Towards a Low-Carbon Future for China's Power Supply Chain: Critical Sectors Identification and Scenario Analysis

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Abstract

The power sector is a significant contributor to global carbon emissions and has received widespread attention from scholars, but the path to achieving supply chain-wide carbon reductions in China from a provincial perspective remains unclear. Combining multi-regional input-output and betweenness-based methods, we identified the critical upstream sectors that indirectly drive large amounts of carbon emissions through power supply chains. Point source data of coal-fired units were collected to ensure the accuracy of the disaggregated input-output table. In addition, scenario analysis was conducted to examine the effects of different electricity policy combinations on supply-chain wide emissions during the 14th Five-Year Plan period. Our findings indicate that the embodied carbon

intensity of coal-fired power sector in Northwest China is among the highest in the country, with a range of 36.39 tons/10000 CNY - 82.10 tons/10000 CNY. The shift of the power sector to Western China during the 14th Five-Year Plan period will therefore partially offset the positive emission reduction effect of the structural transformation of power system. To achieve a low carbon power supply chain, improving the production efficiency of critical transmission sectors and the low carbon technology level of major emitting sectors will be necessary. Our results provide valuable insights for provincial governments planning low-carbon transformation paths for the power sector.

Keywords

Multi-Region Input-Output Model, CO_2 Emission, Critical Sectors Identification, Scenario Analysis, Emission Reduction Strategy

1 Introduction

The increasing prominence of varied global environmental issues, especially global warming, policymakers worldwide prioritize greenhouse gas emissions reduction to slow climate change(Li and Wei, 2021). In recent years, China has witnessed a noteworthy increase in its carbon emissions, even amidst the COVID-19 epidemic. CO_2 emissions in China reached 11.9 billion tonnes in 2021, a 5% increase over 2020 (IEA, 2022). Increasing coal use in the electricity sector is the major contributor to China's CO_2 emissions, accounting for 60% of the increase in emissions (IEA, 2021a). Considering the substantial carbon emissions from the power sector, a new low-carbon electricity system with solar and wind as its primary energy sources was proposed at the ninth meeting of the Central Finance Committee in March 2021. It should be noted, however, that China's rapidly expanding renewable energy capacity in recent years has not kept pace with the constantly growing electricity demand (IEA, 2021b). A certain number of thermal power installations are still required to guarantee the energy supply security. The total new capacity of coal-fired units is estimated to be 316 GW during the 14th Five-Year Plan (FYP) period even though the entry thresholds for new coal-fired plants are raised by the Chinese government. In light of China's high proportion of coal power installations, achieving a low-carbon transformation of the power structure has become an urgent topic.

Changes in the electricity mix will not only have an impact on direct carbon emissions, but also on indirect carbon emissions from the upstream sector due to the substantial differences in the supply chains associated with the various generation technologies (Hammond et al., 2017). The indirect emissions should thereby be fully considered in the low-carbon transition of the electricity mix. Moreover, to achieve a low-carbon energy mix from a supply-chain perspective, special attention should be paid to identifying the key upstream sectors of different power generation technologies that have the highest carbon reduction potential. For example, the mining and washing of coal sector has a higher priority for reducing carbon emissions than other sectors in coal-based power systems. It is therefore necessary to reduce indirect CO_2 emissions resulting from the growth of electricity supply and the restructuring of the electricity sector by identifying the critical sectors of different power technologies and implementing effective strategies.

When assessing indirect upstream environmental impacts of power sector, the input-output method and the process analysis method are typically used (Ghasemi-Mobtaker et al., 2022; Howard et al., 2018; Lindner and Guan, 2014; Moosavi-Nezhad et al., 2022; Perčić et al., 2020; Toniolo et al., 2021). As compared to the process analysis method, the input-output method is more appropriate for assessing macrosystems holistically and avoids truncation bias (Tukker and Jansen, 2006; Yuan et al., 2022). Many scholars have chosen to use the input-output method for estimating environmental pressures such as carbon (Qu et al., 2020; Yu et al., 2021; Yuan et al., 2022), energy (B. Chen et al., 2018; Z.-M. Chen et al., 2022), water (Ridoutt et al., 2018; Wang et al., 2013), and pollutant footprint (Li et al., 2021). At the same time, the input-output method has emerged as a popular approach to investigating the environmental impacts of specific electricity technologies. For instance, Banacloche et al. (2020) examined the CO_2 effects of nuclear fusion power plants in Europe. Zafrilla et al. (2019) computed the environmental footprints of the solar power sector in Spain in 2016.

The input-output model is often incorporated with other methods to identify the critical upstream sectors. Through structural path analysis (SPA) method, consumption-based method, and betweenness-based method, the input-output model can trace environmental impacts along the supply chain. However, SPA only focuses on accounting for specific paths and cannot identify infinite paths that include a particular transaction (Hanaka et al., 2017). In contrast, the consumption-based method considers the total demand-driven upstream emissions, enabling us to analyze the emissions flow among sectors and regions (Z.-M. Chen et al., 2018; Karakaya et al., 2019; Qian et al., 2022). Utilizing consumption-based method facilitates the identification of critical upstream carbon emitting sectors, which provides a foundation for the target setting of carbon control in critical industries. Besides, Liang et al. (2016) proposed a betweenness-based method by applying the concept of betweenness in network analysis (Freeman, 1978, 1977) to structural path analysis. The purpose of the method is to evaluate the importance of intermediate input sectors in supply chains by summing the environmental impacts of each chain that passes through the intermediate sector. For example, Wu et al. (2018) used the betweenness-based method to identify critical water transmission sectors. Similarly, Zhao et al. (2021a) also used a betweenness-based method to define key transmission sectors from the electricity sector to the final domestic consumption. Overall, the consumption-based method focuses on the critical carbon-emitting sectors which is located at the beginning of the supply chain, while the betweenness-based method focuses on the carbon-transmitting sectors in the middle of the supply chain.The location of these critical sectors determines the measures they should adopt to achieve emissions reductions in the entire power sector supply chain more efficiently.

Although the existing research results have laid a good foundation for carbon reduction in power supply chain, there are still some shortcomings. First, previous studies on the structural transformation of electricity generation have mainly focused on the whole country or a specific region, without taking regional differences into account. As a matter of fact, both the electricity mix and the development of power technology are significantly imbalanced throughout different regions of a country (Lei et al., 2020; Wen and Yan, 2018; Zhao et al., 2021b). For example, the majority of coal-fired power plants with high capacity but inefficiency are located in less-developed or border regions in China (Chen et al., 2019). By accounting for direct and indirect carbon emissions from different electricity technologies on a provincial scale, regional emission reduction initiatives can be made more effective and efficient. At the same time, upstream industry sectors also have strong regional characteristics in terms of energy consumption and technology level(Wu et al., 2022), which is an essential reason for the identification of critical upstream sectors along the power supply chain at spatial scale. Additionally, most existing studies have focused on critical upstream emitting sectors(Faturay et al., 2020; Gao et al., 2022). The carbon reduction policy is bound to be insufficient in sectoral variation as a result of the lack of attention to the critical upstream transmission sectors in the power supply chain.

In this study, we first used a multi-regional input-output model based on disaggregation of power sectors to assess the embodied carbon intensity of different power technology sectors in 30 provinces in China and identified major upstream carbon emitters and transmission sectors in the electricity supply chain. Further, we performed scenario analysis based on government reports, such as the provincial 14th Five-Year Plans and the Implementation Plan for Transforming and Upgrading Coal-Fired Power Plants (NDRC and NEA, 2021). The scenario analysis section aims to answer the following questions: What strategies will result in maximum emissions reductions in the power sector? What is the impact of the upstream sector on electrical supply chain-wide emissions? Our study makes the following contributions: (i) From a provincial rather than a national perspective, the power sector was disaggregated in provincial input-output tables according to power technology, and its direct and embodied emission intensity were accounted for to reveal the different levels of power generation technology in each province; (ii) The provincial carbon emissions inventories of different power generation technologies in the power sector were compiled based on point source data of coal-fired units, which served as the basis of this study to improve the accuracy of the division of the coal-fired power generation sector in the input-output table; (iii) To our knowledge, this is the first systematic identification of the critical upstream carbon sectors of different electricity technologies from both a consumption perspective and a betweenness perspective. This study can be used to inform low-carbon policy decisions for the power sector supply chain at both national and regional levels.

The remainder of this study is organized into four sections. In Section 2, the basic methodology and data sources are described in detail. The main results are presented in Section 3. Finally, Section 4 offers a comprehensive discussion and analysis of the findings.

2 Methods and Data

2.1 Disaggregation of the electricity sector in the input-output table

The low resolution of existing multi-regional input-output tables in China does not support a detailed assessment of power generation technologies in different regions. We constructed a multi-region input-output (MRIO) model by sectoral disaggregation of the power sector based on bottom-up process data. The production and distribution of electric power and heat power sectors of the MRIO table for 31 provinces and 42 sectors in China by 2017 were disaggregated into power transmission and distribution sectors and power generation sectors based on the proportion of investment expenditure, following the method proposed by Lindner et al. (2013). Next, we have disaggregated the power generation sector into eight subsectors: subcritical coal, supercritical coal, ultra-supercritical coal, gas, nuclear, hydro, wind and solar. Specifically, the disaggregation of the power sector consists of the inputs from upstream sectors, the outputs to downstream sectors, and the internal disaggregation of power sectors (see Figure 1). First of all, the upstream sectors were divided into capital-related, fuel-related, and general sectors in this paper depending on the characteristics of the various generation technologies referring to Wan et al. (2016). The allocation of intermediate inputs from the fuel-related sectors to the power subsectors followed three assumptions: (i) All intermediate inputs from the mining and washing of coal sector are allocated to the coal-fired power sector. (ii) The intermediate inputs from the production and distribution of gas sector are only assigned to the gas-fired power sector. (iii) The remaining fuel sectors are distributed according to the fuel cost of each generation technology. For the capital-related and general sectors, the upstream sector inputs were calculated based on each generation technology's overnight investment cost and operation and maintenance cost. The detailed categorization of sectors is shown in Table S1 in the supplementary materials.

Secondly, the downstream sectors were separated depending on the output weight index p_i of various generation technologies. p_i can be calculated as follows:

$$p_i = g_i \times e_i / \sum g_i \times e_i \tag{1}$$

where g_i means the amount of power generated by various generation technologies; e_i means the provincial electricity price.

<table>
<tr><td colspan="3" rowspan="3">Input/output</td><td colspan="12">Intermediate demand</td></tr>
<tr><td rowspan="2">Sector 1</td><td rowspan="2">..</td><td rowspan="2">Sector n</td><td colspan="9">Power sector</td></tr>
<tr><td>T&D</td><td>Sub-C</td><td>SC</td><td>USC</td><td>Gas</td><td>Hydro</td><td>Nuclear</td><td>Wind</td><td>Solar</td></tr>
<tr><td rowspan="7">Intermediate input</td><td colspan="2">Sector 1</td><td colspan="3" rowspan="3"></td><td colspan="9" rowspan="3">Upstream Disaggregation</td></tr>
<tr><td colspan="2">..</td></tr>
<tr><td colspan="2">Sector n</td></tr>
<tr><td rowspan="4">Power sector</td><td>T&D</td><td colspan="3" rowspan="4">Downstream Disaggregation</td><td colspan="9" rowspan="4">Internal Disaggregation</td></tr>
<tr><td>Sub-C</td></tr>
<tr><td>..</td></tr>
<tr><td>Solar</td></tr>
</table>

Figure 1. Format of the electricity disaggregated IO table in China.

Finally, each subsector was assumed to utilize solely electricity generated itself. The upstream input factor and the downstream output factor were multiplied to get the internal disaggregating factor for the electrical sector.

2.2 Embodied carbon emission accounting

Since Wassily Leontief proposed the input-output method in 1936, input-output analysis has been widely used to investigate the relationship between different sectors of the economy or between different regional economies. Bullard and Herendeen established a model of embodied energy conservation in commodities using the input-output method (Bullard and Herendeen, 1975). Chen et al. (2010) subsequently integrated this model with system ecology theory, and for the first time extended the embodied accounting framework to ecological elements. This framework has since been applied to various environmental factors, including water (Wu et al., 2019a, 2019b), land (X. D. Wu et al., 2018b), carbon emissions (X. D. Wu et al., 2018a), and mercury emissions (Li et al., 2017). The equilibrium relationship under this accounting system could be depicted as: The summation of the direct carbon emissions and emissions embodied in intermediate economic inputs into this sector is equivalent to the carbon emissions embodied in the sectoral output, as shown in Eq.(2).

$$F + \varepsilon Z = \varepsilon X \tag{2}$$

where F means the row vector of direct carbon emissions for each sector; ε means the row vector of embodied carbon emissions intensity for each sector; Z means the matrix of intermediate inputs and intermediate uses; X means the diagonal matrix of total outputs.

The embodied carbon emission intensity refers to the total (direct and indirect) carbon emissions generated from per monetary unit of the sectoral output products, which is defined for all the output products of the sector, either they are used for intermediate production activities or final demand. Therefore, we can obtain the matrix for embodied carbon emission intensity by solving Eq.(2):

$$\varepsilon = F(X - Z)^{-1} \tag{3}$$

This paper focuses on the emissions generated during the operation of different power technologies rather than the entire life-cycle environmental impacts.

2.3 Identification of critical upstream carbon emitting and carbon transmission sectors

In this study, both consumption-based and betweenness-based methods are used to identify critical upstream sectors in the power supply chain. Figure 2 depicts a four-sector illustrative example that serves to elucidate the core principles of the two methods. Suppose there are three pathways leading to sector D. Using the consumption-based method, the carbon emissions produced by sectors A, B, and C, induced by sector D, are quantified as e_1, e_3, and e_2, respectively. Conversely, the betweenness-based framework assigns zero carbon emissions to intermediary sectors A and C, while attributing e_1+e_2 carbon emissions to sector B. Through meticulous analysis and interpretation of this example, we can develop a profound understanding of the fundamental differences between these two methods. Specifically, the betweenness-based method gauges the amount of CO_2 transmitted from a sector situated in the intermediary position between the two ends of the supply chain to the downstream final demand sector. The consumption-based method, in contrast, measures the CO_2 emissions attributed to a sector functioning as the production end of the supply chain for the downstream final demand sector. It is important to note that, the term "consumption" in consumption-based method refers to the final consumption of electricity in this study.

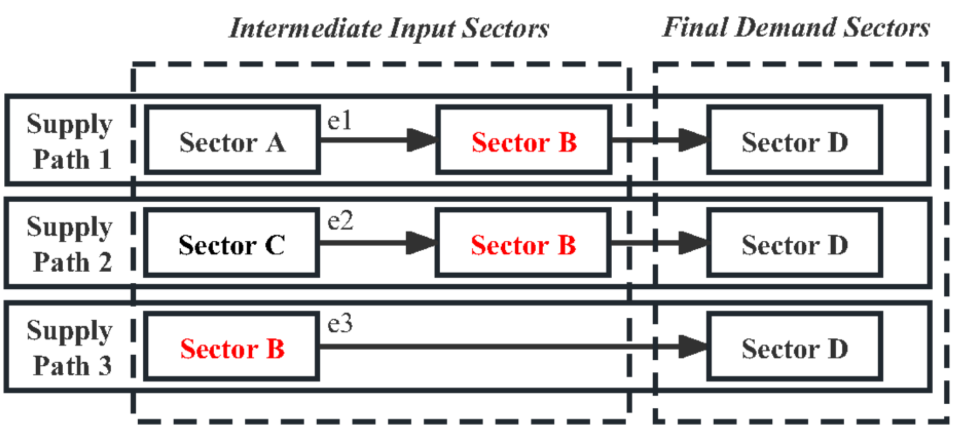

Figure 2. A four-sector example with three supply paths illustrating the comparison between the betweenness-based method and the consumption-based method.

Our objective is to determine the relative significance of different sectors in terms of their carbon emissions and transmission within the power supply chain. Specifically, we aim to identify which sectors are more significant upstream in the power sector, rather than focusing solely on the amount of CO_2 that they specifically emit or transmit within the power chain. Notably, the upstream configuration of a power sector within a supply chain remains invariant, regardless of whether the electricity sector is utilized as an intermediate or final use (additional details can be found in supplementary materials). Therefore, although both methods of identifying critical sectors are based on the final consumption of the electricity sector as the termination of the supply chain, they can also be utilized to elucidate the structure of the entire upstream power chain.

2.3.1 Consumption-based method

The consumption-based method refers to determining the carbon reduction responsibility of the upstream sector corresponding to each power subsector by accounting for the indirect carbon emissions resulting from the final consumption of different power technologies. This method is a breakdown of consumption-based carbon emissions accounting results of power sectors, which shows the origin of main carbon emissions from different industries that are emitted along the whole supply chain of different electricity generation technologies. The critical upstream carbon emitting sectors identified by the consumption-based method can play a role in carbon reduction in the supply chain by encouraging the development of low-carbon technologies in these sectors. The indirect carbon emissions from the upstream sector t caused by the final consumption of each power subsector k can be measured by Eq.(5).

$$L = (I - A)^{-1} \quad (4)$$

$$P(t,k) = \sum_{o=1}^{r} e_t L(t,k) y_k^o \quad (5)$$

where r means the number of regions; e_t means the direct carbon emission intensity of upstream sector t; L means Leontief inverse matrix; y_k^o means the final demand of electricity subsector k in region o.

2.3.2 Betweenness-based method

Liang et al. (2016) proposed a betweenness-based method to identify critical intermediate sectors that are located between the two ends of the chain path with high transmissibility. The more frequently appearing sectors in supply chains have a greater potential to alleviate upstream environmental pressures. Reducing production taxes or providing production subsidies can encourage these sectors to increase production efficiency, which will reduce carbon emissions by using less upstream inputs. The ends of the supply chains in this study are power subsectors. To facilitate our analysis, we define $g_1, g_2, \ldots, g_u$ as the upstream sectors of sector t, and $h_1, h_2, \ldots, h_v$ as the downstream sectors of sector t. Considering a supply chain with u sectors upstream and v sectors downstream, where the total length of the supply chain is u+v+1, we can compute the carbon emissions passed through sector t as follows:

$$\begin{aligned} B_t(g_1, h_v) &= \sum_{1 \le g_1,\ldots,g_u \le n} \sum_{1 \le h_1,\ldots,h_v \le n} e_{g_1} a_{g_1 g_2} \cdots a_{g_u t}\, a_{t h_1} \cdots a_{h_{v-1} h_v} y_{h_v} \quad (6) \\ &= \sum_{1 \le g_1,\ldots,g_u \le n} (e_{g_1} a_{g_1 g_2} \cdots a_{g_u t}) \sum_{1 \le h_1,\ldots,h_v \le n} (a_{t h_1} \cdots a_{h_{v-1} h_v} y_{h_v}) \\ &= (eA^u)_t (A^v y)_t = eA^u J_t A^v y \end{aligned}$$

where n means the number of sectors; $(eA^u)_t$ means the t-th elements of the vector; $(A^v y)_t$ means the t-th elements of the vector; J_t means an n*n matrix with its (t, t) element as 1 and other elements as zeros.

Then, we sum up the carbon emissions transmitted by supply chains ranging from length 1 to infinity. Given that the Leontief inverse matrix can be expressed as the power series expansion: $L = (I - A)^{-1} = I + A + A^2 + \cdots$. The betweenness-based carbon emissions of sector t can be measured by Eq.(7).

$$B_t = \sum_{u=1}^{\infty} \sum_{v=1}^{\infty} eA^u J_t A^v y = \sum_{u=1}^{\infty} (eA^u J_t) \sum_{v=1}^{\infty} (A^v y) \tag{7}$$
$$= e\left(\sum_{u=1}^{\infty} A^u\right) J_t \left(\sum_{v=1}^{\infty} A^v\right) y = e(L - I) J_t (L - I) y$$

The betweenness-based carbon emissions from the upstream sector t caused by the final consumption of each power subsector k can be measured by Eq.(8).

$$B(t, k) = e(L - I) J_t (L - I) y_k \tag{8}$$

2.4 Scenario settings

Both the central and provincial governments have implemented different regulations on emissions reductions in China's power sector. Four factors determine the change in direct and indirect emissions from power sector: spatial distribution of power generation, generation mix, and direct carbon intensity of both the power subsectors and upstream sectors. The power subsector can reduce its direct carbon emissions intensity in two ways, either by upgrading the equipment of existing coal-fired power plants or by replacing inefficient plants with high-efficiency plants. As an example, the Chinese government has been implementing the “Replacing Small Generator Units with Large Generator Units” coal power policy since 2006 to replace small, outdated, and inefficient coal-fired plants with larger, more efficient ones.

We have collected government reports related to power construction in 30 provinces during the 14th FYP, including 14th FYP for Power Development, 14th FYP for Energy Development and 14th FYP for Renewable Energy Development. These government documents contain information on the projected installed capacity of different power technologies at the provincial level in 2025 (as shown in Figure 3). We assume that the outputs of the power sectors have a direct linear relationship with the installed capacity to construct the Business As Usual (BAU) scenario using projected nationwide installed capacity in 2025. To evaluate the potential impacts of different factors on embodied emissions from the power sector, we have designed six scenarios on the basis of BAU, considering the spatial distribution, generation mix, and direct carbon emissions from power subsectors (as shown in Table 1). Each scenario varies in terms of these factors, allowing us to assess the relative contributions of each to overall emissions.

Table 1 Scenario Settings

Name	spatial distribution	generation mix	direct carbon emissions
SN1	√		
SN2		√	

SN3	√	√	
SN4			√
SN5			√
SN6	√		

To examine the impact of spatial distribution on embodied emissions from the power sector, we have designed SN1 and SN6. The inter-provincial power supply proportion will be restructured according to the projected installed capacity of each province in 2025 without changing the provincial power generation structure in 2017 (as shown in Table S7). According to the provincial results of the embodied carbon emission intensity of different electricity technologies in section 3.1, the newly installed power capacity of different technologies will be realigned to provinces with comparative low-carbon advantages in SN6 (as shown in Table S6).

SN2 reflectes the influence of the generation mix on embodied emissions. It readjusts the proportion of different power technologies generation in each province according to their projected installed capacity of each technologies in 2025 without changing the inter-provincial power supply ratios in 2017 (as shown in Table S8).

SN3 restructures both the proportion of different power technologies generation in each province and the inter-provincial power supply ratios to consider the integrated effects of spatial distribution and generation mix. This scenario captures the embodied carbon emissions from the power sector under the projected installed capacity of provincial governments in 2025.

Given the impact of direct carbon emissions from power subsectors, we have compared two pathways for carbon reduction in the coal power sector (as shown in Table 1). In particular, the coal consumption of sub-critical units will be increased to 300 tce/kWh in SN4. The sub-critical units operating for 15 years and below 300MW will be replaced by ultra-supercritical units of equal capacity in SN5. Detailed parameter settings and scenario data are summarized in supplementary materials.

Additionally, we have devised six more scenarios to consider the impact of critical upstream emitting sectors identified by Section 3.2. These scenarios, referred to as critical sector carbon reduction (CSCR), assume a 10% reduction in emissions intensity of sectors ranked top 30% by consumption-based method, while retaining the underlying assumptions of the initial six scenarios. Given the relative maturity of electricity technology, the upstream input structure is unlikely to change rapidly during the research period of this study.

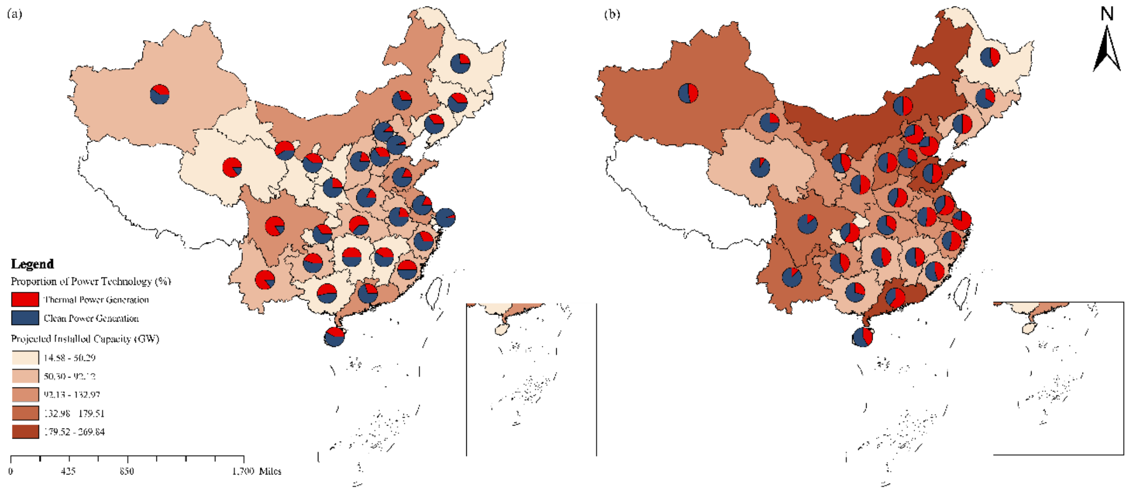

Figure 3. Installed capacity of different electricity technologies by province in 2017 (a) and 2025 (b).

2.5 Data

Power generation data of different power generation technologies is collected through a combination of Compilation of Power Industry Statistics published by China Electricity Council (CEC), Provincial Power Statistical Yearbook, and Statistical Yearbook of cities and official websites of power generation enterprises. The S&P World Electric Power Plants Database provided microdata on coal-fired power plants, such as name, location, year of production, installed capacity, and the type of unit. Provincial electricity prices for different power technologies are obtained from “Regulatory Notification on National Electricity Price Situation” published by National Energy Administration (NEA). Generation costs are derived from “Annual Development Report of China's Power Industry” published by CEC and “Projected Costs of Generating Electricity” published by IEA.

The study uses the China multi-regional input-output table for 2017 published by China's carbon emissions database (CEADS). The direct carbon emissions data were calculated based on the energy use inventories of different sectors in each province in 2017 (Shan et al., 2020), with direct energy use in the renewable energy generation sector set to zero and energy consumption in the fossil fuel sector allocated regarding the type of energy consumed in each power subsector. In addition, the coal-fired efficiency of subcritical power plants is assumed to be 35%, that of supercritical power plants is 42%, and that of ultra-supercritical power plants is 47% (Lindner et al., 2013; Zhang et al., 2019). The direct carbon emissions of different power sectors are shown in Table S3 in the supplementary materials. In this paper, Tibet, Hong Kong, Macao, and Taiwan were excluded due to missing data.

3 Results and Discussions

3.1 Comparison of Embodied Carbon Emission Intensity of Different Electricity Technologies in 30 Provinces

The embodied and direct carbon intensities of different electricity generation types in provinces are shown in Figure 4. With the improvement of coal-fired unit efficiency and the promotion of renewable energy generation technologies, the overall carbon emissions intensity of the power sector can be effectively reduced. Subcritical coal-fired power has the highest average carbon intensity for both direct (22.67 tons/10000 CNY) and embodied (27.98 tons/10000 CNY), exceeding those of other technologies. Solar power lies on the other end of the range with an average embodied intensity of only 1.25 tons/10000 CNY. This is similar to the results of a critical review of the past 47 studies of the environmental impact of electricity generation conducted by Barros et al., (2020). Compared to other energy sources, wind and solar have the smallest impact on global warming during their power generation(Barros et al., 2020).

For a specific power generation sector, there is a difference in the carbon intensity between the provinces, and the impact of such divergence depends on the amount of power generation determined by each province's resource endowment or regional positioning. Compared to the average intensity of hydropower generation sector (6.42 tons/10000 CNY), Sichuan Province has the lowest carbon intensity with 0.70 tons/10000 CNY which have advantageous geographical conditions for hydropower. Beijing has the highest intensity with 25.41 tons/10000 CNY. Chen et al., (2022) reported similar results. The hydropower carbon intensity of eastern coast and North China are significantly higher than the southwest regions (X. Chen et al., 2022). It is evident that the current spatial distribution of hydropower generation aligns well with the demand for carbon emission reduction in the power sector.

Nevertheless, the current regional distribution of other power generation technologies, especially thermal power, poses an impediment to the reduction of carbon emissions. Specifically, the average embodied intensities of subcritical and supercritical coal-fired power are 27.98 tons/10000 CNY and 24.34 tons/10000 CNY. Xinjiang province, which has the top 30% of installed capacity, has the highest embodied carbon intensity, with 72.15 tons/10000 CNY and 66.40 tons/10000 CNY. The average intensity of ultra-supercritical coal-fired power is 15.63 tons/10000 CNY, while Ningxia province has the highest embodied carbon emission intensity with 57.04 tons/10000 CNY. The coal-fired power with the lowest embodied intensity are clustered in Tianjin, where the intensity of the subcritical, supercritical and ultra-supercritical coal-fired power generation sectors is 9.33 tons/10000 CNY, 10.46 tons/10000 CNY and 11.47 tons/10000 CNY, respectively.

Interprovincial differences in carbon intensity can lead to inconsistent results in policy implementation. Although the average embodied carbon intensity of gas-fired power is 21.10 tons/10000 CNY, which is lower than that of subcritical coal-fired power and supercritical coal-fired power, Gansu Province, Shanghai and Heilongjiang Province have higher carbon intensities of gas-fired power than that of coal-fired power. Therefore coal-to-gas policies may lead to a spike in carbon emissions in those provinces.

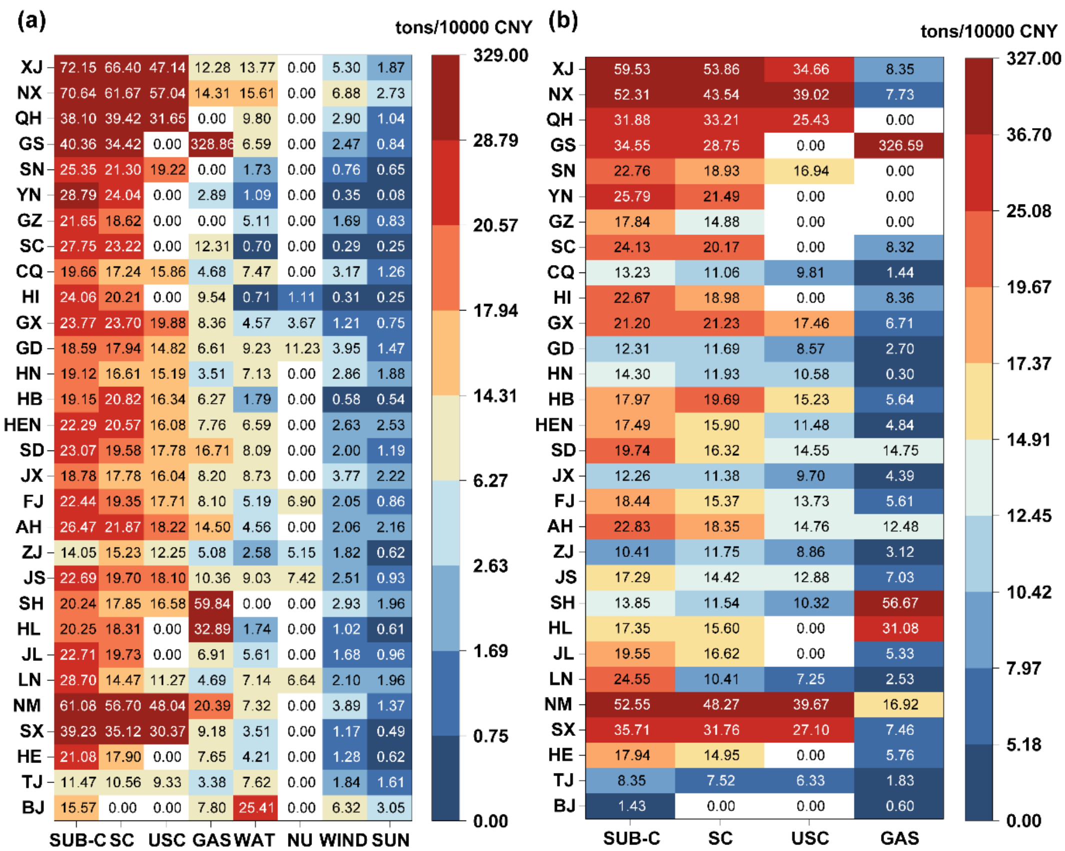

Figure 4. Embodied carbon emission intensity (a) and direct carbon emission intensity (b) of different electricity technologies in 30 Chinese provinces.

Under the gradual decarbonization of the power system and the acceleration of grid interconnection, it is more appropriate to retain more coal-fired units in Eastern China (e.g., Zhejiang Province, Guangdong Province), where the embodied carbon intensity is relatively low, to guarantee power supply and satisfy peak demand on a larger scale. Additionally, Heilongjiang Province, Liaoning Province, Jilin Province, Gansu Province, and some eastern coastal areas have high wind power density and low embodied carbon intensity, despite the current low installed capacity. In the future, these areas would be ideal locations for the construction of wind farms. It should also be noted that Yunnan Province, Hainan Province, and Sichuan Province both have an embodied carbon intensity of less than 0.50 tons/10000 CNY in solar power sectors, making them well-suited to the production of solar energy.

	LOW (Top 30%)	MEDIUM (Top 30% - Last 30%)	HIGH (Last 30%)
SUB-C	BJ, TJ, SH, ZJ, JX, HB, HN, GD, CQ	HE, JL, HL, JS, AH, FJ, SD, HEN, GX, HI, GZ, SN	SX, NM, LN, SC, YN, GS, QH, NX, XJ
SC	TJ, HE, LN, SH, ZJ, JX, HN, CQ	JL, HL, JS, AH, FJ, SD, HEN, HB, GD, HI, SC, GZ, SN	SX, NM, GX, YN, GS, QH, NX, XJ
USC	TJ, LN, ZJ, HN, GD, CQ	SH, JS, AH, FJ, JX, SD, HEN, HB	SX, NM, GX, QH, NX, XJ （SN）
GAS	TJ, LN, ZJ, HB, HN, GD, CQ, YN	TJ, LN, ZJ, HB, HN, GD, CQ, YN	NM, HL, SH, AH, SD, SC, GS, NX
WAT	SX, HL, ZJ, HB, HI, SC, YN, SN	TJ, HE, NM, LN, JL, AH, FJ, HEN, HN, GX, CQ, GZ, GS,	BJ, JS, JX, SD, GD, QH, NX, XJ
NU	GX, HI	LN, ZJ, FJ	JS, GD
WIND	HE, SX, HL, HB, GX, HI, SC, YN, SN	TJ, LN, JL, JS, ZJ, AH, FJ, SD, HEN, HN, GZ, GS	BJ, NM, SH, JX, GD, CQ, QH, NX, XJ
SOLAR	HE, SX, HL, ZJ, HB, HI, SC, YN, SN	TJ, NM, JL, JS, FJ, SD, GD, GX, CQ, GZ, GS, QH	BJ, LN, SH, AH, JX, HEN, HN, NX, XJ

3.2 Identification of critical upstream sectors of different power technologies

Figure 5 shows the major contributors to consumption-based carbon emissions in the upstream supply chain of different power subsectors. The critical upstream sectors are concentrated in the energy sectors (S02, S11), energy-intensive sectors (S14, S27), manufacturing sectors (S16, S19), and service sectors (S26, S28). By improving the low-carbon technologies of these upstream sectors, carbon emissions along the supply chain of electricity generation can be reduced.

Sources of indirect carbon emissions differ significantly between renewable and fossil energy generation sectors. The mining and washing of coal sector (S02) emits the highest carbon emissions to satisfy the final demand for fossil energy generation sectors, accounting from 72.79% (ultra-supercritical coal-fired power sector) to 86.63% (nuclear power sector) of the total upstream carbon emissions. Odeh and Cockerill (2008), Yin et al., (2017), and Wang et al., (2018) similarly reported the important contribution of coal mining in upstream indirect emissions from coal-fired electricity generation. Thus, energy-saving and high-efficiency technologies for coal mining should be vigorously promoted to reduce indirect carbon emissions from fossil energy generation.

Some non-energy-intensive manufacturing sectors contribute considerable indirect carbon emissions to the wind power, hydropower, and solar power sectors, which do not require fuel supplies. The hydropower sector mainly drives carbon emissions from the manufacture of non-metallic mineral products sectors (S13), smelting and processing of metals sectors (S14) and the manufacture of electrical machinery and equipment sectors (S19); the manufacture of general purpose machinery sectors (S16) and the manufacture of electrical machinery and equipment sectors (S19) are the major sources of embodied carbon emissions from the solar power sector; a major contribution to the embodied carbon emissions of the wind sector comes from smelting and processing of metals sectors (S14).

Upstream indirect carbon emissions are contributed most by Shandong province, which accounts for 13.66% of total emissions. Also, Shandong Province plays an imperative role in various power supply chains (excluding hydropower), with its share of upstream carbon emissions ranging from 7.06% for nuclear power to 18.54% for ultra-supercritical coal-fired power. As for wind and solar power generation, Liaoning Province and Shanxi Province account for more than 20% of carbon emissions upstream.

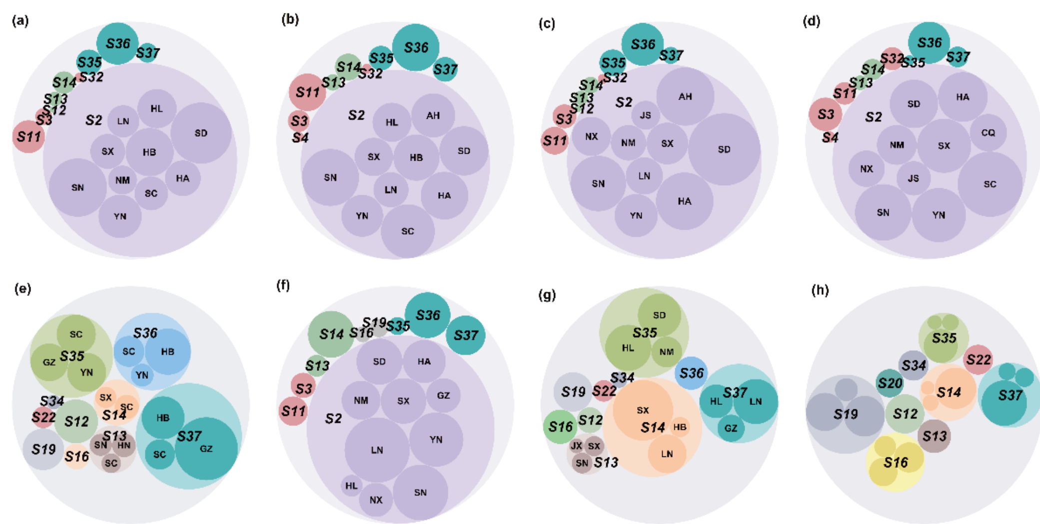

Figure 5. Critical upstream carbon emitting sectors of different power technologies. Note: (a) Subcritical coal-fired power sector (b) Supercritical coal-fired power sector (c) Ultra-supercritical coal-fired power sector (d) Gas-fired power sector (e) Hydropower sector (f) Nuclear power sector (g) Wind power sector (h) Solar power sector. In each figure, the circles on the second layer represent the sectors ranked top 10, and the circles on the third layer represent the provinces with significant contributions. The larger circles indicate the greater the carbon emissions pulled by the power sector for that sector.

Figure 6 shows the major contributors to betweenness-based carbon emissions in the electricity upstream supply chain. Even though they are not direct emitters of carbon emissions in the upstream power supply chain, key transmission sectors can mitigate environmental pressures on the power sector through improvements in production efficiency. By effectively minimizing intermediate inputs from upstream emitting sectors to critical transmission sectors, carbon emission reductions can also be accomplished, circumventing the necessity for advancements in environmental technology. There is some overlap between the critical sectors identified using the betweenness-based method and the consumption-based method (S02, S14, S19, S27, S28). However, the betweenness-based analysis additionally highlights the crucial transmission role of the manufacture of metal products sectors (S15). In addition, the manufacture of chemical products sectors (S12) transmit large amounts of CO_2 downstream to the fossil fuel power generation sectors, while the manufacture of communication equipment, computers and other electronic equipment sectors (S20) are identified as important carbon transmission sectors for the solar power sector and the wind power sector.

In particular, the importance of the manufacture of electrical machinery and equipment sectors (S19) to the coal-fired power sectors has risen as the efficiency of coal-fired generation units increased. The upstream carbon emissions share attributed to the manufacture of electrical machinery and equipment sectors (S19) has increased from 5.26% for the subcritical coal-fired power sector to 7.48% for the ultra-supercritical coal-fired power sectors. At the same time, the manufacture of electrical machinery and equipment sectors (S19) is also an important transmission sector in the upstream chain of the renewable energy generation sector. In the context of ultra-supercritical units becoming the mainstream units for new coal power projects and the growing scale of renewable energy installations, it is imperative to emphasize that productivity improvements in the manufacture of electrical machinery and equipment sectors (S19) have the potential to reduce carbon emissions. Besides, the supporting policies to improve technological innovation capabilities in Shandong Province, Jiangsu Province, Hebei Province, and Anhui Province, which are important sectors of upstream carbon transmission for solar and wind power generation, will exert a great indirect carbon reduction effect on a national scale.

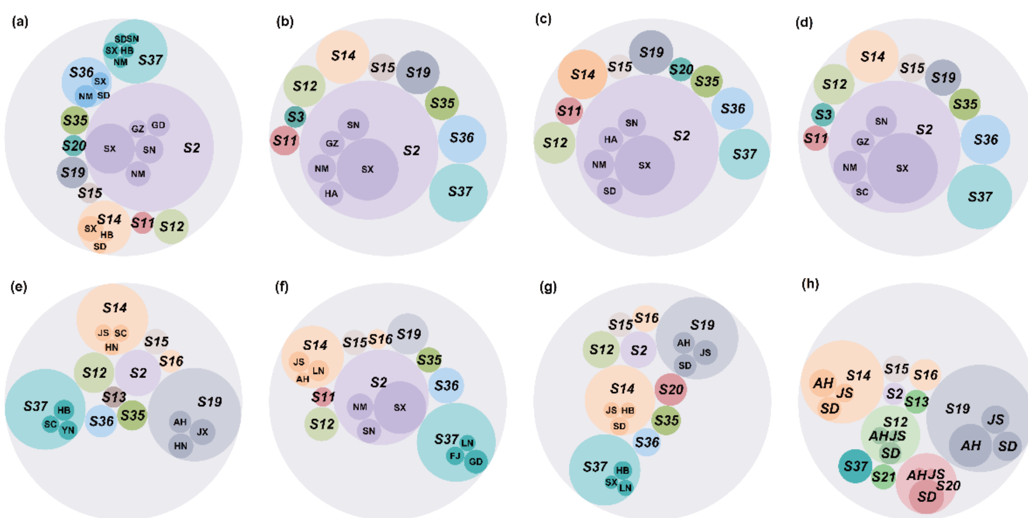

Figure 6. Critical upstream carbon transmission sectors of different power technologies. Note: (a) Subcritical coal-fired power sector (b) Supercritical coal-fired power sector (c)

Ultra-supercritical coal-fired power sector (d) Gas-fired power sector (e) Hydropower sector (f) Nuclear power sector (g) Wind power sector (h) Solar power sector. In each figure, the circles on the second layer represent the sectors ranked top 10, and the circles on the third layer represent the provinces. The larger circles indicate the greater the carbon emissions transmitted by that sector to the power sector.

3.3 Carbon emission reductions under the different scenarios

As demonstrated in Section 3.1, there is a significant variation in the intensity of embodied carbon emissions across provinces in the electricity sector. This implies that carbon emissions from the electricity sector are affected by both the spatial deployment of new power installations and the choice of power technologies. Therefore, SN1-SN6 examine the extent to which different provincial power policies and combinations will reduce power sector carbon emissions along the whole supply chain. Using a comparison of BAU and CSCR, we examine the impact of the upstream sector on emissions throughout the electricity supply chain.

As expected, a reduction in carbon emissions is attained in all scenarios (see Figure 7). Yet the magnitude of the carbon reduction potential differs. A comprehensive comparison shows that the initiative of governments to positively build clean energy generation to replace traditional thermal power will bring the highest emission reduction. Better than the abatement strategy of reducing coal consumption per unit of electricity generated by coal power. Meanwhile, the extent to which different interprovincial spatial distributions of the power system affect emissions reductions varies widely. In the most aggressive scenarios, it will result in better emission reductions effects than optimization of the generation mix.

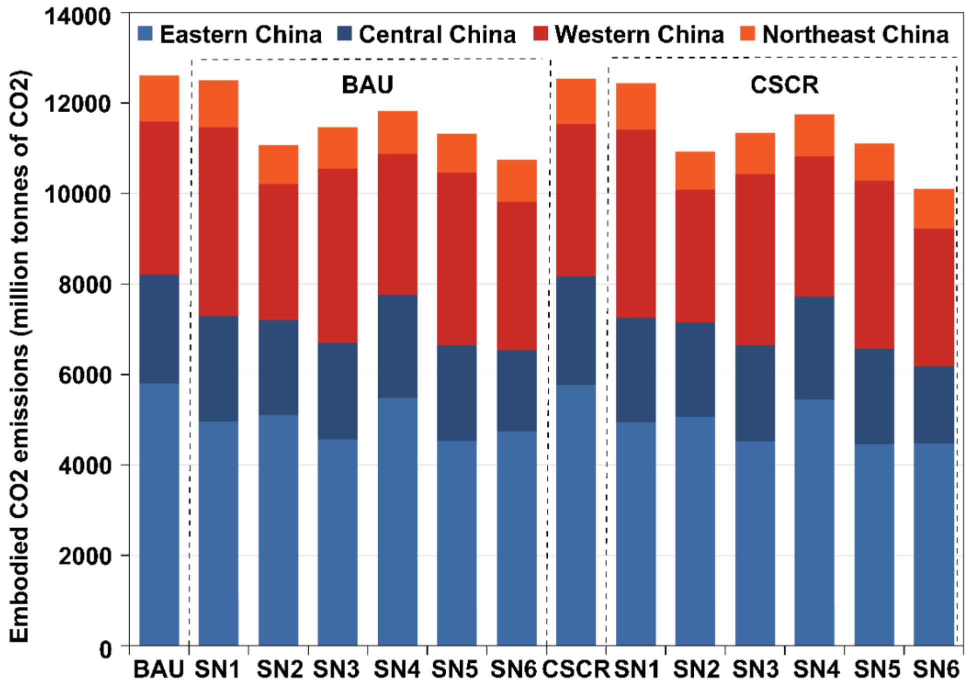

Figure 7. Embodied carbon emissions from China's power system under different scenarios in 2025.

Specifically, the highest reductions can be achieved by changing the generation mix (BAU-SN2), where emissions are reduced by 1540.1Mt compared to the baseline. This is due to active development of renewable energy generation with low embodied intensity in the provinces. Eastern China can achieve the greatest pace of transition to a low-carbon power system, with total emissions reductions of 697.6Mt. Shandong, Guangdong, and Hebei provinces ranked among the top three in Eastern China, contributing 26.0%, 24.7%, and 14.9%, respectively. Inner Mongolia is also a typical example active promotion of low-carbon power, with emission reductions reaching 113.3 Mt, accounting for 29.86% of the total emission reductions in Western China.

In contrast, under the worst-case scenario of only changing the spatial distribution (BAU-SN1), embodied carbon emissions account for 12500.6Mt in 2025, which also indicates that the power sector continues to shift to the western region during the 14th FYP period. The embodied carbon emissions of the power sector in Western China increased by 791.9Mt in comparison to the baseline scenario. Inner Mongolia, Shaanxi Province, and Guangxi Province, which contributed the top three in Western China, increased 331.9 Mt, 144.4 Mt, and 99.2 Mt, respectively. Meanwhile, the optimization of spatial distribution in Eastern China can reduce embodied carbon emissions by 832.7Mt.

The reduction in direct carbon intensity of the power sector (SN4, SN5) brings about reduction benefits that are closer to those of SN3, with 779.4 Mt and 1,290.3 Mt of emission reductions. Regarding the coal-fired generation sector, compared with improving the coal efficiency of subcritical coal units (BAU-SN4), replacing high-capacity subcritical units with ultra-supercritical units (BAU-SN5) reduces CO_2 emissions by 511.03 Mt. It is particularly effective in Shandong Province, Jiangsu Province, and other provinces with a high number of subcritical units of smaller capacities.

Under the strict implementation of the 14th FYP in all provinces (BAU-SN3), the embodied carbon emissions of the power sector are reduced by 1132.2Mt, which is lower than BAU-SN2 but higher than BAU-SN1. A large part of this can be attributed to the addition of coal-fired power in the high-carbon-intensity region (Western China), which counteracts the positive impact of the power mix transformation. China recently announced that it would tightly control the growth of coal power projects and coal consumption during the 14th FYP period. However, considering rapidly rising electricity demands, the central document may not achieve its intended guiding and constraining effects as coal power projects are approved by provincial governments.

Assuming perfect electricity transmission within the regional grid, SN6 as an ideal scenario demonstrates that leveraging the advantages of low-carbon technologies for electricity in each province within the regional grid would result in the highest carbon reduction (1855.5Mt). Especially the power sectors in Central China would achieve the best reduction of 612.4Mt. Inter-province transmission capacity will be further enhanced with the transformation of the regional electricity supply system and the acceleration of the construction of inter-province UHV transmission channels (NDRC., 2022). Hence, the comparative low-carbon advantages of the same power technology between provinces can be exploited on a larger scale in the future.

Through the development of low-carbon technologies in the upstream power sector (CSCR), emissions across the electricity supply chain can be decreased more efficiently. CSCR reduces the embodied carbon emissions from the electricity sector by 66.9 Mt compared to BAU. With the exception of SN1, all power sector transition scenarios have achieved better emission reductions with lower carbon intensity in upstream sectors. The highest reduction of carbon emission is 651.4 Mt, in comparison with BAU-SN6 and CSCR-SN6. In other words, if provinces with low-carbon comparative advantages take on a higher share of power generation, the development of low-carbon technologies will have a higher multiplier impact on carbon reduction.

However, the change in spatial distribution (SN1) offsets a portion of the carbon reduction benefits from the reduced carbon intensity of upstream sectors. CSCR-SN1 results in only an additional 64.5 Mt of emission reduction compared to BAU-SN1, which is even lower than the difference between BAU and CSCR. It is also an evidence that the restructuring of spatial layout during the 14th FYP will result in an increase in indirect emissions from electricity. Therefore, regional heterogeneity needs to be taken into account in promoting the reduction of carbon intensity in critical upstream sectors, actively matching the trend of regional migration of the power industry.

4 Conclusions

All provinces have committed to developing renewable energy as a mainstay of a new power system during the 14th FYP. As a result of differences in the power structure of each province and the inputs of each power technology, there are regional differences in the decarbonization pathways of the power sector. This study captures carbon emissions embodied in different electricity supply chains through the identification of critical sectors using a multi-regional input-output model, and examines the impact of technology and demand changes on carbon emissions in conjunction with scenario analysis. Critical sectors are identified based on two policy-guided uses: enhancing the efficiency of intermediate products in the chain and promoting the development of low-carbon technologies upstream. This study delivers the following conclusions and policy implications:

(1) The embodied carbon intensity of the electricity subsector varies significantly by province, resulting from differences in both direct carbon intensity and upstream indirect carbon emissions. For coal-fired power, the embodied intensity of different coal-fired technologies is lower in the Eastern China than in other regions. Sichuan province has the lowest intensity (0.29 tons/10000 CNY) for wind power. With regard to solar power, Yunnan province has the lowest embodied carbon intensity (0.08 tons/10000 CNY). To achieve emission reductions in the power sector on a national scale, it is necessary to exploit the advantages of low-carbon technologies related to power in each province and promote the sharing of power resources on a larger scale across the country.

(2) There is a mismatch between current installation and carbon reduction targets in the coal-fired and wind power sectors. The results show that the average intensity of subcritical, supercritical and ultra-supercritical coal-fired power generation sectors in Western China is 39.0 tons/10000 CNY, 35.2 tons/10000 CNY and 34.1 tons/10000 CNY, respectively, which is significantly higher than that in other regions. However, Western China is responsible for about 30% of China's power generation. Similarly, both Inner Mongolia and Xinjiang provinces have relatively high embodied carbon intensities for wind power.

Yet they are the two provinces with the highest installed wind power capacity in 2017. This mismatch between carbon intensity and power generation responsibilities suggests that China's power system could receive higher emission reduction benefits through spatial distribution optimization.

(3) The coal-fired power generation sector mainly drives upstream emissions from energy-related sectors, while wind and solar power sectors drive upstream emissions from some non-energy-intensive manufacturing sectors (e.g., smelting and processing of metals sectors, the manufacture of general purpose machinery sectors and the manufacture of electrical machinery and equipment sectors). The development of low carbon technologies in these sectors will reduce upstream emissions from the electricity supply chain.

(4) The important transmission roles of the manufacture of metal products sectors, the manufacture of chemical products sectors, and the manufacture of communication equipment, computers and other electronic equipment sectors were identified through betweenness-based method. Industries associated with these sectors can contribute to a more low-carbon electricity supply chain by increasing their overall productivity (i.e., reducing the use of intermediate inputs). Such productivity improvements are mostly initiated by companies on their own, as they can reduce production costs and bring additional economic benefits.

(5) Carbon intensity reductions in critical upstream sectors have a positive impact on any of the power system transformation scenarios, be it spatial distribution optimization,

increasing clean energy power supply capacity and reducing direct emissions from coal power. Under the assumption of a 10% reduction in the carbon intensity of critical upstream sectors, China's power system will add an additional 133.1 Mt of embodied carbon emission reductions by the end of the 14th FYP. In the process of structural transformation of the power system, the development of low-carbon technologies in upstream sectors will have multiplier effects on reducing emissions of the whole power supply chain.

These conclusions have three policy implications for the low-carbon power supply chain:(1) The concentrated development of energy resources will have a positive impact on achieving emission reduction targets. To achieve optimal allocation of electricity nationwide and realize emissions reduction throughout the entire supply chain, two efforts are needed. Firstly, strengthening the construction of power infrastructure to improve inter-provincial and inter-regional electricity transmission capacity and channel utilization efficiency. Secondly, promoting the construction of a unified national electricity market to break down barriers to cross-provincial and cross-regional transactions.

(2) Promoting coal power policy of “Replacing Small Generator Units with Large Generator Units” in each province is the most effective strategy to achieve emission reduction targets in coal power. It is particularly pertinent for Western China, which has greater power generation responsibility, to formulate policies aimed at optimizing technical structures and strengthening supervision over the elimination of old coal-fired power plants.

While improving the efficiency of coal combustion may have limitations under current technologies (such as technical revamp of flow passage of steam turbine, vapor seal transformation for steam turbine, etc), it is important to actively develop key technologies and equipment for energy saving and emission reduction of coal power. For example, the nationwide promotion of high-temperature subcritical technology can bring about a win-win outcome regarding cost and emission reduction.

(3) The National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) have proposed a target of over 1.2 GW of total installed capacity for wind power and solar power in China by 2030. All provinces have committed to developing renewable energy as a mainstay of a new power system during the 14th FYP. For renewable energy generation, a more carbon-light power supply chain relies on the actions of critical upstream sectors. Considering the important roles of the smelting and processing of metals sectors and the manufacture of general purpose machinery sectors in the wind and solar power supply chains, the use of low-carbon technologies in these sectors (such as winding type magnetic coupling governor, new carbon-free clay wet sand casting technology, etc.) should be actively promoted. Additionally, greater attention is recommended to be given to the sustainable development of the manufacture of communication equipment, computers and other electronic equipment sectors, as they are closely related to the renewable energy power supply chain.

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