central	Henan, Hubei, Hunan, Jiangxi, Sichuan and Chongqing
Northeast	Liaoning, Jilin, Heilongjiang and East Inner-Mongolia
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang and Tibet[b]
South	Guangdong, Guangxi, Yunnan, Guizhou and Hainan

[a] West Inner-Mongolia covers areas of Chifeng, Tongliao, Hulunbuir and Hinggan League of the Inner Mongolioa autonomous region; and East Inner Monlia is the rest part of Inner Mongolia.

[b] While Tibet used to be independent from the main power system, this work takes Tibet as part of the Northwest power system considering growing interconnections between Tibet and the regions of the Northwest power system (e.g. Qinghai).

In our model, each regional power system is represented by a single node with different generation portfolio and electricity demand. Specifically, the generation portfolio is represented by the combination of eleven generation technologies including seven fossil fuel-based technologies and four non-fossil generation technologies. The fossil-based technologies include small-coal,[1] sub-critical, supercritical (SC), ultra-supercritical (USC) and inte-

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[1] In the Chinese context, small-coal represents low-efficiency and high-polluting coal generation units, which specifically refers to the units with a capacity below 50 MW, or with operating lifetime longer than 20 years and a capacity is lower than 100 MW, or with a capacity lower than 200 MW yet reaching its economic lifetime.

grated gasification combined cycle (IGCC) coal turbines, combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT). The non-fossil generation technologies here are nuclear, hydro, wind and solar power. For a given fossil fuel-based technology, its generation capacity is composed of a group of generation units with the same economic and technical performance.

With regard to the modeling of non-fossil fuel-based power generation, we assume that: (1) the availability of RES power is exogenously determined based on the installed capacity and meteorological data; (2) curtailment of wind and solar generation is allowed; and (3) hydro power (except for pumped hydro storage) is used for base load and pumped hydro storage (PHS) is used either for generating or storing power depending on the demand. Modeling hydro power for base load basically implies that we neglect the role of reservoir plants[2] for supplying peak demand. We do so for the following practical reasons. In practice, run of river plants and reservoir plants can be combined in cascading river systems, and PHS can utilize the water stored in reservoirs plants, but we do not have access to data regarding the generation potential of reservoirs in China. Even if such data are available, to what percentage reservoir plants are used for supplying base load and for peak demand is hard to tell given the fact that reservoir plants are local-specific [23].

Modeling transmission capacity constraints is challenging considering market-based power transactions between two nodes cannot be directly translated to physical power flows on specific lines that connect these nodes in meshed networks [24]. Normally, intensive calculations of the power transfer distribution factor (PTDF) are required at each time step of the modeling to determine the physical power flows on specific lines. Given the limited computational capacity at hand, this work simplifies the modeling of power flows in the inter-regional transmission grid using market-based power flows. This means that the power flows are subject to the net transfer capacity between regions rather than the physical capacity constraints of specific transmission lines. In addition, to highlight the role of the inter-regional transmission grid in this work, the intra-regional grid congestion is not considered here, which means that the intra-regional grid is assumed as a copper-plate with perfect transmission capability.

2.2. Mathematical formulations

The proposed power dispatch model is a unit commitment (UC) model, which minimizes the system costs through optimizing the power output and the commitment states of generation units while satisfying certain system constraints. The unit commitment model in this work incorporates the transmission grid, pumped hydro storage and flexible demand (e.g. electric vehicles' charging),[3] which enables us to compare different flexibility providers for the power system operation. Compared with the conventional unit commitment model, our model adopts the clustered integer approach developed by Palmintier et al. in [19,25], which largely reduces the amount of the commitment state for generation units and thus makes it applicable for large-scale power systems. The key idea of the clustered integer approach is to group generation units by technology, so that the commitment state for a given technology group with N_g units can be expressed as an integer varying from 0 to N_g, representing how many units of this group are turned on. Hence, with the clustered integer approach, the amount of combinatorial commitment states for a group of N_g units is $N_g + 1$, which is much smaller than the conventional UC model with binary integer variables.

The mathematical formulation of the model is mainly based on the work in [20,19,25–29], as elaborated in Appendix A. Specifically, a UC model incorporating the constraints on transmission capacity is developed in [20], which provides the basic framework of the mathematical formulation here. How to reduce the amount of decision variables by using the clustered integer approach is introduced in [19,25]. The adoption of the clustered integer approach in UC models is applied in [26] to study the value of energy storage systems (ESS) in Europe. The modeling regarding the flexible demand here is mainly inspired by the work in [28,29].

3. Scenario definitions and data collection

3.1. Scenario definitions

The scenario year of 2030 is chosen to study the impact of the inter-regional transmission grid for China, since the year of 2030 includes most accessible projections of generation portfolio and the government's plan of the inter-regional transmission grid development. To experiment with different levels of inter-regional transmission capacity within the expected 2030 power system, four scenarios were defined, as shown in Table 2. Specifically, the "RefGE" represents the government planned transmission capacity, and other scenarios differ from the government plan in terms of transmission capacity. Since part of the data for the expected 2030 power system have been published by the authors in [30], here we only introduce the key data for this paper.

3.2. 2030 plan: inter-regional transmission grid

3.2.1. Grid topology and transmission capacity

Fig. 3 shows the government planned inter-regional transmission grid by 2030, which mainly reflects the overall design of the State Grid Corporation (SGC) and the China Southern Grid Corporation (CSG) [3]. The data in this figure are adapted from [3] with the following changes. First, this work integrates Tibet into the Northwest power system considering the increasing grid connections between them. Second, cross-border interconnection is beyond the scope of this research. Given that the planned cross-border transmission capacity will be around 20% of the inter-regional transmission capacity by 2030 (see Table 3), this work assumes cross-border transmission as a negative demand for the importing regions in China. Taking the cross-border transmission grid between Myanmar and the South for instance, a negative demand which equals the amount of the cross-border transmission capacity, 20 GW, is imposed on the South power system.

Based on these assumptions, the total inter-regional transmission capacity is planned to be expanded from 47.40 GW in 2012 to 308.40 GW in 2030. Comparing Fig. 1 with Fig. 3, we can observe that apart from the reinforcement of the existing inter-regional connectors, new transmission lines connecting the Northwest-East, Northwest-South, and the North-East will be built by 2030.

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[2] Hydro power plants are usually grouped into three categories: run of river, reservoir (storage) and pumped hydro storage. First, run of river plants are mostly driven by natural river flows or by releases from upstream reservoir plants. In the absence of reservoirs plants, run of river generation has a large dependence on the variability of inflows, which makes it mainly used for supplying base load. Second, reservoir plants can store water in upstream reservoirs, which are normally operated to follow the demand. Depending on the ratio of capacity and generation intentional, reservoir plants can be used for supplying base load or for peak demand. Third, in the PHS plants, water is pumped from a lower reservoir to an upper one or in the opposite direction, depending on the demand.

[3] The proposed model is originally developed to study and compare the values of different technical options that can increase the power system flexibility, including grid expansion, energy storage systems and flexible demand (which refers to flexible EV charging here). However, the authors have not incorporated the case of flexible demand by the time of writing, the value of flexible demand is therefore not studied in this paper. Just to provide reference for relevant studies considering the three flexibility options above, the model in this work keeps the flexible demand part.

Table 2
The scenario definitions with different expansion of the inter-regional transmission capacity.

Scenario name	Settings
NoGE (GE: grid expansion)	No new expansion of the transmission capacity during 2012–2030
LowGE	The capacity of each transmission line by 2030 is 50% of the planned capacity
RefGE	The transmission capacity by 2030 equals the planned capacity
HighGE	The capacity of each transmission line by 2030 is 1.5 times of the planned capacity

Table 3
The planned cross-border transmission grid by 2030 [3].

No.	Connected regions		Capacity (GW)
	From	To	
1	Myanmar	South	20.00
2	Kazakhstan	Central	9.00
3	Mongolia	North	18.40
4	Russia	Northeast	11.95

3.2.2. Transmission loss and cost

China has made much progress in improving energy efficiency for long-distance power transmission, and the average energy loss of the inter-regional transmission is expected to decrease from 6.5% in 2010 to 4.34% in 2030 [3]. Additionally, this work uses the transmission costs of the North-East line as the baseline, and the transmission costs of other lines are inversely proportional to energy loss. More data regarding the energy loss of transmission lines and the transmission costs are explained in [30].

3.3. 2030 projections: generation portfolio

3.3.1. National generation portfolio

China's macro-planning of the energy system is regularly issued on a five-year basis. Consequently, the planning of the mid-term generation portfolio by 2030 is not available. Hence, this work reviews the projections in the literature to gain an overall picture of the possible generation capacity expansion in China. The review scope covers projections published by key organizations in China (e.g. China Electricity Council [31], National Energy Administration [32]), industries, the scientific literature [3,33] and international associations [34], etc. Based on these resources, Table 4 summarizes the development of generation portfolio during 2012–2030. It mainly shows that: (1) in terms of the absolute amount of generation capacity, coal power will still be the largest one till 2030, followed by hydro, wind and nuclear power; and (2) in terms of the growth rate during 2012–2030, solar power will be the fastest one, followed by nuclear power, wind power and pumped hydro storage.

3.3.2. Regional generation portfolio

The national generation capacity in Table 4 is further allocated to the six regional power systems according to the following principles: (1) the national generation capacity for nuclear, wind, solar and hydro power is divided into the six regions using the same distribution ratio of the installed capacity by December 2013; and (2) the division of the national generation capacity for coal and natural gas power is mainly based on the regional data in [3]. The derived regional generation portfolios are illustrated in Fig. 4, which

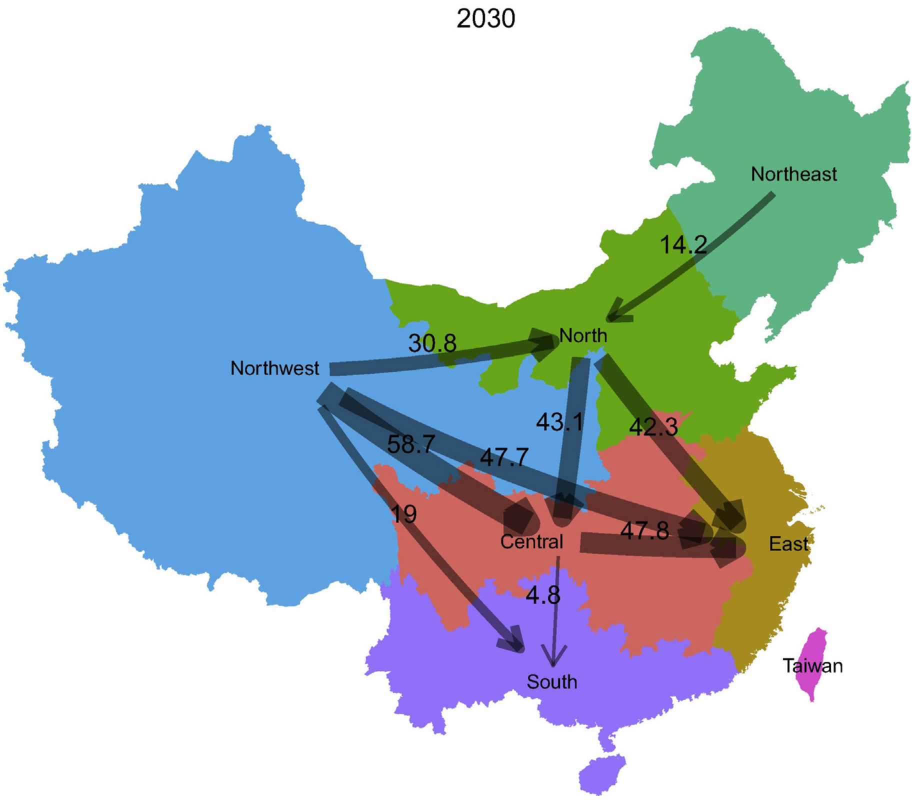

Fig. 3. The planned inter-regional transmission grid in 2030. Note that the numbers close to the lines indicate transmission capacity (in GW), and the arrows reflect main directions of power flows.

Table 4
The development of generation capacity by fuel type during 2012–2030.

Fuel	Generation capacity			Percentage	
	2012 (GW)	2030 (GW)	2030/2012	2012	2030
Coal	780.91	1388.25	1.78	67.03	51.48
Gas	38.27	142.44	3.72	3.29	5.28
Nuclear	12.58	200.00	15.90	1.08	7.42
Hydro	248.90	400.00	1.61	21.37	14.83
Wind	60.82	315.00	5.18	5.22	11.60
Solar	3.29	151.00	45.90	0.28	5.60
Hydro-pumping storage	20.20	100.00	4.95	1.73	3.71
Total	1164.97	2696.69	2.31	100	100

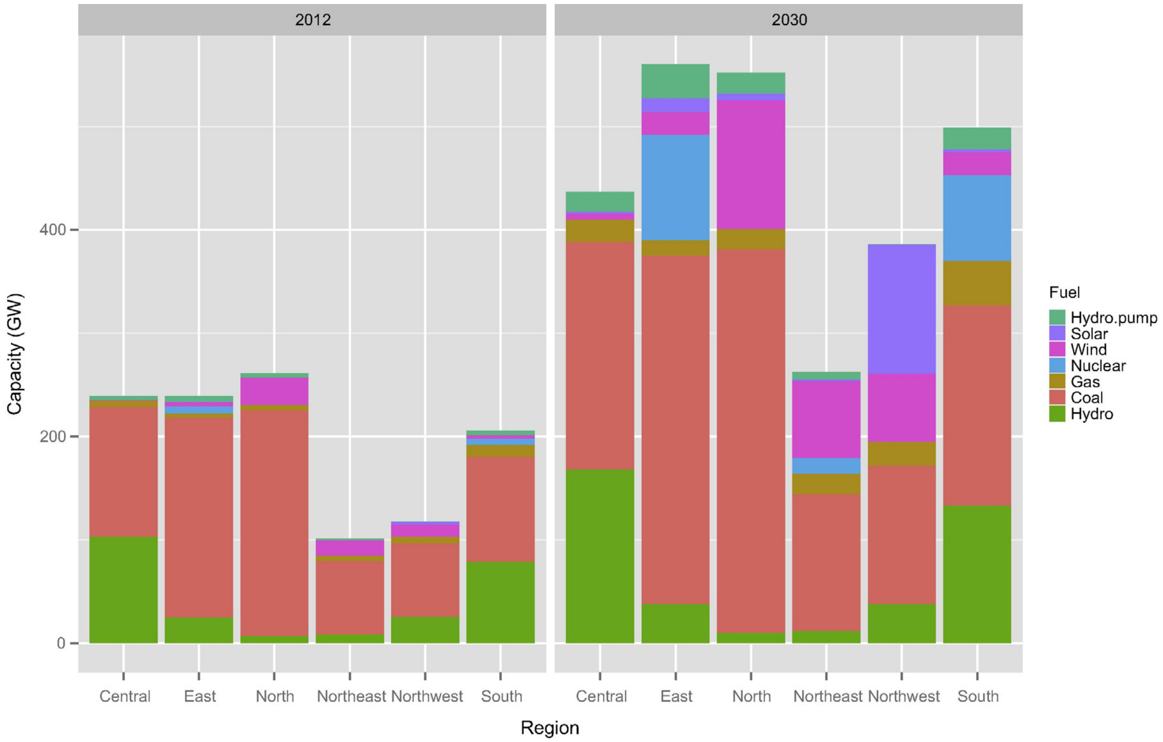

Fig. 4. The regional generation portfolio of 2012 and 2030. The data of 2012 are from [35], and the data of 2030 are compiled by the authors based on projections in the literature.

reflects a large diversity of power sources across regions. For instance, hydro power is mainly distributed in the Central and the South, solar power is concentrated in the Northwest, while nuclear power is mainly in the East, South and the Northeast.

3.3.3. *Fossil fuel-based generation technologies and fuel prices*

The parameters regarding the economic and technological performance of fossil fuel-based generation technologies are listed in Table B.13. The following paragraphs briefly introduce China's fuel prices.

Coal price. The electricity coal market in China has been deregulated since 2002. Currently, the North is the largest coal exporter with large coal mines in Shanxi, Inner Mongolia and Ningxia, followed by the Northwest with large coal bases in Xinjiang, Shaanxi, Gansu and Qinghai. The other regions are mainly coal importers [3]. The export of coal from the North and the Northwest is expected to increase considering the continuous growth of electricity demand in the load centers of China. In this work, the regional coal prices are simplified by setting the coal price of the North as a benchmark, and varying the prices of other regions depending on their geographical distances away from the North and the local economic prosperity. The variation of coal prices between regions is calibrated with historical data of 2010 and 2012. In addition, to reflect the scarcity of natural resources over time, this work assumes an increasing coal price during 2012–2030 with an average annual rate of 1%. More data regarding the coal price are shown in Table 5.

Natural gas price. China has a very limited amount of natural gas production, which has historically constrained gas-based power supply (currently at about 2%) [38]. Natural gas is mainly produced in Sichuan (Central), Shanxi (Northwest) and Xinjiang (Northwest). Different from the coal market, the gas market in China is still under government's regulation [38]. Since 2013, the state has started market-oriented reforms of the gas market[4] to gradually make the gas price reflect the balance between supply and demand, and to promote investments in gas infrastructure [37]. After the

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[4] The gas price after the reform is called two-tier price. Based on the volume of natural gas consumption in 2012, the natural gas in 2013 is divided into two tiers. The consumption that is lower than the 2012 quota remains the city-gate price with an increase not exceeding 0.4 CNY/m^3, which is also know as "quota" price. While the gas price for the consumption that exceeds the 2012 quota is dynamically calculated based on the price of fuel oil and liquefied petroleum gas (LPG) [37], which is also known as "above-quota" price.

Table 5
The fuel price data used in this work. The data are compiled by the authors with sources: [33,36,37,22]. The percentage within the bracket shows the variation of regional fuel prices relative to the benchmark (as shown by "Ref."), in which the North and the Northwest are the benchmark region for coal and gas prices respectively.

Regions	Coal price ($/ton)		Gas price ($/m^3)	
	2012	2030	2012	2030
North	64.00 (Ref.)	76.55	0.3584 (+40%)	0.4278
East	112.00 (+75%)	133.97	0.3880 (+52%)	0.4641
Central	112.00 (+75%)	133.97	0.3552 (+39%)	0.4249
Northeast	96.00 (+50%)	114.83	0.3232 (+26%)	0.3866
Northwest	51.20 (−25%)	61.24	0.2560 (Ref.)	0.3062
South	128.00 (+100%)	153.11	0.3632 (+42%)	0.4344

reform, the natural gas price has slightly increased in 2013, as shown in Fig. B.21. The market-oriented reform of the natural gas market is expected to be further expanded nationwide at the end of 2015. Similar to the coal price, this work assumes an annual growth rate of 1% for the natural gas price during 2012–2030. The specific data regarding regional gas prices are shown in Table 5.

Although we are fully aware that coal and gas prices in reality are highly uncertain and fluctuating, the difference between the real market price and the estimates used in this work hardly affects our results as long as the merit order of coal-fired and gas-fired power plants remains the same.

3.3.4. Meteorological data for RES power

The wind speed data is provided in the form of surface flux data which is composed of two vector components at a 10 m height with a six-hour interval [39]. Further processing of wind speed data is done, including spline interpolations to adjust to hourly wind speed data and converting wind speed to wind power based on wind turbine model E-33 [40]. More explanations regarding the wind power data are shown in [30].

The calculation of solar PV production is mainly based on the PVWatts calculator from the NREL,[5] which can automatically estimate the solar resource at or near a given location. For each regional power system, a location is chosen to represent the average solar power output in the region. More explanations regarding solar power data are illustrated in Fig. B.19.

As we mentioned in the model structure part, hydro power in this work is simplified as run of river power plants. The generation of run of river power plants highly depends on the amount of natural rainfall inflows, which varies substantially between seasons. The average annual utilization of hydro power generation in China is about 0.4 [36]. Depending on the abundance of hydro resources, this work categorizes the six regions into two groups, namely abundant and scarce areas. Specifically, the North and the Northwest have relatively less rainfalls so that they are considered to be scarce in hydro resources, while other regions are abundant. The hourly availability of hydro power is assumed to be the same for a given month, as illustrated in Fig. B.20, which is mainly based on the historical data in Guangxi province in the South [38].

3.4. 2030 projections: electricity demand

3.4.1. Total demand

During the past decade, China has experienced a fast growth of electricity demand with an average annual growth rate (AAGR) above 10%. Recently, the AAGR has slowed down from 7.5% in 2013 to 3.8% in 2014 [31]. Depending on the settings of population, GDP, economic structure, etc., the projections of electricity demand in the literature are widely different, as shown in [41,3,22]. Instead of providing an accurate forecast, this work focuses on testing out the impact of the grid expansion within certain scenarios of electricity demand growth. Hence, this work directly uses the electricity demand data in [3] given that it shows a relatively moderate projection. As shown in Fig. 5, the projected growth of electricity demand decreases over time considering the slow-down of economic development, from 5.80% during 2012–2020, to 3.08% during 2020–2030. The growth rate differs between regions. In general, the developed regions (e.g. North, East, Central and South) are in line with the national trend in terms of the growth rate. However, in the Northwest, a high drop of demand growth is expected during 2012–2020, while after that the growth becomes more stable.

3.4.2. Demand profiles

The data of regional demand profiles on an hourly basis for the Chinese case is not available. Therefore, this paper uses the data of four EU member states including Germany, France, Denmark, Italy to represent the regional demand profiles in China.[6] These four countries are chosen mainly because they show a large diversity in seasonal electricity demand, which is similar to the regional power systems in China. This work matches the reference of demand profile data between EU countries and the regional power systems in China. More explanations about this are provided [30].

4. Results analysis

This work first analyzes the impact of the inter-regional transmission capacity expansion from the economic efficiency, energy portfolio and environmental perspectives. To highlight the impact of the grid in the given 2030 reference scenario, CO_2 pricing is not yet considered in this section. Furthermore, this section investigates the utilization of the inter-regional transmission lines.

4.1. Economic efficiency

4.1.1. Total generation costs

Fig. 6 shows that expanding the inter-regional transmission grid obviously reduces the total generation costs of power supply. Specifically, the planned 2030 transmission expansion ("RefGE") reduces the total variable generation costs by 11% compared with that without any new expansion ("NoGE"). The marginal reduction in the costs decreases with transmission capacity, so that the differences in the costs between the "LowGE", "RefGE" and "HighGE" scenarios become negligible.

4.1.2. Cost decomposition

Fig. 7 shows that the reduction in the total costs caused by expanding the transmission capacity is mainly due to the reduction

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[5] NREL: National Renewable Energy Laboratory, http://pvwatts.nrel.gov/pvwatts.php.

[6] The data of demand profiles of EU member states are available on the website of the European Network of Transmission System Operators for Electricity (ENTSOE), with the link of https://www.entsoe.eu/data/data-portal/country-packages/Pages/default.aspx.

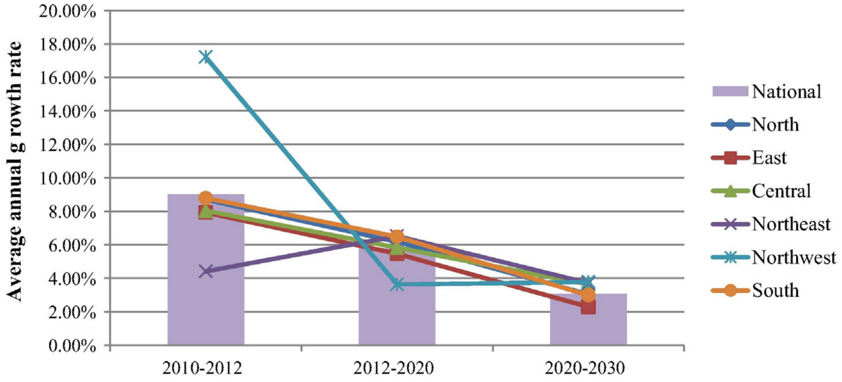

Fig. 5. The projected growth rates of electricity demand during 2012–2030 for the national and six regional power systems. The projections are from [3], and the historical data are from [42]. Note that the bars show the growth rates of the national electricity demand, and the marks represent the growth rates of regional electricity demand.

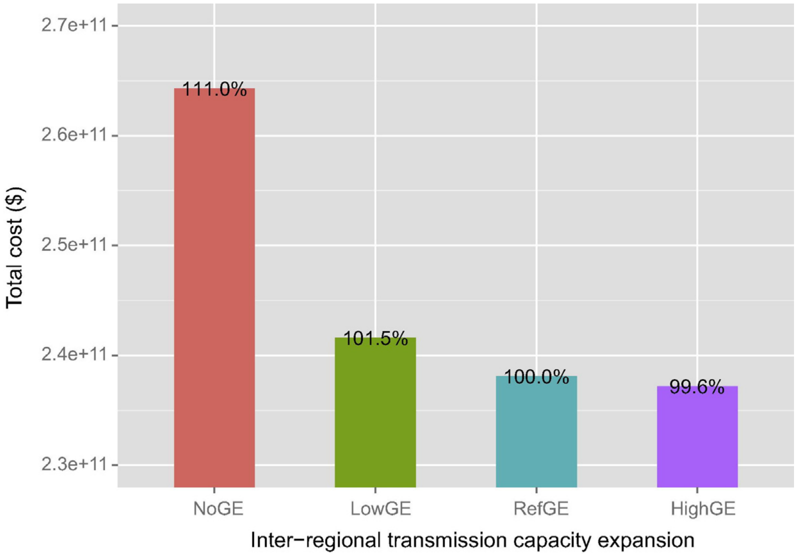

Fig. 6. The total variable generation costs for different scenarios. Note that the number close to the bar shows the relative difference of the costs between scenarios in percentage, in which the "RefGE" scenario is the reference case and thus is marked with 100%.

in fuel costs and in non-served load costs. The changes in other types of costs (e.g. transmission costs and start-up costs) are relatively smaller.

First, the reduction in fuel costs is because of the increased ability of the transmission grid to deliver power with low marginal generation costs. The degree to which the inter-regional transmission grid can reduce fuel costs largely depends on the difference in regional marginal generation costs, and this difference is mainly influenced by regional fuel prices. Second, the reduction in non-served load costs reflect the mitigation of non-served load, as the costs for per unit of non-served load are fixed in the model and assumed to be 1 million $/GWh. Non-served load is mainly caused by insufficient generation capacity at certain peak demand hours for some regions when the inter-regional transmission capacity is insufficient. Expanding inter-regional transmission capacity largely mitigates the insufficiency of generation capability for some regions through inter-regional electricity exchange, and thus contributes to mitigating the non-served load.

4.2. Energy portfolio

4.2.1. Non-RES generation

Fig. 8 shows that, first, expanding the grid capacity increases coal-based generation in the North, Northwest and the Northeast, while reducing coal-based generation in other regions. This happens because the marginal generation costs of coal-based power in the three North regions are lower than other regions for their low regional coal prices. In these circumstances, the expansion of the inter-regional transmission grid facilitates more exchange of coal-based generation across regions. Second, the grid capacity expansion largely reduces gas-based generation in the Central, Northwest and North, while the gas-based generation in other regions is not much affected. The implications, then, are expanding the inter-regional transmission capacity reduces the need for flexibility of the power system operation that is provided by gas power plants, especially for the regions where the penetration level of RES power is high. Third, the grid capacity expansion does not obviously affect the use of nuclear generation, except for the slight increase of nuclear generation in the South.

Fig. 9 shows what types of fossil fuel-based generation technologies are most influenced by the transmission capacity expansion. First, we observe that the generation from sub-critical technology in the North, Northwest and Northeast largely increases with the transmission capacity, while the generation from ultra-supercritical technology in the Central, East and South reduces. This implies that expanding the inter-regional transmission capacity promotes more low-efficiency coal-based generation in the regions where coal prices are low, as long as their marginal

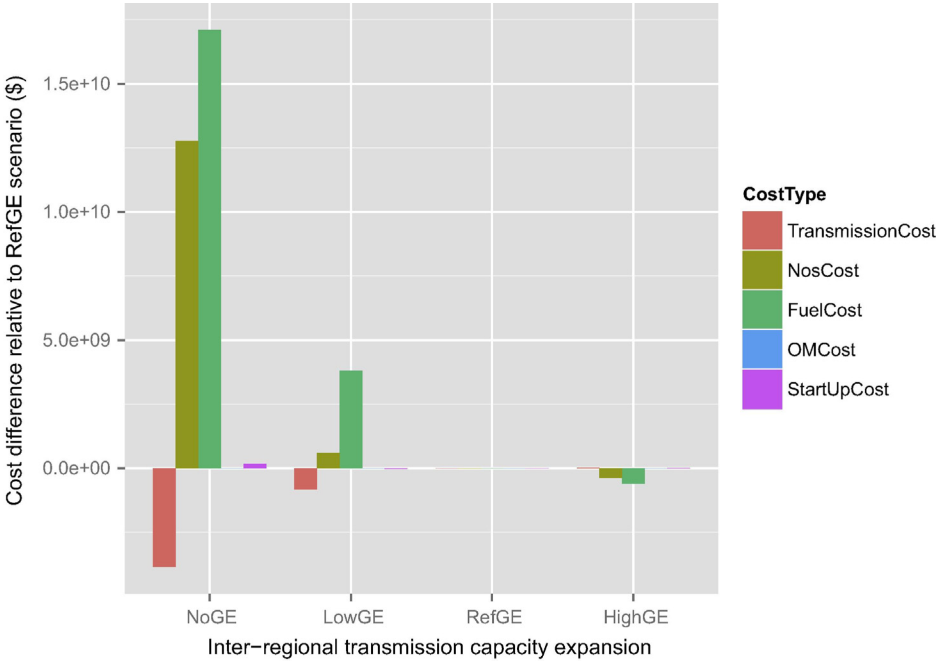

Fig. 7. The difference of costs between the "RefGE" and other scenarios. The "RefGE" scenario is the reference case so that its cost difference is zero. The total generation costs are comprised of: start-up cost (StartUpCost), operation and maintenance cost (OMCost), fuel cost (FuelCost), non-served power cost (NosCost) and transmission cost (TransmissionCost).

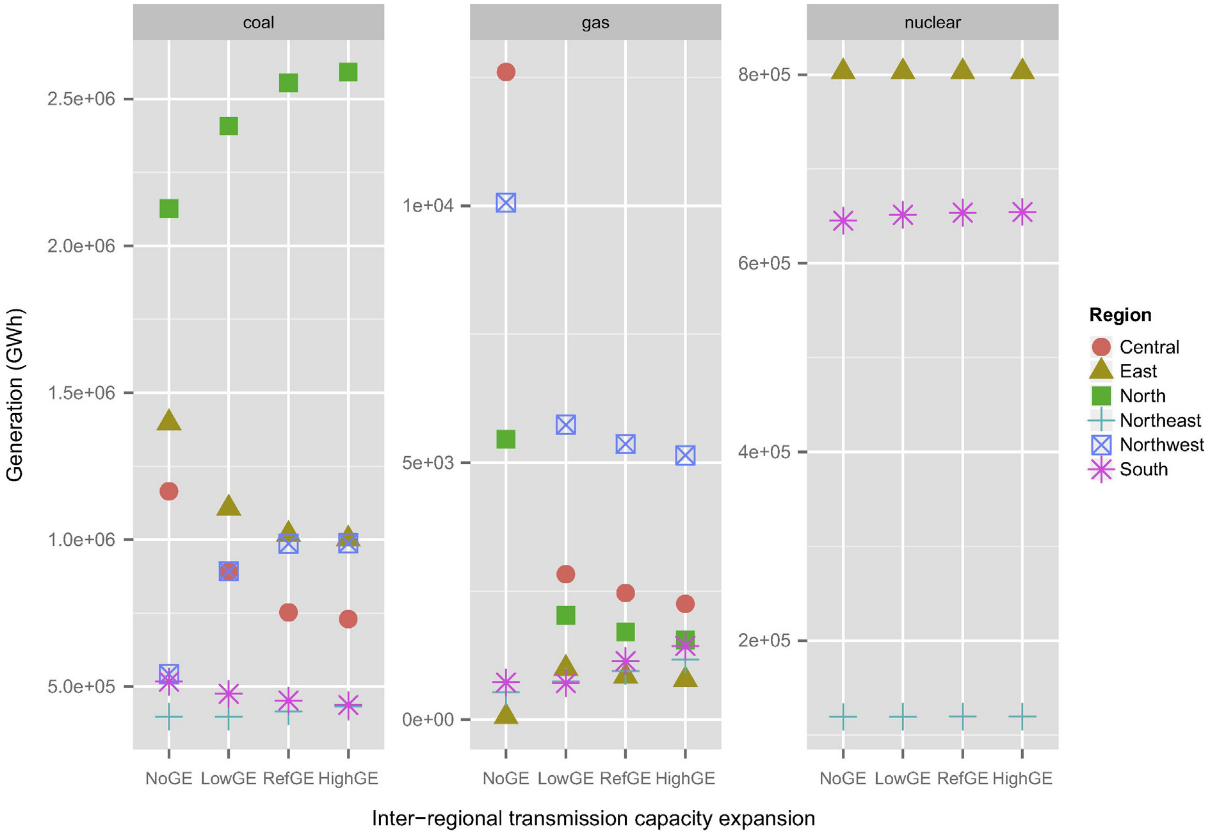

Fig. 8. The non-RES generation by fuel type for each regional power system under different scenarios.

costs are lower than those of high-efficiency technologies in other regions. Considering the slight difference in generation efficiency between technologies, regional coal prices are decisive in determining the differences in marginal generation costs of various technologies across regions.

With regard to the national generation mix, it is clear that expanding the inter-regional transmission grid increases the generation from sub-critical coal technology, which in turn substitutes part of the generation from ultra-supercritical technology. The influence of the transmission capacity expansion on gas-based

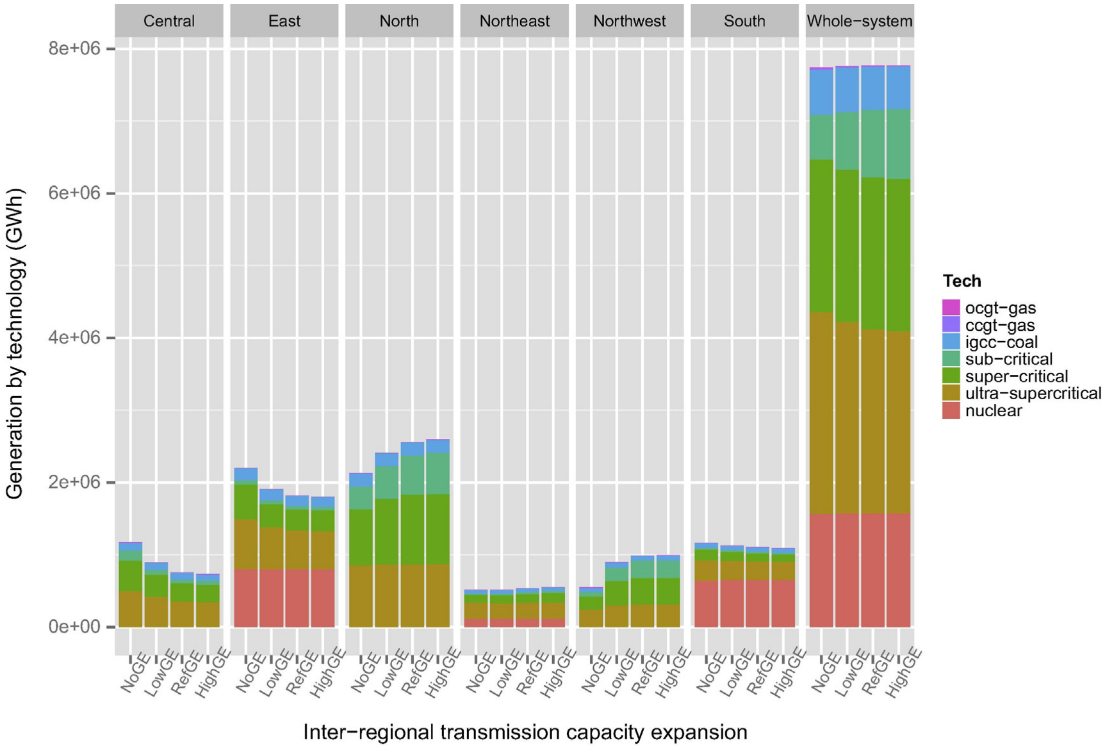

Fig. 9. The non-RES generation by technology for each regional power system under different scenarios. Note that the whole-system in this figure represents the national power system.

Table 6
The curtailment rate of wind and solar generation in percentage under different transmission capacity scenarios.

No.	Grid expansion scenario	Curtailment rate (%)		
		Solar	Wind	Wind & solar
1	NoGE	5.44	2.88	3.37
2	LowGE	0.35	0.11	0.16
3	RefGE	0.00	0.05	0.04
4	HighGE	0.00	0.04	0.03

generation is negligible given the fact that the share of gas-based generation is very small.

4.2.2. RES generation

Table 6 shows to which extent expanding the inter-regional transmission capacity can mitigate the curtailment of wind and solar generation. In general, expanding the inter-regional transmission capacity has a limited impact on promoting the use of RES generation.[7] For instance, the planned 2030 grid expansion merely reduces the curtailment of wind and solar generation by 3.34% relative to the “NoGE” scenario.

Furthermore, we observe that the curtailment rates of wind and solar generation in the “LowGE”, “RefGE” and “HighGE” scenarios are all lower than 0.5%, and the differences between these scenarios are negligible. Hence, we deduce that the government planned inter-regional transmission capacity expansion is basically sufficient for promoting RES generation, if the RES penetration level develops as expected.

4.2.3. Non-RES vs. RES generation

Although inter-regional transmission capacity expansion slightly changes the national generation mix by technology, it does not change the fact that China’s power supply still heavily relies on fossil fuels by 2030. Specially, coal-based generation in total accounts for about 58% of the national power supply. RES generation accounts for merely 22% of the national total, in which hydro power has the largest share (12.9%), followed by wind power (7.4%) and solar power (1.7%). Nuclear generation accounts for about 15% of the national power supply. In general, the ratio between RES and Non-RES generation does not change much with different levels of transmission capacity expansion.

4.2.4. Fuel consumption

Fig. 10 shows to what degree expanding the inter-regional transmission grid can affect the fuel consumption for national power supply. We find that, in terms of the relative proportion, the expansion slightly increases coal consumption and largely reduces gas consumption. Hence, the expansion is more likely to promote more use of coal in power supply and largely discourage the use of gas, especially in the absence of CO_2 emission-related regulations.

4.3. Environmental impact

Fig. 11 shows that expanding the inter-regional transmission capacity increases the CO_2 emissions of power supply. Compared with the “NoGE” scenario, the planned transmission expansion (“RefGE”) increases the CO_2 emissions in 2030 by around 2%. Based on the analysis in Section 4.2, the causes of the increase in CO_2 emissions are evident. First, expanding transmission capacity facilitates more use of coal generation, yet less gas-based generation, as shown in Fig. 8. Second, the expansion facilitates more use of low-efficiency coal generation in regions with low coal prices, which partially substitutes high-efficiency coal generation in other regions, as illustrated in Fig. 9. With the absence of CO_2 emission-concerned regulations, the inter-regional transmission capacity expansion is therefore at risks of resulting in more CO_2 emissions of the power supply.

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[7] Here the RES generation merely refers to wind and solar generation, since this work assumes that hydro generation is fully utilized so that we do not consider the impact of grid on hydro power generation here.

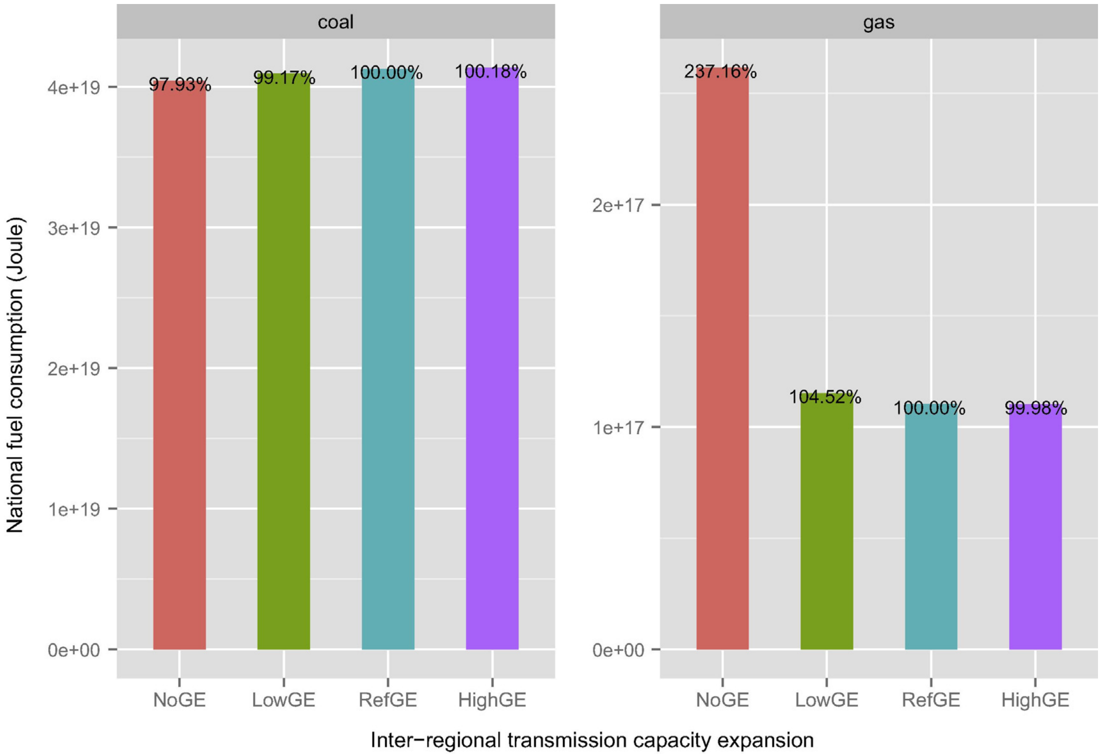

Fig. 10. The national fuel consumption for different scenarios. Note that the number close to the bar shows the relative difference of fuel consumption between scenarios in percentage. The “RefGE” scenario is used as the reference case so that it is marked with 100%.

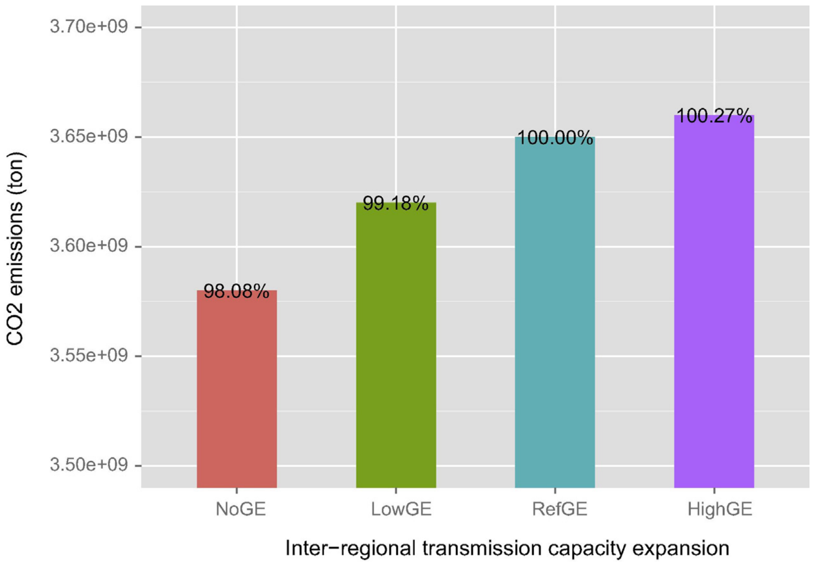

Fig. 11. The CO_2 emissions for different scenarios. Note that the number close to the bar shows the relative difference of the CO_2 emissions between scenarios in percentage. The “RefGE” scenario is the reference case so that it is marked with 100%.

4.4. Utilization of the inter-regional transmission lines

4.4.1. Inter-regional power exchange

Fig. 12 shows the amount and directions of exported power each transmission line[8] in 2030. This figure shows that, first, three transmission lines are most used in terms of the total amount of power exchange going through them, namely the lines connecting the North-East, North-Central and the Northwest-Central. Second, with the increase of transmission capacity, the power exchange between the Northwest-East is partly substituted by that of the North-East.

Table 7 shows that the percentage of inter-regional power exchange in national electricity demand for different scenarios. With the “RefGE” scenario, the inter-regional power exchange accounts for about 11% of the national electricity demand. The marginal increase in inter-regional power exchange between the “RefGE” and “HighGE” scenario becomes negligible, which implies that the amount of transmission capacity in the “RefGE” scenario is basically sufficient for enabling inter-regional power exchange.

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[8] Note that the line hereinafter represents an aggregated connection of all lines between two regions, rather than one physical line.

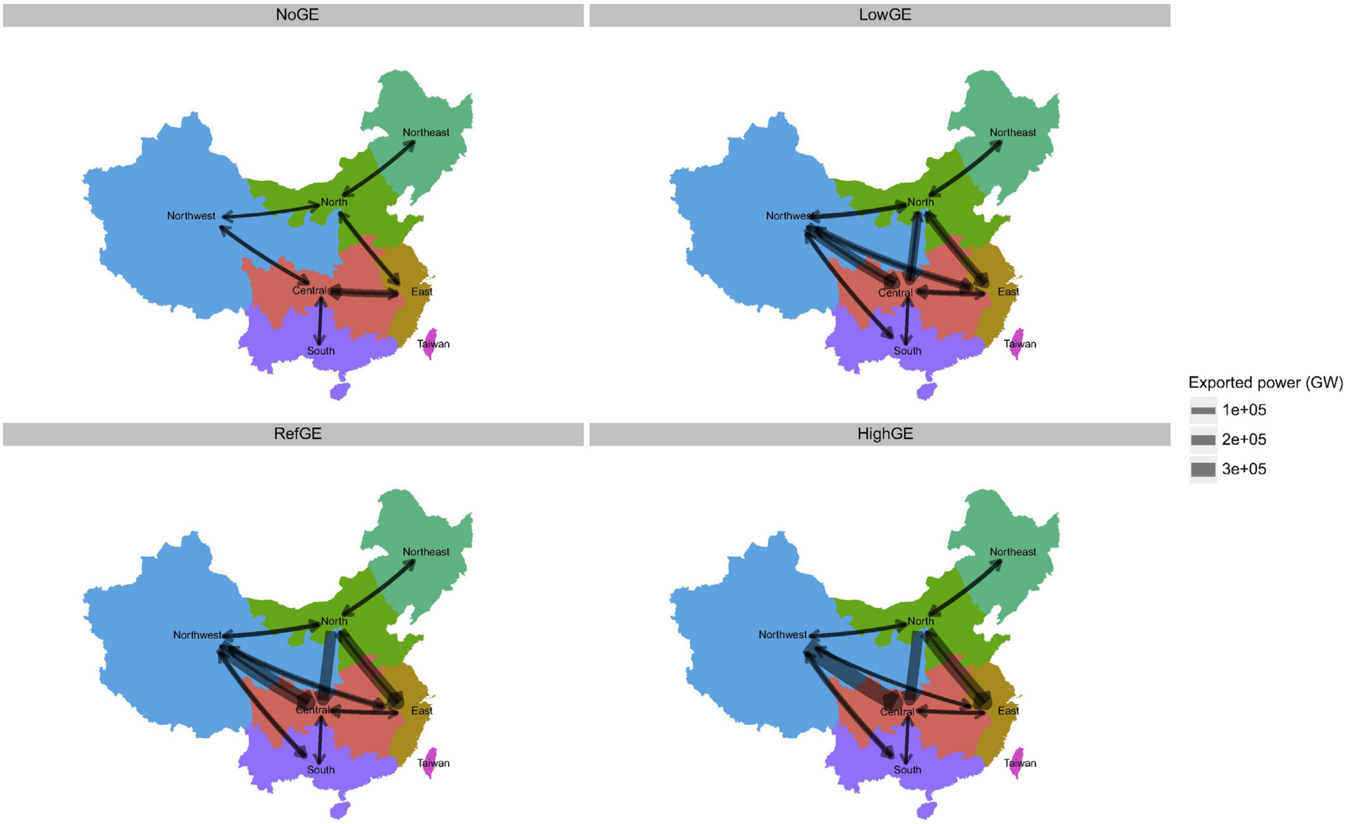

Fig. 12. The amount and directions of exported power for each transmission line in 2030 (in GW). Note that the width of the line indicates the amount of exported power through the line, and the arrow shows the direction in which the power is exported to.

Table 7
The amount of the inter-regional power exchange in national electricity demand.

No.	Grid expansion scenario	Amount of inter-regional power exchange (GWh)	Power exchange vs. national electricity demand (%)
1	NoGE	264983.40	2.51
2	LowGE	963703.90	9.12
3	RefGE	1186646.40	11.23
4	HighGE	1216265.70	11.51

4.4.2. Utilization rates of the transmission lines

Fig. 13 shows the utilization rate for each transmission line, which is calculated by the percentage of hours that a line is used to deliver power in the whole year. Clearly, the utilization rates of all transmission lines decrease with increasing transmission capacity. However, the lines between the Northwest-Central, Northwest-North, North-East, Northwest-South and the Northeast-North, all have utilization rates higher than 70% even in the “HighGE” scenario. In addition, it shows that the utilization rates of some lines largely decrease with transmission capacity. For instance, the utilization rate of the Central-South line reduces to about 20% with the “HighGE” scenario. Considering the relative cost competitiveness between transmission lines, the power flow through one line might be replaced by that through other lines, when sufficient transmission capacity is in place.

This work also analyzes the congestion of transmission lines which is indicated by the amount of hours that the exported power through a given line exceeds its maximum transmitting capacity. The results show that only the Central-East line is more likely to be congested yet only for few hours per year. For instance, the congestion rate of this line in the planned scenario is about 0.2% (17.52 h).

5. Sensitivity analysis

This section focuses on the sensitivity of the above scenario results to the following key uncertainties: (1) CO_2 price; (2) electricity demand; and (3) RES penetration levels. The settings of these three sensitivity factors are listed in Table 8.

5.1. CO_2 price

Fig. 14 shows that imposing an assumed CO_2 price of 50 $/ton largely increases the total generation costs, as expected. The CO_2 price lowers the capability of a certain amount of grid expansion in reducing the generation costs. For instance, in the “HighCP” scenario, the planned expansion (“RefGE”) reduces the total costs by 5.6% (relative to the “NoGE”), while it can reduce the costs by around 11% in the “NoCP” scenario. This is mainly due to: (1) the CO_2 price makes gas power having lower marginal generation costs in some regions (e.g. Northwest) than coal power in other regions (e.g. South), which slightly promotes gas generation which has higher costs than coal generation; and (2) it reduces the differences in marginal generation costs between various coal power technologies across regions, which reduces the incentive for inter-regional exchange of coal power (see Table 9).

Fig. 15 shows that the CO_2 price reduces the additional CO_2 emissions caused by a given amount of inter-regional transmission capacity expansion, yet to a negligible degree. This is mainly due to the fact that the assumed CO_2 price only slightly increases the use of gas in some regions (e.g. Northwest), which cannot fundamentally change the merit order between coal and gas-based generation, so that the share of gas-based generation remains limited. Hence, CO_2 pricing hardly increases the cost competitiveness of gas power against coal power, given the big gap between coal and gas prices in China.

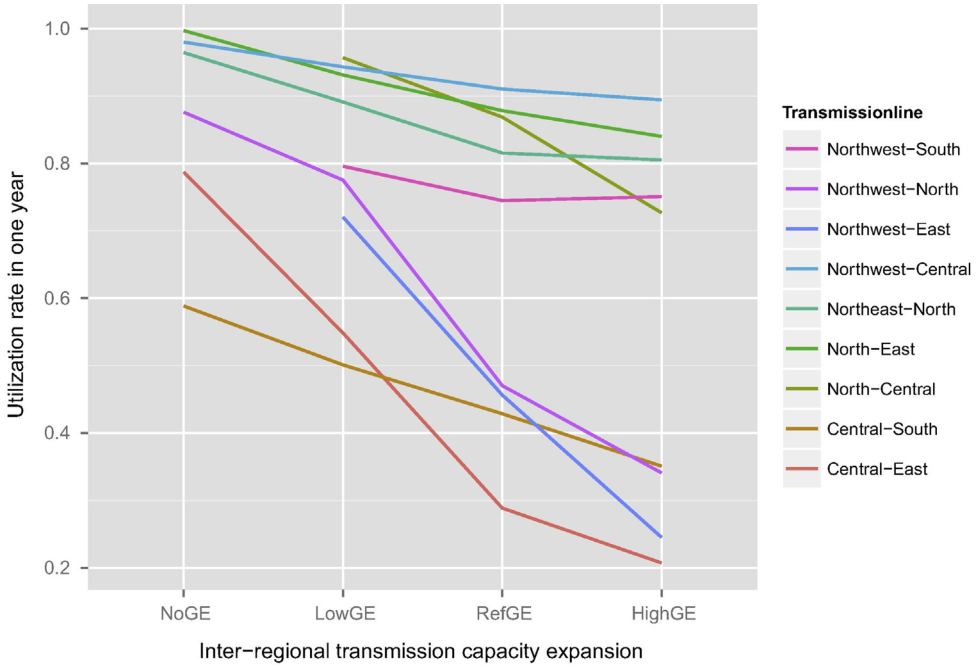

Fig. 13. The utilization rate of each transmission line, which is calculated by the percentage of hours that the line is used to transport power in the whole year.

Table 8
The settings of the sensitivity factors.

Sensitivity factors	Scenario indicator	Settings
1. CO_2 price	NoCP HighCP	The reference value, no CO_2 price The CO_2 price is 50 $ per ton CO_2 emissions
2. Electricity demand	RefDem HighDem LowDem	The reference value Regional electricity demand is 1.2 times of that in the "RefDem" scenario Regional demand is 20% less than that in the "RefDem" scenario
3. RES penetration levels	RefRES HighWind HighSolar	The reference value The wind power capacity for each region in 2030 is 1.5 times of that in the "RefRES" scenario The solar power capacity for each region in 2030 is 1.5 times of that in the "RefRES" scenario

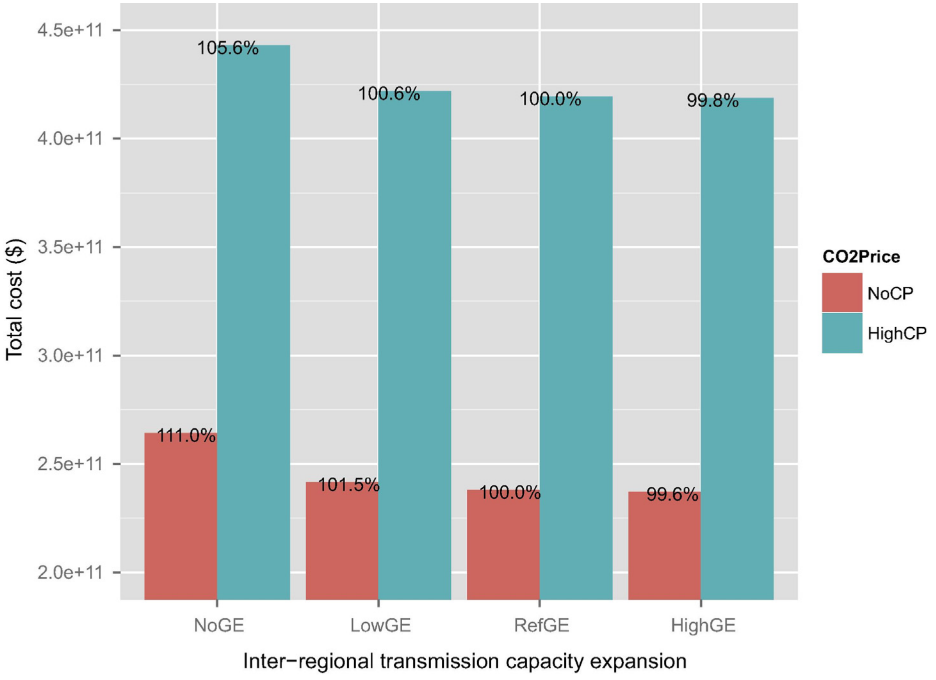

Fig. 14. The total generation costs for the scenarios with different inter-regional transmission capacity expansion and CO_2 prices. Note that the number close to the bar shows the relative difference of the costs between scenarios in percentage. The "RefGE" scenario is used as the reference case so that it is marked with 100%.

Table 9
The amount of inter-regional power exchange with different inter-regional transmission expansion and CO_2 prices.

No.	Grid expansion scenario	Power exchange vs. national demand (%)	
		NoCP	HighCP
1	NoGE	2.51	2.46
2	LowGE	9.12	8.01
3	RefGE	11.23	9.26
4	HighGE	11.51	9.43

5.2. Electricity demand

Fig. 16 shows that the economic benefit for a given amount of transmission capacity largely increases with electricity demand. For instance, within the "HighDem" scenario, the "RefGE" reduces the total generation costs by 24.5% (relative to the "NoGE"), which is 13.5% higher than that in the "LowDem" scenario. The increased economic benefit from the grid expansion in the high demand situation stems from the reduction in the non-served load costs. The amount of non-served load badly increases with electricity demand, especially in the regions where RES penetration levels are high. Hence, expanding transmission grid capacity is especially more important in high demand scenarios by mitigating the amount of non-served load.

5.3. RES penetration levels

Fig. 17 shows that the degree to which expanding inter-regional transmission capacity can reduce RES generation curtailment

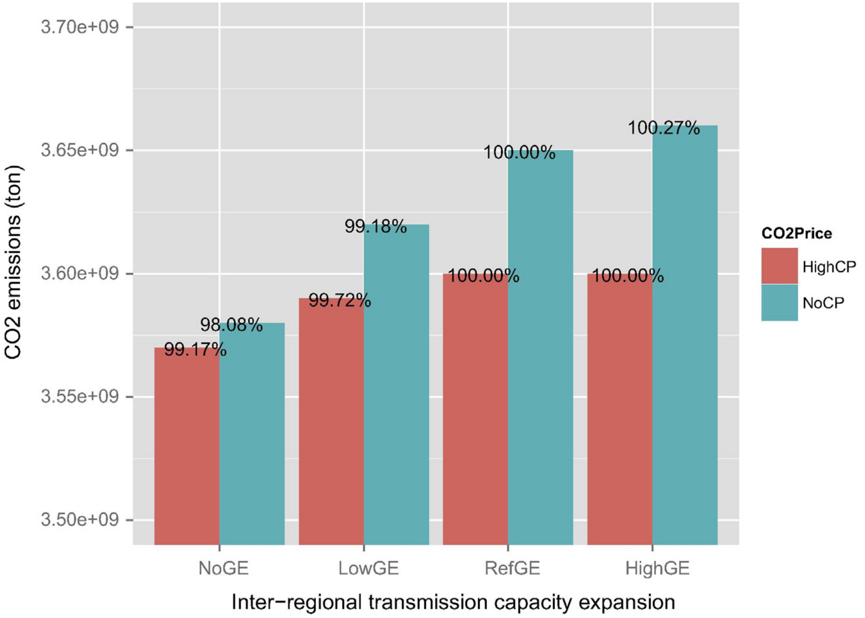

Fig. 15. The total CO_2 emissions with different inter-regional transmission expansion and CO_2 prices. Note that the number close to the bar shows the relative difference of the CO_2 emissions between scenarios in percentage. The "RefGE" scenario is used as the reference case so that it is marked with 100%.

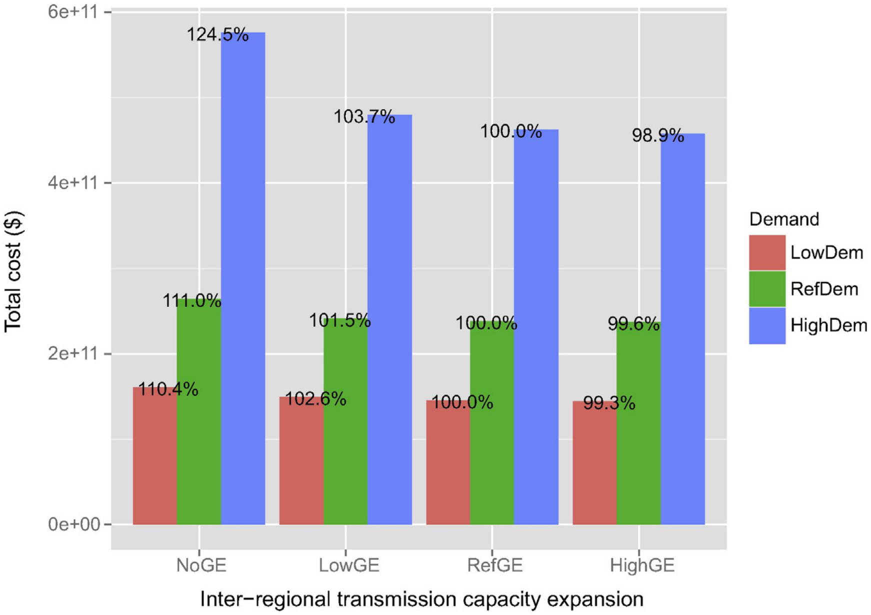

Fig. 16. The total generation costs for the scenarios with different inter-regional transmission capacity expansion and electricity demand. Note that the number close to the bar shows the relative difference of the costs between scenarios in percentage. The "RefGE" scenario is used as the reference case so that it is marked with 100%.

increases with the RES penetration level. For instance, with the “HighSolar” scenario, the “RefGE” can reduce wind and solar generation curtailment by 7.59% (relative to “NoGE”), which is around 2.5% higher than that in the “RefRES” scenario. Inter-regional transmission expansion will become more significant for mitigating RES generation curtailment as the penetration level of RES power increases. However, unless the RES penetration level is much higher than what we assumed, the impact of expanding inter-regional transmission capacity on promoting wind and solar generation is very limited by 2030. For instance, the maximum reduction in wind and solar generation curtailment facilitated by the grid expansion in all scenarios of this work is less than 8%.

Fig. 18 shows that, the higher the RES penetration level, the lower the CO_2 emissions of national power supply, which is just as expected. However, within all the assumed scenarios, expanding inter-regional transmission capacity increases the CO_2 emissions of national power supply in all scenarios although at different degrees. This implies that unless the penetration level of RES becomes extremely high (which should of course be much more ambitious than our assumptions), the increased CO_2 emissions facilitated by grid expansion (mainly from increased use of coal-based generation) cannot be counteracted by the increased use of RES generation.

6. Discussions and policy implications

The scenario results and sensitivity analysis above clearly show the trade-offs of expanding the inter-regional transmission grid capacity in achieving energy security, economic efficiency and the environmental goals. To better deliver the value of the inter-regional transmission grid for China’s power sector decarbonization, this section discusses the policy implications of this work for the planning of grid development considering various uncertainties in the future (e.g. CO_2 pricing and the penetration levels of renewable power).

6.1. The grid expansion and the development of renewable power

It is often reported that the inter-regional transmission grid expansion can help China to address the curtailment of RES generation in light of the mismatches between energy resources and electricity demand across regions. However, the analysis in this work shows that the value of the inter-regional transmission capacity expansion highly depends on the percentage of RES power in the generation portfolio. With the projected development of RES power capacity in this paper, the extent to which the inter-regional grid expansion can increase the use of RES generation is rather limited, at around 3% in 2030. In other words, most RES generation can be absorbed by the intra-regional electricity demand in the mid-term, unless the penetration level of RES power is much higher than our assumptions. Therefore, the planning of RES development, and the inter-regional and intra-regional grid development should be better coordinated.

It is also worth mentioning that changes in the distribution of RES power from large-scale and centralized wind farms to small-scale and decentralized solar power in the future, will increase the complexity and uncertainties for grid companies in the planning of grid development. This is primarily due to the fact that large-scale wind farms are mainly built by large power producers (either state-owned or local-government owned); while the development of small-scale solar power might engage an increasing amount of diverse private investors and prosumers, which requires grid companies to make more effort in coordinating with these decentralized power producers. Accordingly, new policies are needed to address these challenges from coordinating the development of RES power and the grid.

6.2. The grid expansion, CO_2 pricing and dispatch mechanisms

In particular, expanding the inter-regional transmission grid according to the government plan largely reduces the variable generation costs by around 11% relative to the case of no grid expansion in 2030. This is mainly because of increased transportation of the coal power with low marginal generation costs, and the reduction in non-served load especially when electricity demand is high. Hence, expanding the inter-regional transmission grid will be strategically important to improve the economic efficiency and the security of national power supply in China. However, from the energy portfolio perspective, the inter-regional transmission grid expansion increases the coal consumption of power supply by

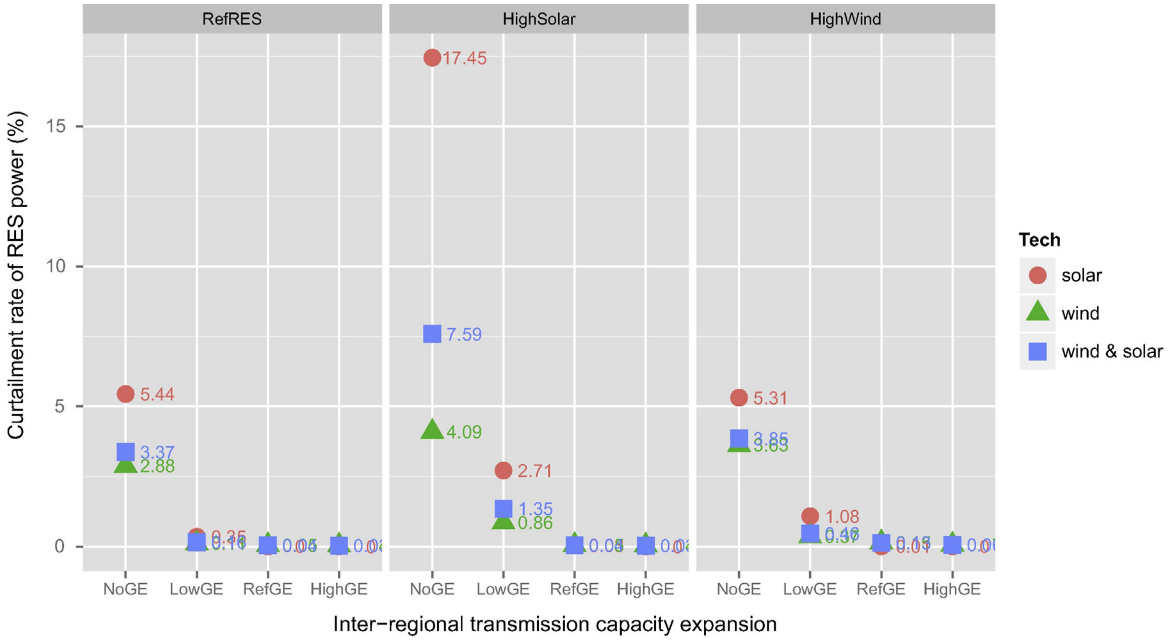

Fig. 17. The curtailment rate of renewable energy generation with different inter-regional transmission expansion and RES penetration levels. Note that the number close to the dots specifies the curtailment rate of renewable energy generation in percentage.

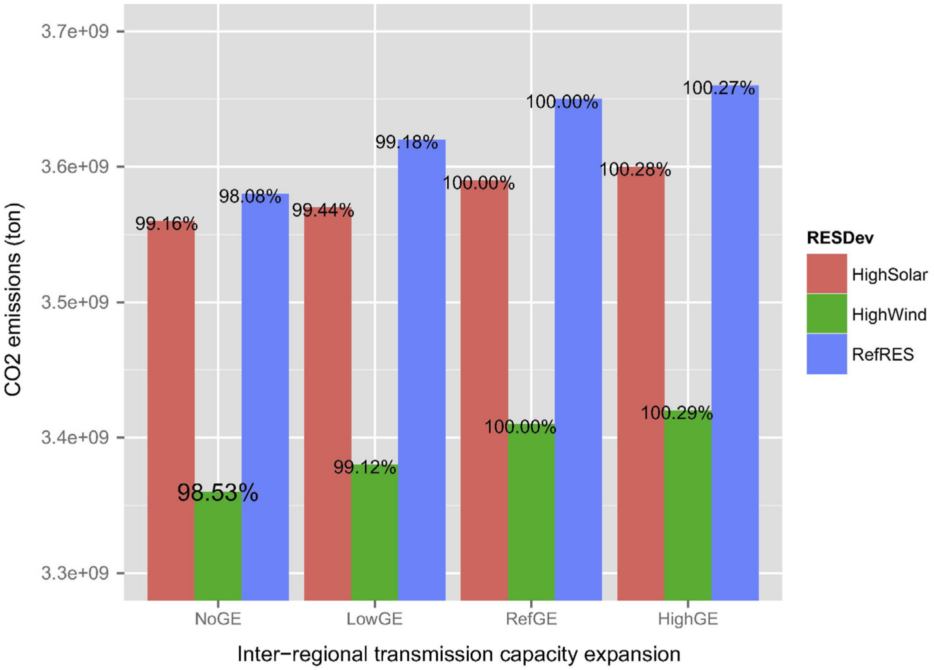

Fig. 18. The amount CO_2 emissions for different inter-regional transmission expansion and RES penetration levels. The number close to the bar shows the relative difference of CO_2 emissions between scenarios in percentage. The "RefGE" scenario is used as the reference case so that it is marked with 100%.

around 2% (relative to no grid expansion), with the given system in 2030. This not only because the grid expansion increases the use of coal generation in regions where coal prices are low, but also because part of the high-efficiency coal generation in coastal regions is replaced by low-efficiency coal generation in other regions. As a consequence, the expansion increases CO_2 emissions of the power supply by around 2%.

Additionally, as shown by the results in Section 5.1, a moderate CO_2 price hardly changes the merit-order between coal and gas generation, which limits the effect of CO_2 pricing on mitigating CO_2 emissions of the power supply. Given this, we reflect that it is ineffective for China to reduce CO_2 emissions merely relying on CO_2 pricing, as long as the big gap between coal price and fuel price remains. Instead, appropriate power dispatch mechanisms which can distinguish electricity generation from different technologies in terms of CO_2 emissions and generation efficiency across regions should be established to ensure that coal power can be efficiently used. Otherwise, the inter-regional transmission grid expansion is at risks of facilitating more use of low-efficiency coal generation across regions and results in more CO_2 emissions.

6.3. Need for investments in the grid

With the government planned expansion of the inter-regional transmission grid, the inter-regional power exchange accounts for about 11% of the national electricity consumption in 2030. The scenario results also indicate that further increasing the government planned capacity merely results in a very limited increase in the amount of the inter-regional power exchange (around 0.03%). Therefore, this paper deduces that the government planned grid capacity is basically sufficient in enabling bulk power delivery and promoting renewable generation across the regions.

With regard to the utilization rates of the transmission lines, first, the interconnections of the North-Central, North-East and the Northwest-Central are most efficiently used in terms of the total amount of the inter-regional power exchange in 2030. Accordingly, these grid connections will be the key corridors for China to deliver bulk power across regions. Second, the transmission lines between the Northwest-Central, Northwest-North, North-East, Northwest-South and the Northeast-North all have utilization rates higher than 70% for the entire year. This justifies the need for substantial investments in these transmission lines.

7. Conclusions

This paper investigated the impact of expanding the inter-regional transmission capacity on of China's power sector decarbonization from the energy portfolio, economic efficiency and environmental perspectives, considering uncertainties arising from RES penetration levels, CO_2 pricing and electricity demand in the future. This study was done with a least-cost multi-region power dispatch model which features high computational performance by integrating the cluster integer technique into the conventional unit commitment models.

Our scenario analysis of the China's power system in 2030 leads us to identify the following insight. First, expanding the inter-regional transmission capacity obviously reduces the variable generation costs mainly due to: (1) the increased ability of transporting coal power with low marginal generation costs across regions; and (2) the mitigation of non-served load, which becomes more significant if electricity demand is high. Second, expanding the inter-regional transmission grid has a very limited impact on promoting the use of RES generation by 2030 unless renewable power develops much faster than what we assumed. Based on this, we argue that the intra-regional grid congestion is more likely to be critical for promoting RES generation in the short term. However, the degree to which the inter-regional transmission expansion can mitigate RES generation curtailment largely increases with the penetration level of RES power, which implies that the inter-regional transmission grid will be more significant if the RES penetration level becomes much higher in the long term. Moreover, the inter-regional transmission grid expansion is at risks of facilitating more use of low-efficiency coal generation across regions and results in more CO_2 emissions. Additionally, the government's plan of inter-regional grid expansion is basically sufficient in enabling bulk power delivery and promoting RES integration across regions. In particular, the transmission lines connecting the North-Central, North-East and the Northwest-Central are three key corridors in terms of the total amount of power exchange, and the lines between the Northwest-Central, Northwest-North, North-East, Northwest-South and the Northeast-North have high utilization rates, which justifies substantial investments in these lines.

The results of this paper can inform China's policy makers regarding the trade-offs of expanding the inter-regional transmission grid for achieving different policy goals. Moreover, this paper gives policy recommendations regarding the need for institutional adaptations of the power system to better deliver the expected value of physical grid capacity expansion. Specifically, the coherency of planning between the grid development and renewable power development, and the need for establishing effective dispatch mechanisms which account for CO_2 emissions or generation efficiency are highlighted in our policy recommendations. Still, it should be also noted that the results in this paper are based on a set of parameters associated with assumptions, such as generation portfolio projections and the exogenous meteorological data. As the parameter settings can easily be adapted, the proposed model can support policy makers in coping with the complexities of power sector decarbonization in the future.

From the international perspective, the methods we have developed for the Chinese case can be used as a template for similar studies for other countries. First, the cluster integer unit commitment model of this work can be easily adapted to study the grid expansion issue for other large-scale power systems. Furthermore, the need for combining the objectives of energy security, economic efficiency and environmental sustainability should be highlighted for policy makings concerning grid development. In addition, other countries and regions, especially the ones with a coal-intensive generation mix, or with an imbalanced geographical distribution between (renewable) energy resources and energy demand can learn lessons from the Chinese case. They should be aware that expanding the grid does not necessarily bring benefits for the environment, even though it might come with economic savings and improved power supply security. In addition, they can also learn from the policy implications for China regarding the need for institutional adaptation of the power system to better deliver the expected value of physical grid expansion.

Last but not least, considering more technical options (incl. energy storage technologies and smart grid technologies) are emerging and implemented worldwide aiming at improving the flexibility of power system operations, the impact of grid capacity expansion should be further investigated considering these dynamics. Accordingly, the interaction between grid capacity expansion and other flexibility options is recommended for further research.

Acknowledgments

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Appendix A. Model description

For the purpose of consistency, variables and sets in the model are expressed in uppercase, indexes and parameters are in lowercase.

A.1. Objective function

The objective function is to minimize the total variable generation costs (C^{Var}) for all the six regions over one year, including the fuel costs (C^{Fuel}), operation and maintenance costs ($C^{O\&M}$), start-up costs ($C^{Startup}$), non-served load costs (C^{Nos}), CO_2 emission costs (C^{CO_2}) and the transmission costs (C^{Tran}), as shown in Eq. (A.1). More explanations regarding each type of costs are shown from Eqs. (A.2)–(A.7).

$$\min\ C^{Var} = C^{Fuel} + C^{O\&M} + C^{Startup} + C^{Nos} + C^{CO_2} + C^{Tran} \tag{A.1}$$

$$C^{Fuel} = \sum_{r\in R}\sum_{g\in G}\sum_{t\in T}\sum_{f\in F} P_{r,g,t} * \Delta t * \delta_{g,f} * c_{r,f}^{Fuel} \tag{A.2}$$

$$C^{O\&M} = \sum_{r\in R}\sum_{g\in G}\sum_{t\in T} P_{r,g,t} * \Delta t * c_g^{O\&M} \tag{A.3}$$

$$C^{Startup} = \sum_{r\in R}\sum_{g\in G}\sum_{t\in T} SU_{r,g,t} * c_g^{Startup} \tag{A.4}$$

$$C^{Nos} = \sum_{r\in R}\sum_{t\in T} P_{r,t}^{Nos} * \Delta t * c_r^{Nos} \tag{A.5}$$

$$C^{CO_2} = \sum_{r\in R}\sum_{g\in G}\sum_{t\in T}\sum_{f\in F} P_{r,g,t} * \Delta t * \delta_{g,f} * e_f^{CO_2} * c_r^{CO_2} \tag{A.6}$$

$$C^{Tran} = \sum_{r\in R}\sum_{r_c\in R}\sum_{t\in T} P_{r,r_c,t}^{Ex} * \Delta t * c^{Tran} \tag{A.7}$$

As shown in Table A.11, the decision variables mainly include: the power output of all generation units for a given technology ($P_{r,g,t}$), the power output or input of energy storage system (ESS) and flexible demand (electric vehicles here); the commitment states, start-up and the shut-down actions of fossil fuel-based generation units; and the power exchange between regions. The optimization is done for the whole year on an hourly basis.

A.2. Constraints

The model is subject to the following constraints.

$$\begin{aligned}&\sum_{g\in G} P_{r,g,t} - \sum_{g\in G^{Res}} P_{r,g,t}^{Cur} + \sum_{r_c\in R}\left(P_{r,r_c,t}^{Im} - P_{r_c,r,t}^{Ex}\right)\\ &\quad + \sum_{s\in S}\left(P_{r,s,t}^{Gen} - P_{r,s,t}^{Sto}\right) = d_{r,t}^{Dem} - P_{r,t}^{Nos} + \left(P_{r,t}^{Cha} - P_{r,t}^{Dis}\right)\end{aligned} \tag{A.8}$$

$$U_{r,g,t} = U_{r,g,t-1} + SU_{r,g,t} - SD_{r,g,t}, \quad \forall g \in G^{Fossil} \tag{A.9}$$

$$U_{r,g,t}, SU_{r,g,t}, SD_{r,g,t} \in [0,1,2,,n_{r,g}]$$

$$U_{r,g,t} * p_g^{min} \leqslant P_{r,g,t} \leqslant U_{r,g,t} * p_g^{max}, \quad \forall g \in G^{Fossil} \tag{A.10}$$

$$P_{r,g,t} = p_{r,g,t}^{Ava} * \alpha_{r,g,t}^{Cp}, \quad \forall g \in G^{Res} \tag{A.11}$$

$$0 \leqslant P_{r,g,t}^{Cur} \leqslant p_{r,g,t}^{Ava}, \forall g \in G^{Res} \tag{A.12}$$

$$0 \leqslant P_{r,g,t} \leqslant p_{r,g,t}^{Ava}, \quad \forall g \in G^{Non(fossil\&Res)} \tag{A.13}$$

$$\begin{aligned}&P_{r,g,t+1} - P_{r,g,t} \leqslant \left(U_{r,g,t+1} - SU_{r,g,t+1}\right) * \Delta p_g^{Up} * \Delta t\\ &\quad + SU_{r,g,t+1} * max\left(\Delta p_g^{Up} * \Delta t, p_g^{min}\right) - SD_{r,g,t+1} * p_g^{min}, \quad \forall g \in G^{Fossil},\ t \in T\end{aligned} \tag{A.14}$$

$$\begin{aligned}&P_{r,g,t} - P_{r,g,t+1} \leqslant \left(U_{r,g,t+1} - SU_{r,g,t+1}\right) * \Delta p_g^{Down} * \Delta t\\ &\quad + SD_{r,g,t+1} * max\left(\Delta p_g^{Down} * \Delta t, p_g^{min}\right) - SU_{r,g,t+1} * p_g^{min},\\ &\quad \forall g \in G^{Fossil},\ t \in T-1\end{aligned} \tag{A.15}$$

$$P_{r,g,t+1} - P_{r,g,t} \leqslant n_{r,g} * \Delta p_g^{Up} * \Delta t, \quad \forall g \in G^{Non(fossil\&Res)},\ t \in T \tag{A.16}$$

$$P_{r,g,t} - P_{r,g,t+1} \leqslant n_{r,g} * \Delta p_g^{Down} * \Delta t, \quad \forall g \in G^{Non(fossil\&Res)},\ t \in T-1 \tag{A.17}$$

$$P_{r,r_c,t}^{Ex} \leqslant p_{r,r_c,t}^{Ntc}, \quad \forall r, r_c \in R \tag{A.18}$$

$$P_{r,r_c,t}^{Im} = P_{r,r_c,t}^{Ex}\left(1 - e^{loss} * l_{r,r_c}\right) \tag{A.19}$$

$$E_{r,s,t} = E_{r,s,t-1} - P_{r,s,t}^{Gen} * \Delta t / \eta_s^{Gen} + P_{r,s,t}^{Sto} * \Delta t * \eta_s^{Sto} + E_{r,s,t}^{Hadd} \tag{A.20}$$

$$\left(e_{r,s}^{Ini}\right) * r^{ESSmin} \leqslant E_{r,s,t} \leqslant \left(e_{r,s}^{Ini}\right) * r^{ESSmax} \tag{A.21}$$

$$0 \leqslant P_{r,s,t}^{Gen}, P_{r,s,t}^{Sto} \leqslant p_{r,s}^{Ini} \tag{A.22}$$

$$SOC_{r,t} = SOC_{r,t-1} - p_{r,t}^{Dri} * \Delta t / \eta^{Dri} + P_{r,t}^{Cha} * \Delta t * \eta^{Cha} - P_{r,t}^{Dis} * \Delta t * / \eta^{Dis} \tag{A.23}$$

$$soc_r^{Rated} * r^{EVmin} \leqslant SOC_{r,t} \leqslant soc_r^{Rated} * r^{EVmax} \tag{A.24}$$

$$0 \leqslant P_{r,t}^{Cha}, P_{r,t}^{Dis} \leqslant p_r^{EVrated} \tag{A.25}$$

Eq. (A.8) shows that power supply should continuously equal power demand for all regions at each time step, in which the left side represents the power supply from regional power plants, inter-regional power exchange and from the ESS, and the right side represents the net electricity demand. As the RES generation for a given region is exogenously determined (as shown in Eq. (A.11)) so that $P_{r,t}^{Cur}$ is introduced to represent curtailment of wind and solar generation (as constrained in Eq. (A.12)). Considering electric vehicles (EVs) as a flexible demand case which works similarly to ESS, the charging and discharging power of EV in region r at time step t are represented by $P_{r,t}^{Cha}$ and $P_{r,t}^{Dis}$ respectively. Eq. (A.20) represents the dynamics of commitment states for the generation units within a given technology, g. Eq. (A.10) shows the maximum and minimum power output constraints for the group of units which are of fossil fuel-based technology g at time step t. Eq. (A.13) shows the power output constraints for non-fossil and non-RES power (which basically refers to nuclear power in this work). Eqs. (A.14) and (A.15) show the ramping up and ramping down constraints for generation units within the given fossil fuel-based technology group respectively. Eqs. (A.16) and (A.17) represent the ramping up and ramping down constraints for nuclear power in this work. Eq. (A.18) shows that the exported power between regions must be lower than the net transfer capacity, and the relations between exported power and imported power between two given regions are shown in Eq. (A.19). Eq. (A.20) shows the dynamics of energy in the energy storage system which is of technology s in region r. Eqs. (A.21) and (A.22) show the minimum and maximum energy and power for a given type of ESS respectively. The constraints for EVs' charing are shown from Eqs. (A.23)–(A.25).

A.3. Nomenclatures

See Tables A.10–A.12.

Table A.10
The sets and indexes.

Sets and indexes	Specifications
T, t	The set and index of time
R, r	The set and index of regions
G, g	The set and index of generation technologies
S, s	The set and index of ESS technologies
F, f	The set and index of fossil fuels, including coal, gas and uranium
G^{Res}	The subset of G, which includes all the RES power technologies
G^{Fossil}	The subset of G, which includes all the fossil fuel-based power technologies
$G^{Non(fossil\&Res)}$	The subset of G, which includes all the non-fossil fuel and non-RES based power technologies (e.g. nuclear)

Table A.11
The decision variables.

Decision variables	Specifications [units]	Types
$P_{r,g,t}$	The power output of the units of technology g in region r at time t [GW]	Continuous
$SU_{r,g,t}$	The amount of the units of technology g which start up at time t in region r, $[0, 1, \ldots, n_g]$	Integer
$SD_{r,g,t}$	The amount of the units of technology g which shut down at time t in region r, $[0, 1, \ldots, n_g]$	Integer
$U_{r,g,t}$	The amount of the units of technology g which are committed at time t in region r, $[0, 1, \ldots, n_g]$	Integer
$P_{r,t}^{Nos}$	The non-served demand in region r at time t [GW]	Continuous
$P_{r,g,t}^{Cur}$	The curtailed power for RES technology g in region r at time t [GW]	Continuous
$P_{r,r_c,t}^{Ex}$	The power exported from region r_c to region r at time t [GW]	Continuous
$P_{r,r_c,t}^{Im}$	The power imported from region r_c to region r at time t [GW]	Continuous
$P_{r,s,t}^{Gen}$	The power generated from ESS technology s in region r at time t [GW]	Continuous
$P_{r,s,t}^{Sto}$	The power flows to ESS technology s in region r at time t [GW]	Continuous
$E_{r,s,t}$	The energy stored in ESS technology s at time t [GWh]	Continuous
$P_{r,t}^{Cha}$	The charging power of EVs in region r at time t [GW]	Continuous
$P_{r,t}^{Dis}$	The discharging power of EVs in region r at time t [GW]	Continuous
$SOC_{r,t}$	The energy stored in EV batteries in region r at time t [GWh]	Continuous

Table A.12
The parameters.

Parameters	Specifications [units]
Time related	
Δt	The time interval which is one hour in this case
Generation related	
p_g^{min}, p_g^{max}	The minimum and maximum power output of power technology g respectively [%]
$\Delta p_g^{Up}, \Delta p_g^{Down}$	The maximum ramping up and ramping down capability of technology g in one time [GW/h]
$\delta_{g,f}$	The consumption intensity of technology g for fuel f [J/GWh]
$e_f^{CO_2}$	The CO_2 emission factor for fuel f [ton CO_2 emissions per Joule]
$c_g^{O\&M}$	The variable operation and maintenance costs per generation unit for technology g [\$/GWh]
$c_g^{Startup}$	The start up costs for technology g [\$ per time]
$n_{r,g}$	The number of generation units of technology g in region r
$p_{r,g,t}^{Ava}$	The available generation capacity of technology g in region r at time t [GW]
$\alpha_{r,g,t}^{Cp}$	The capacity factor for RES technology g in region r at time t
$c_{r,f}^{Fuel}$	The price for fuel f in region r [\$/J]
$c_r^{CO_2}$	The CO_2 emission price in region r [\$/ton of CO_2 emissions]
c_r^{Nos}	The penalty for per unit of non-served power in region r [\$/GWh]
Demand related	
$d_{r,t}^{Dem}$	The power demand in region r at time t [GW]

Table A.12 (*continued*)

Parameters	Specifications [units]
Transmission related	
c^{Tran}	The transmission cost per unit of power [\$/GWh]
e^{loss}	The power loss per unit of transmission distance [GW/km]
l_{r,r_c}	The distance between region r and r_c [km]
p^{Ntc}_{r,r_c}	The net transfer capacity between region r and r_c [GW]
ESS related	
$p^{Ini}_{r,s}$	The initial capacity of ESS technology s [GW]
$e^{Ini}_{r,s}$	The initial energy stored in ESS technology s [GWh]
r^{P2E}_{s}	The power to energy ratio of ESS technology s
$e^{Hadd}_{r,s,t}$	The rainfall energy added to the reservoirs of pumped-hydro plants [GWh]
$c^{AInv}_{r,s}$	The annualized capital cost to invest ESS technology s in region r [\$/GW]
$\eta^{Gen}_{s}, \eta^{Sto}_{s}$	The generation and storage efficiency of storage technology s [%]
r^{ESSmin}, r^{ESSmax}	The minimum and maximum utilization factor for the energy of ESS
EV related	
$\eta^{Dri}, \eta^{Cha}, \eta^{Discha}$	The power efficiency for EV driving, charging and discharging [%]
soc^{Rated}_{r}	The rated energy of EV batteries in region r [GWh]
r^{EVmin}, r^{EVmax}	The minimum and maximum utilization factors of EV energy [%]
$p^{EVrated}_{r}$	The rated capacity of EV batteries in region r [GW]
$p^{Dri}_{r,t}$	The power of EV used for driving in region r at time t [GW]

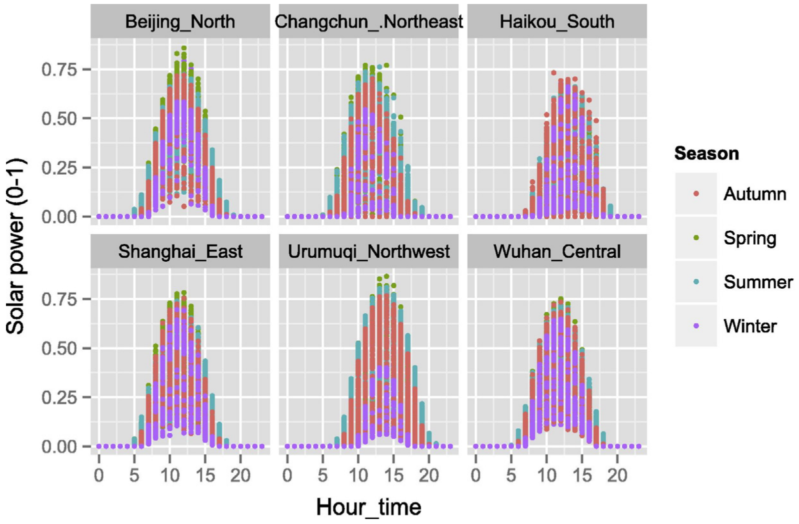

Fig. B.19. Illustration of normalized solar power output grouped by day and season in the six regions.

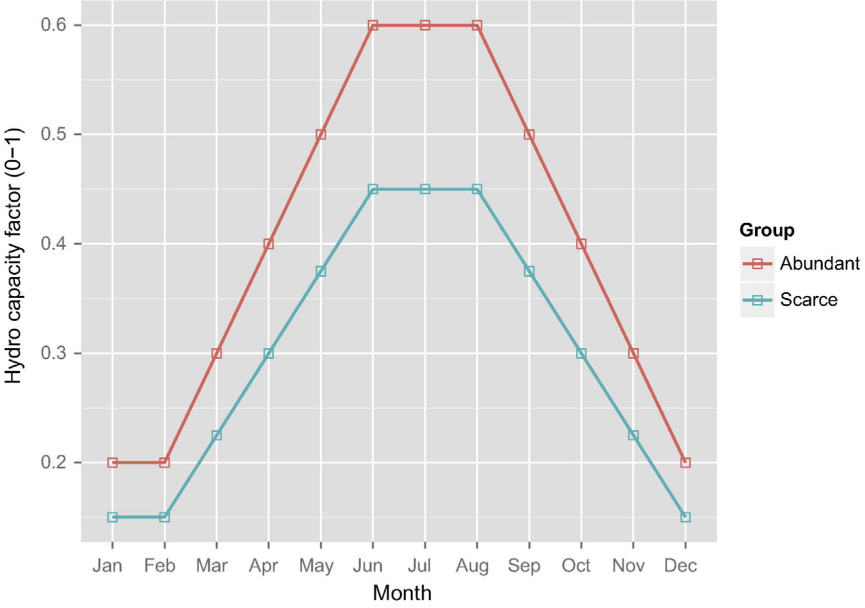

Fig. B.20. The average hydro power availability depending on month and the group of the regional power systems.

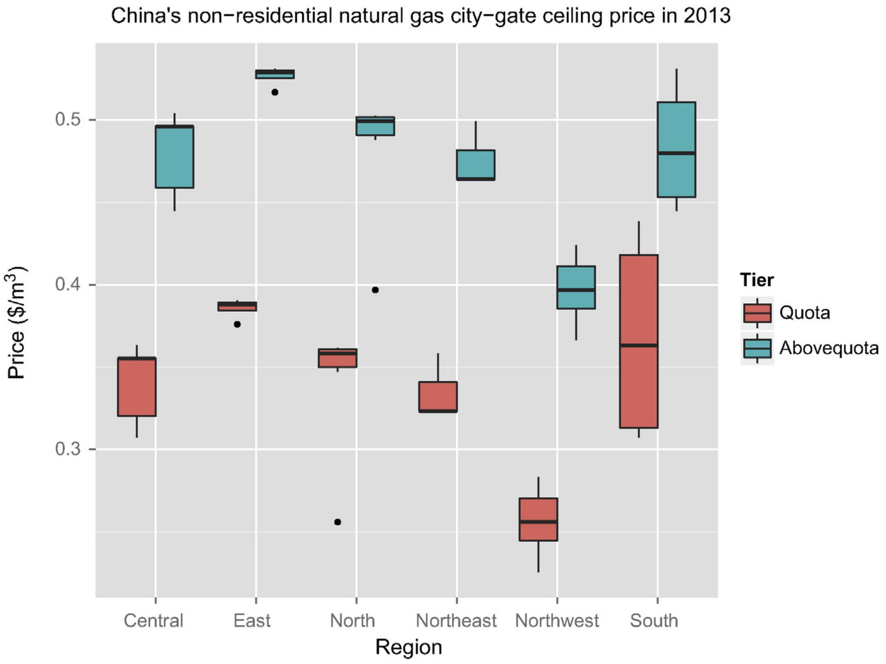

Fig. B.21. China's non-residential natural gas city-gate ceiling prices by region, data source: [43]. Note that the regional price data used in this work are the mean of the provincial (and sub-provincial administrative) gas prices.

Table B.13
The key technical and economic parameters of fossil fuel-based generation units. Data source: [15,26].

Technology	Capacity of a single unit (GW)	Unit availability (%)	Maximum power output (%)	Minimum power output (%)	Ramp up[a] (%)	Ramp down (%)	Efficiency of power output (%)	Emission factor (ton/GWh)	Start up cost ($/time)	OM cost ($/GW/hour)	Fuel consumption (GJ/GWh[b])
Small-coal	0.25	0.99	0.85	0.20	0.10	0.10	0.90	882.00	16800	3995.43	9270.00
Sub-critical	0.30	0.99	0.85	0.20	0.09	0.09	0.90	770.28	20000	4000.00	8095.80
Super-critical	0.60	0.99	0.85	0.20	0.12	0.12	0.90	686.00	25200	4109.59	7210.00
Ultra-supercritical	1.00	0.99	0.85	0.20	0.20	0.20	0.90	574.28	33600	4680.37	6035.80
IGCC-coal	1.00	0.99	0.85	0.20	0.20	0.20	0.90	548.80	11760	3082.20	5356.00
CCGT-gas	0.50	0.99	0.85	0.20	0.40	0.40	0.90	240.00	11760	2283.11	9552.50
OCGT-gas	0.50	0.99	0.85	0.20	0.50	0.50	0.90	240.00	9408	2283.11	8406.20
Nuclear	0.80	0.99	0.90	0.50	0.04	0.04	0.90	0	50400	5538.81	0
Wind	0	1	0	0	0	0	0	0	0	0	0
Solar	0	1	0	0	0	0	0	0	0	0	0
Hydro	0	1	0	0	0	0	0	0	0	0	0
Coal-biomass	0	1	0	0	0	0	0	0	0	0	0
Gas-biomass	0	1	0	0	0	0	0	0	0	0	0

[a] The ramp up and ramp down capability is relative to the capacity of a single unit.
[b] The conversion factor used here is 1 ton coal = 20.6 ∗ $E + 10$ J, and 1 m^3 gas = 3.82 ∗ $E + 07$ J.

Appendix B. Key data used in this work

The solar power output for the six regions are sampled from major cities inside the region, as shown in Fig. B.19. For most regions, solar power output gets to peaks in the noon, which is quite predictable. The duration of solar power output depends on seasons, in which summer normally has longer and higher solar power output than winter. Specially, the solar power in the Northwest is about 2–3 h behind after other regions (see Table B.13).

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