Available online at www.sciencedirect.com

ScienceDirect

Advances in Climate Change Research 13 (2022) 721−728

www.keaipublishing.com/en/journals/accr/

Economic and employment effects of China's power transition based on input−output and scenario simulation

Dong SUN[a], Yan-Yan LIU[a], Xiao-Wen YANG[a], Liang-Qiu LYU[b], Jia-Hai YUAN[a,*]

[a] School of Economics and Management, North China Electric Power University, Beijing 102206, China
[b] School of Foreign Languages, North China Electric Power University, Beijing 102206, China

Received 18 January 2022; revised 27 June 2022; accepted 6 September 2022
Available online 14 September 2022

Abstract

With high carbon emission, the low-carbon transition of power sector will be critical for China to achieve the carbon peaking and carbon neutrality goals. The power transition will have an impact on the economy and employment through the value chain. Quantifying the impact is important for China's future energy and welfare policies. This study adopts input−output model to analyze the impact on economy and employment based on accelerated and slow power transition scenarios. The results show that the low-carbon power transition will have a negative impact on coal power and coal mining and washing sectors, while a positive impact on machine manufacturing and equipment sector. Low-carbon power transition will have a positive economic and employment effect to promote inclusive growth. By 2060, economic output will increase by about 8.50 trillion CNY, value-added by about 3.39 trillion CNY, and employment will increase by about 3.74 million. Although slower coal power transition can stabilize the economic and employment effect in the short and medium run, accelerating the power transition will produce more positive effect and lower job losses by coal power in the long run. By 2060, accelerating transition will boost output by 8.21%, value-added by 8.20% and jobs by 7.97%. Accordingly, the government should establish an all-round just low-carbon transition mechanism.

Keywords: Low-carbon power transition; Input-output model; Scenario simulation; Economic effect; Employment effect

1. Introduction

To promote sustainable development, China has pledged to achieve carbon peak by 2030 and carbon neutrality by 2060 (hereafter as 3060 targets). China's CO_2 emission per unit of GDP is above the global average, and the contradiction between economy and environment is prominent. China is committed to reducing CO_2 emission intensity by 60%−65% by 2030 compared with the level in 2005, posing new challenges to the low-carbon transition of China's energy structure in the short term (Su et al., 2021). The primary mission of promoting China's 3060 targets is to gradually substitute fossil energy with renewable energy and promote energy transition. In terms of carbon emission sources, the power sector contributed the highest carbon emissions in China, emitting 4.13 Gt of CO_2 in 2020, accounting for 41.77% of China's total emissions, among which coal-fired power contributed 86.19% (IEA, 2021). Compared with other sectors, the power sector has the largest potential contribution to emission reduction (Liu et al., 2021), and the decarbonization of the power sector will be pivotal under the vision of carbon neutrality.

China's power sector has undergone great changes in the past ten years. From 2010 to 2020, the capacity proportion of non-hydro renewable energy power increased from 3.30% to 24.32%, while coal power was reduced from 66.91% to 48.45%. In 2020, coal power contributed 58.46% of China's total power generation, while wind power altogether with photovoltaic power generations accounted for 35.27% of renewable energy power generation (NEAC, 2021). Nuclear

* Corresponding author.
E-mail address: yuanjh126@126.com (YUAN J.-H.).

Peer review under responsibility of National Climate Center (China Meteorological Administration).

https://doi.org/10.1016/j.accre.2022.09.001

power growth is restricted due to safety issues, at the same time hydropower will be lack of substantial potential growth under the ecological and environmental pressure (Lin, 2021). Under the 3060 targets, China will shift to be dominated by wind and photovoltaic power from coal power. However, large-scale grid connection with a high proportion of renewable energy has posed a great challenge to the flexibility and safe and stable operation of the power system. In 2021, there were many power blackout events in China, and coal power still needs to assume the role of power security and supply for a long time. In this context, many researches began to focus on the power planning and operation under the 3060 target, and analyzed the development of transition paths and strategies based on the multi-objective requirements of reliability, economy and low carbon (Zhang et al., 2021; He et al., 2021), compare transition paths and costs under different emission targets, and evaluate the long-term optimal transition development path (Li et al., 2021; Lin et al., 2019). In addition, the environmental and health benefits of low-carbon transition are also a hot research issue. Many researches have analyzed the benefits of power transition on improving ambient air quality and population health (Tang et al., 2022).

In fact, the low-carbon power transition will also have a great impact on the economy and society, thus raising concerns about social justice. A good evidence is that with reducing excessive capacity, the employment in China's coal industry decreased by 2.64 million from 2013 to 2018, and many migrant workers are facing unemployment. Both individuals and families have formed a greater impact (NRDC, 2017). In the low-carbon energy and power transition, coal power will phase out and new energy will be developed on a large scale, which will further cause greater impact on the economy and society. Developed regions/countries such as Europe and the United States have a relatively fast low-carbon transition process, and have paid early attention to the impact of power transition on the economy and society, such as the impact of climate policy on stranded assets and employment (Johnson et al., 2015; Chateau and Saint-Martin, 2013). They gradually began to pay attention to the unfair distribution of benefits related to the transition of energy justice, calling for identifying vulnerable groups and avoiding the formation of sacrifice zones (White, 2020; Brock et al., 2021). On this basis, developed countries have gradually explored and established a relatively perfect just transition mechanism to facilitate the smooth transition of energy and power (European Commission, 2014, 2020).

Many studies have analyzed the positive impact of renewable energy, and discussed the impact of coal power and coal mining industry from the perspective of political economy. It is generally accepted that investment in renewable energy contributes to economic and employment growth in the renewable energy sector (Dai et al., 2016; Huang et al., 2020). Some studies also consider the possible impact of the coal industry from the perspective of political economy, and call for the establishment of a just transition mechanism (He et al., 2020; Wang and Lo, 2022). Econometrics and analysis methods are used to analyze the employment impact of power transition, ignoring the correlation and impact of the industry, that is, only direct employment is analyzed (Zhang et al., 2017). Some studies have comprehensively analyzed the economic and social impact of power (Lin et al., 2019; Jin et al., 2018), however the time dimension of their analysis is before 2017, which is quite different from the current power industry, and it is difficult to provide guidance for the low-carbon power transition under the 3060 targets (Wang et al., 2013; Mu et al., 2018; Zhang et al., 2017).

Based on these, this study analyzes and compares the economic and employment impacts of coal power and renewable energy under different power transition schemes, hoping to provide valuable information for power transition plan and promote just transition.

2. Methodology and data

2.1. Input-output model

2.1.1. Basic framework

The input−output (IO) model describes the source of inputs and the destination of output use in the production of each sector over a certain period in a input−output matrix form, revealing the interdependent and mutually constraining quantitative relationships among the various sectors of regional economy. The basic equation of the IO model consisting of N sectors can be shown as Eq. 1.

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y} \tag{1}$$

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{2}$$

$\boldsymbol{X}$ is a $N \times 1$ output vector and $\boldsymbol{Y}$ is a $N \times 1$ final demand vector in the IO table. (1) can be obtained by deforming Eq. 2, indicating that the output of each sector driven by the final demand $\boldsymbol{Y}$ is $\boldsymbol{X}$, which $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is called a Leontief inverse matrix.

v_j is the value-added coefficient of j sector, equal to the value-added in the out-put table divide the output of sector j, as shown in Eq. 3. Similar to value-added, the employment coefficient e_j of sector j is the ratio of the jobs E_j to the output X_j, as shown in Eq. 4. The total impact $\boldsymbol{T}$ arised by $\boldsymbol{Y}$ through industrial association can be calculated by Eq. 5 and the direct impact $\boldsymbol{D}$ arised by $\boldsymbol{Y}$ can be calculated by Eq. 6, where $\boldsymbol{M}$ represents value-added coefficient V or employment coefficient E, $\boldsymbol{Y}$ is predicted according to the method in previous studies (Kim and Yoo, 2021; Wang et al., 2013).

$$v_j = \frac{V_j}{X_j} \tag{3}$$

$$e_j = \frac{E_j}{X_j} \tag{4}$$

$$\boldsymbol{T} = \boldsymbol{M}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{5}$$

$$\boldsymbol{D} = \boldsymbol{MY} \tag{6}$$

2.1.2. Processing of input−output table

149 sectors included in the original input−output table are aggregated to 15 sectors as shown in Table 1.

The power supply and all power technology sectors are included in the power sector. Luo et al. (2020) split the power sector into the power supply sector and different power production sectors, taking into account differences in sectoral investments and intermediate inputs for power production sectors. Zhu and Ling (2020) split the power sector according to the proportion of power generations. In this study, the production and supply of electric power and heat power (as the power sector below) is divided into eight subsectors: power supply, coal power, gas power, hydroelectric power, nuclear power, wind power, photovoltaic power, and other power production. The data related to power sector in IO table includes three parts and each part will be handled in different ways. Part I represents intermediate use of the power sector by other sectors, and is decomposed into eight subsectors according to the value weights of different power technologies. Part II represents the intermediate input to power sector. We assumed that in part II, the intermediate inputs of coal and water flow only into coal power. Intermediate inputs of gas flow only to gas power. Intermediate inputs of petroleum flow into gas power and coal power. Intermediate inputs of processing of petroleum−coking−nuclear sector flow into coal power, gas power and nuclear power. Manufacture sector is split according to the total investment cost weights, and the agricultural sector is only used for biomass power which is included in other power production sectors. The intermediate inputs to subsectors from other sectors excluding the above sectors are spilt for each power technology according to the cost weights. Part III represents the intermediate input between different subsectors. Since the power plants also need to consume electricity in the daily work process, which is not available from the current data, this study assumes that different power generation sectors consume only their own power, that is, each sector is self-sufficient. Auxiliary power reflects the power consumed by power plants, so the subsectors' own demand is split according to plant power weights. According to the principle of equal input and output of each sector, adjust the whole table after decomposing the power sector. The data is shown in Table 2.

2.2. Data sources

Investments in power supply and power grid, power generation costs, power generation, installed capacity and 2017 input−out table are obtained from the National Bureau of Statistics of China (NBSC, 2020). Investment cost data is obtained from Yu (2015) and China Electricity Council. Due to employment caliber and data of sectors in the Population and Employment Statistics Yearbook 2018, 2017 Economic Census, Labor Force Yearbook 2018 are different, this study uses data of the total jobs in China's owned units, urban collective units, and other units by sectors in Population and Employment Statistics Yearbook 2018 which contains the largest employment coverage and most detailed sectors. The data of jobs in the power supply sector is obtained from the 2018 China Electricity Industry Talent Annual Development Report (CEC, 2018). The employment factors of wind, photovoltaic, and nuclear power are derived from the staffing standards of 30 power companies and stations, and the data on coal power and hydropower are derived from China Electricity Council (CEC, 2012) to calculate the jobs in each sector, and then the jobs in subsectors are adjusted according to the total jobs in the power sector. Employment coefficients are shown in Table 3.

Table 1
Fifteen aggregated sectors.

No.	Sector	Abbreviation	No.	Sector	Abbreviation
1	Agriculture, forestry and fishery products and services	Agriculture	9	Production and supply of electric power and heat power	Power
2	Mining and washing of coal	Coal	10	Production and supply of gas	Gas
3	Extraction of petroleum and natural gas	Petroleum	11	Production and supply of water	Water
4	Other mining	Mining	12	Construction	Construct
5	Consumption goods industry	Consumption	13	Finance	Finance
6	Processing of petroleum, coking, and nuclear fuel	Petroleum-coking-nuclear	14	Transportation, storage and postal	Trans
7	Raw material industry	Material	15	Tertiary industry	Tertiary
8	Manufacture of machine and equipment	Manufacture			

Table 2
Investment, value and cost weights.

Sector	Coal power	Gas power	Hydro	Wind power	Photovoltaic power	Others
Investment (100 million CNY)	644	142	700	646	207	1
Value weights (%)	63.55	5.56	12.73	7.03	4.52	2.50
Cost weights (%)	61.21	4.58	14.63	7.41	4.21	3.12

Table 3
Employment coefficient (jobs (10,000 CNY)$^{-1}$).

Sector	Coefficient	Sector	Coefficient	Sector	Coefficient
Agriculture	0.0023	Material	0.0035	Trans	0.0082
Coal	0.0139	Manufacture	0.0061	Tertiary	0.0130
Petroleum	0.0056	Gas	0.0052	Coal power	0.0063
Mining	0.0042	Water	0.0236	Wind power	0.0043
Consumption	0.0046	Construct	0.0116	Photovoltaic power	0.0068
Petroleum-coking-nuclear	0.0016	Finance	0.0073		

2.3. Setting of scenarios

Decarbonizing the energy system as soon as possible is the necessary condition of China's carbon neutrality vision, which puts forward higher requirement for zero-carbon power system. Current studies generally agree that carbon emissions from the power sector need to peak as soon as possible and start to decline rapidly, with a high possibility of peaking around 2025 and achieving zero or negative emissions by 2050 (Zhang et al., 2022). In 2025 and 2030, China's installed capacity of coal power will reach about 1230 GW and 1260 GW (CEC, 2021). National Development and Reform Commission has proposed the policy target of 50% non-fossil power generation by 2030. Based on above researches and target, the following two scenarios are made on the basis of the balance between power supply and demand.

Rapid development of renewable energy and early coal power transition (S_1): with the rapid development of renewable energy, it is very important to fully tap the development space of large-scale controllable power supply and coal power is moderately developed. The capacity of coal power will reach the peak of over 1190 GW in 2025. Wind and photovoltaic power will reach 880 GW and 1000 GW respectively in 2030. Generations of non-fossil energy will be accounting for 53.11% in 2030. After the 14th Five-Year Plan period, it will not be added and the units will phase down as soon as possible. All units will be phased out in 2055. Wind and photovoltaic power will reach 2800 GW and 3600 GW respectively in 2060.

Normal development of renewable energy power and slow coal power transition (S_2): the renewable energy will develop normally. In order to guarantee the power demand, the capacity of coal power will reach a peak of 1290 GW in 2030, with generations of non-fossil energy accounting for 49.11%. Wind and photovoltaic power will reach 750 GW and 860 GW respectively in 2030. After 2030, coal power will phase down and conventional coal power will completely phase down in 2060. Wind and photovoltaic power will reach 2510 GW and 3400 GW respectively in 2060.

Emission trajectories for power under two scenarios are illustrated in Fig. 1. CO_2 emissions will both reach its peak at in 2026, and carbon neutrality by 2050. Installed capacity of other power technologies is consistent in two scenarios. The bioenergy with carbon capture and storage will contribute to net zero carbon in 2050 and negative carbon in 2060.

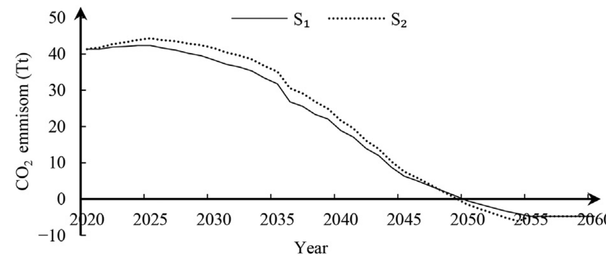

Fig. 1. 2020–2060 CO_2 emission paths in China's power sector under two scenarios.

Future costs are projected through wind and photovoltaic power learning curves. Assuming the cost for coal power generation is constant, learning rate of wind and photovoltaic power is 7.53% and 20% respectively. In S_1, the cost of wind and photovoltaic power will reach 0.304 CNY (kW h)$^{-1}$ and 0.225 CNY (kW h)$^{-1}$ in 2030, and 0.270 CNY (kW h)$^{-1}$ and 0.148 CNY (kW h)$^{-1}$ in 2060. In S_2, the cost in 2030 are 0.310 CNY (kW h)$^{-1}$ and 0.237 CNY (kW h)$^{-1}$ respectively, and 0.270 CNY (kW h)$^{-1}$ and 0.151 CNY (kW h)$^{-1}$ in 2060. The historical installed capacity and cost of wind and photovoltaic power are shown in Figs. 2 and 3.

3. Result and discussion

3.1. Power sector pulling effect

3.1.1. The total effect on other sectors

The final demand per unit in the power sector pulls 2.8 units of total output, 0.26 units of direct EVA, 0.74 units of

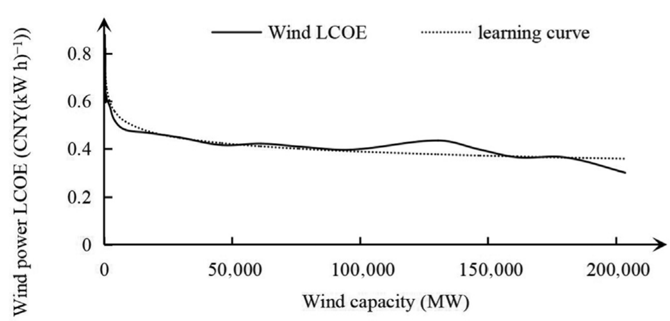

Fig. 2. Historical installed capacity and cost of wind power.

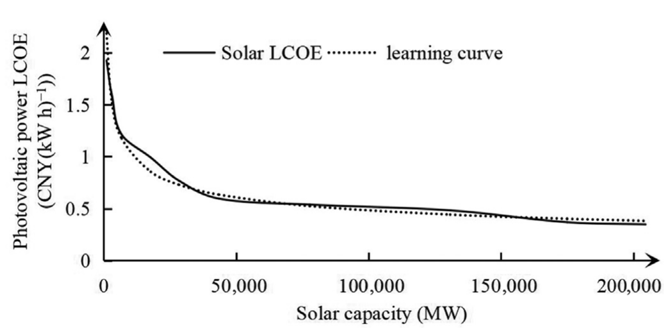

Fig. 3. Historical installed capacity installation and cost of photovoltaic power.

indirect EVA; the final demand per 10,000 CNY in power sector brings 0.018 jobs, including 0.005 in direct employment and 0.013 in indirect employment. Besides the power sector itself, there are five sectors, Manufacture, coal, tertiary industry, material and financial sector, which are influenced significantly as shown in Fig. 4. In terms of economic output, because of coal power dominance in the power sector, the coal sector output is directly affected by the power demand. However, the manufacture sector output change is higher than coal sector through the industrial chain and the entire economic systematic connection. So, the manufacture sector is more indirectly affected.

In terms of EVA and employment, these four sectors: coal, tertiary industry, manufacturing, and financial sectors, are more greatly affected as shown in Fig. 4. Among them the top affected sector is coal sector, and secondly the tertiary industry. This is the reason that coal sector and tertiary industries have lower intermediate product demand and then have higher EVA coefficients than manufacture sector. Moreover, manufacture sector with the improvement of automation level requires less labor per unit output while coal sector and tertiary industry are labor-intensive industries.

It should be considered that low-carbon transition is proceeding in China, especially nowadays with the constraint of Chinese 3060 targets, which would accelerate the power structure shift, coal power will be gradually no longer dominant. Considering the internal changes of power supply structure, the power sector should not simply be regarded as a whole sector.

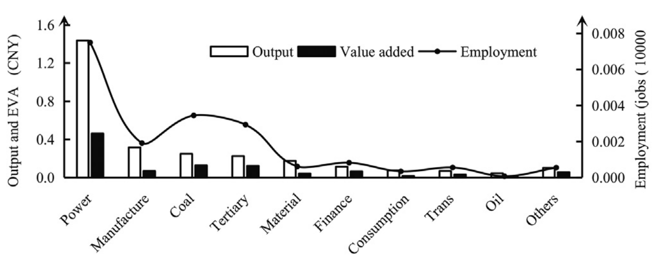

Fig. 4. The influence of the power sector.

3.1.2. Separate effect on other sectors from power subsectors

In order to consider the internal changes in the power supply structure under the constraints of China's 3060 targets, traditional energy power (mainly coal power) and new energy power (mainly wind and photovoltaic power) cannot simply be considered as a whole sector, so we analyzed the three subsectors. As shown in Fig. 5, the three subsectors have substantially different contributions to other sectors.

In terms of output, coal power has a low indirect multiplier, while the opposite is true for wind and photovoltaic power. In addition to the impact on the power sector itself, the coal power sector has the largest impact on the coal sector, while wind and photovoltaic power has the greatest impact on equipment manufacturing sector except the tertiary sector. Although wind and photovoltaic power sectors do not require direct fuel consumption and costs are concentrated on machinery such as wind turbines, which has a large impact on the equipment manufacturing, tertiary and raw materials industries, through the role of industrial linkage, will generate indirect demand for coal, such as equipment manufacturing industry will consume coal, forming an indirect demand for the coal sector from wind and photovoltaic power generation.

In terms of value added, the indirect value added due to changes in final demand per unit of coal power, wind and photovoltaic power is 2.6, 4 and 4.5 times higher than the direct value added, respectively. Except the impact on power sector itself, the coal power sector has the greatest impact on the coal sector. Apart from the tertiary sector, the sector most affected by wind and photovoltaic power is the equipment manufacturing sector. The impact on the tertiary sectors, such as finance, is also very high as it has a relatively higher value-added coefficient.

In terms of employment, the sector with the greatest impact on total employment is the power sector itself. Each billion dollars of coal power final demand generates 180 jobs, the sector that is affected by the coal power sector is the coal sector, due to the combined effect of the direct consumption of coal by coal power as well as the employment coefficient. Wind and photovoltaic power have the strongest employment effects on the equipment manufacturing sector.

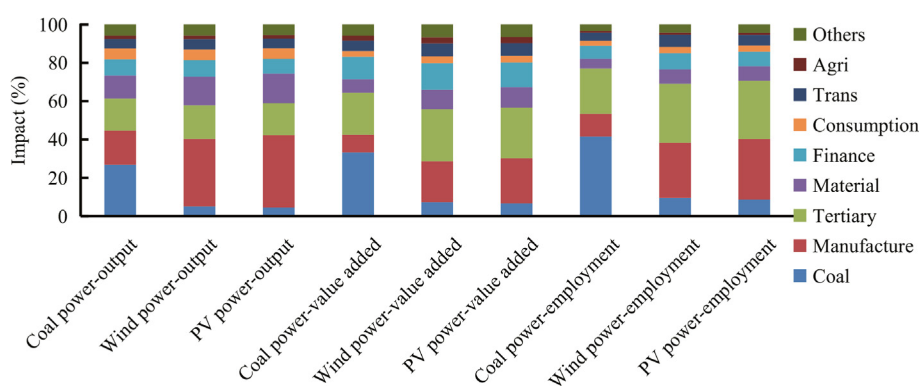

Fig. 5. Influence sectors of coal, wind and photovoltaic power.

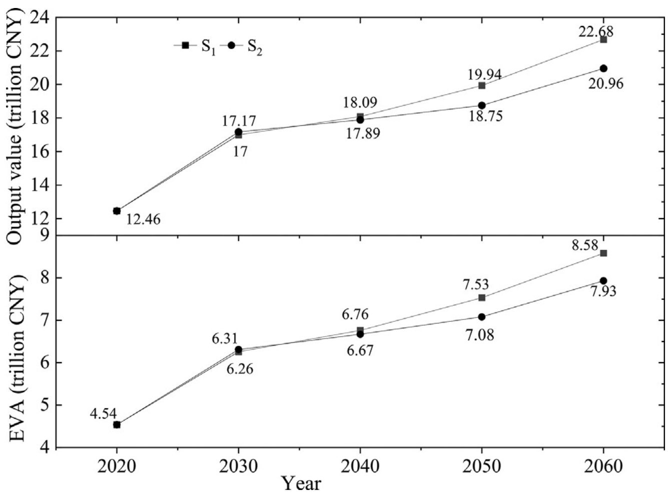

Fig. 6. Economic output and EVA of wind, photovoltaic and coal power.

From the perspective of comprehensive economic output, value added and employment effect, the coal sector is the sector most affected by coal power except tertiary industry, which means the coal power transition will have an impact on the employees of coal power and coal sectors. The equipment manufacturing industry is the sector most affected by wind and photovoltaic power generation, which means the development of renewable power will benefit the manufacture sector. In terms of industry chain, coal as the upstream of coal power and manufacture as the upstream of wind-photovoltaic power, are most affected in the process of power transition.

3.2. Prediction of economic effect

According to the above analysis, we made a prediction and found that power transition would have a positive economic effect during 2020−2060 whatever the pace under the two scenarios is slower or faster. As shown in Fig. 6, the output and EVA both moved upward in the two scenarios.

Under the scenario of the expansion of renewables and the reduction of coal power as soon as possible (S_1), the economic effect induced by coal power with the scale declining in 2030 will be correspondingly decreasing while wind and photovoltaic power will be increasing. There will be no coal power plants by 2055, and the economy will be fully driven by clean power, but the overall economic effect will keep growing. The total output will increase from 12.46 trillion CNY in 2020 to 22.68 trillion CNY in 2060, and the EVA will increase from 4.54 trillion CNY in 2020 to 8.58 trillion CNY. Under the scenario of normal development of renewable energy and continued development of coal power (S_2), coal power will phase down after 2030. The total output will increase from 12.46 trillion CNY in 2020 to 20.96 trillion CNY in 2060, and the EVA will increase from 4.54 trillion CNY in 2020 to 7.93 trillion CNY. The economic effect of coal power will not grow until 2030. Summarily power transition will not lead to an economic shock while always offer a positive stimulation.

Although slow coal power transition (S_2) could stabilize the economic effect in the near and medium term as in Fig. 6, the output and EVA gap between S_1 and S_2 would become wider and wider in the long run. Under S_2, it will pull total output of 17.17 trillion CNY in 2030, with EVA of 6.31 trillion CNY, higher than the total output of 17 trillion CNY and EVA of 6.26 trillion CNY under S_1. But in 2060, the economic output and EVA under S_2 will all gradually lag the S_1 and the gap would continue to widen. The total economic output and EVA under S_1 in 2060 would be 22.68 trillion CNY and 8.58 trillion CNY while 20.96 trillion CNY and 7.93 trillion CNY under S_2.

3.3. Prediction of employment effect

Like the above economic prediction, the power transition would improve the social employment during 2020−2060, whatever the pace is slower or not. As shown in Fig. 7, the employment moved upward under S_1 and S_2.

Slow power transition (S_2) will bring 11.88 million total jobs in 2030 and coal power would demand more employees. Under the scenario of accelerating coal power transition (S_1), coal power sector would start to suffer job losses while the wind and photovoltaic power will increase jobs. Similarly, slow coal power transition (S_2) could stable the employment demand in the near and medium term, as shown in Fig. 7, but the employment gap between S_1 and S_2 would get widened gradually in the long run. In 2030, the social employment demand of 11.65 million jobs under the scenario of fast power transition (S_1) will be induced, which is lower than the scenario of slow power transition (S_2). In 2040, the slow coal power transition scenario (S_2) would face more job losses compared with 2030 and stay longer than S_1. There will be 8.33 million job losses induced by coal power under S_2, higher than 7.72 million job losses under S_1 in 2060. In the unemployment caused by coal power, it is difficult for coal miner to transfer to other sectors, but some sectors, such as the equipment manufacturing sector, are less difficult to convert and easier to convert within the industry. In addition, wind and photovoltaic power will stimulate 13.67 million social jobs in 2060, which is 1.01 million higher than the slow power transition scenario (S_2).

3.4. Discussion

This study represents a timely academic effort to the 3060 targets by advancing our understanding on the social & economic impact of decarbonizing China's power sector, the most important and difficult part of carbon neutrality. Secondly, the methodological advance is that we divided power sector into eight sub-sectors which are matched with the requirement of power transition modelling and calibrate the direct labor input parameters with micro-level data. Last but not the least important, we provided an interesting window of observation by comparing the difference of regular transition and an accelerated one, as social & economic impact is an integral component of carbon neutrality.

The study also suffers to two limitations. Firstly, due to the nature of IO modelling, it cannot capture the dynamic impact of Production restructuring. Secondly, the advance in labor

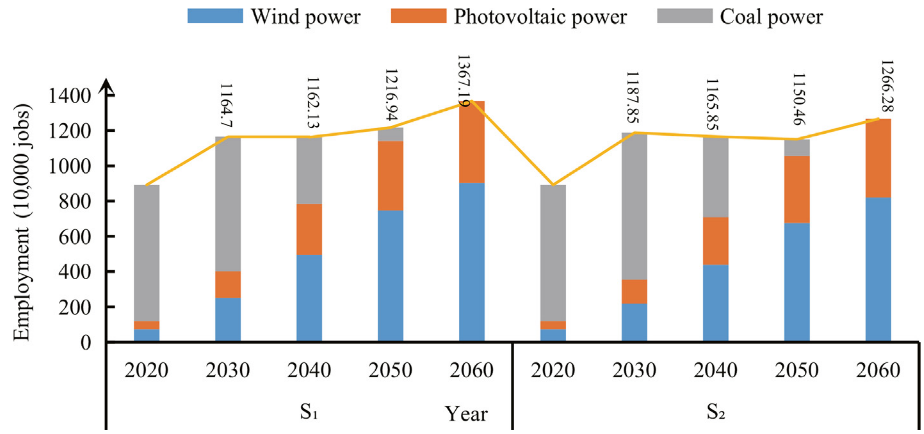

Fig. 7. Total employment in wind, photovoltaic and coal power.

productivity is not considered in our modelling. Future study should take these two factors in the modelling framework and further examine the impacts on labor structure and unbalanced regional shock.

4. Conclusion and suggestion

Utilizing China's input−output table, this study explores the economic and employment effect under the two assumptions of transition scenarios realizing 3060 targets. During attaining the 3060 targets, the coal power transition mainly influences its upstream industry like coal sector, which will lead to great losses to the coal power and coal sectors. Conversely, wind and photovoltaic power will make manufactures seize benefits. The renewable energy development overall, has a positive effect on the economy and employment. Even if there is a massive decline after 2030, the economy and employment will be in a basically stable state, without massive unemployment. The pace of coal power transition would affect the economy and employment to distinct degrees. In the long term, accelerating transition will have more positive effects. By 2060, it will boost output by 8.21%, value-added by 8.20% and jobs by 7.97%. The gap in the economic effect further widens in the process. Slow transition could result in more coal-related job losses as coal power continues to be deployed.

Power transition matters the entire industrial chain, enterprises, and employees of the enterprise, especially the affected sectors in the coal power industry chain. When formulating transition plans, the government needs to consider supporting policies for these sectors and establish a comprehensive and just transition policy system. From the industry level, unemployment caused by coal power cannot be entirely absorbed by the employment demand induced by renewable energy. It requires the government to set up just transition funds, to provide security assistance to the affected workers and the area, and help upgrade the affected industry. At the same time, to make corresponding retraining and resettlement policies to meet the structural changes is also vital. At the national level, there are noticeable differences in resource endowments between regions in China, and there is a flow of factors between regions and industries. While promoting the national economy and employment, it is necessary to adopt policies tailored to local conditions for different regions. The slow transition may stabilize employment in the short term, but in the long run, there will be more job losses related to coal power. In the future, the influence of social and economic should also be taken into account when making the power transition planning.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

The authors acknowledge the funding of National Natural Science Foundation of China (72173043) and Rockefeller Brothers Fund (21-200).

References

Brock, A., Sovacool, B.K., Hook, A., 2021. Volatile photovoltaics: green industrialization, sacrifice zones, and the political ecology of solar energy in Germany. Ann. Assoc. Am. Geogr. 111 (6), 1756−1778. https://doi.org/10.1080/24694452.2020.1856638.

Chateau, J., Saint-Martin, A., 2013. Economic and employment impacts of climate change mitigation policies in OECD: a general-equilibrium perspective. Int. Econ. 135−136, 79−103. https://doi.org/10.1016/j.inteco.2013.08.001.

CEC (China Electricity Council), 2012. The 2012 China Electricity Development Report. https://cec.org.cn/index.html.

CEC (China Electricity Council), 2018. China Electricity Industry Talent Annual Development Report. https://www.cec.org.cn/detail/index.html?3-166307.

CEC (China Electricity Council), 2021. Study on Power Fuel Supply and Demand Pattern in Energy Transition. https://cec.org.cn/detail/index.html?3-305186.

Dai, H.C., Xie, X.X., Xie, Y., et al., 2016. Green growth: the economic impacts of large-scale renewable energy development in China. Appl. Energy 162, 435−449. https://doi.org/10.1016/j.apenergy.2015.10.049.

European Commission, 2014. Green Employment Initiative: Tapping into the Job Creation Potential of the Green Economy. https://ec.europa.eu/environment/gpp/pdf/23_09_2014/Info_Commission_new_policy_development_DG_ENV.pdf.

European Commission, 2020. European Green Deal. https://ec.europa.eu/clima/policies/eu-climate-action_en.

Huang, J.S., Li, W.P., Guo, L.J., et al., 2020. Renewable energy and household economy in rural China. Renew. Energy 155, 669−676. https://doi.org/10.1016/j.renene.2020.03.151.

He, J.K., Li, Z., Zhang, X.L., et al., 2021. Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies. Environ. Sci. Ecotechnol. 9, 100134. https://doi.org/10.1016/j.ese.2021.100134.

He, G., Lin, J., Zhang, Y., et al., 2020. Enabling a rapid and just transition away from coal in China. One Earth 3 (2), 187−194. https://doi.org/10.1016/j.oneear.2020.07.012.

IEA (International Energy Agency), 2021. CO_2 Emissions from Fuel Combustion 2020. https://iea.blob.core.windows.net/assets/474cf91a-636b-4fde-b416-56064e0c7042/WorldCO2_Documentation.pdf.

Jin, Y.M., Wang, X.C., Bian, Y.Z., 2018. Research on evaluation method of economic and social benefits of China's power planning. IOP Conf. Ser. Earth Environ. Sci. 199, 5. https://doi.org/10.1088/1755-1315/199/5/052012.

Johnson, N., Krey, V., McCollum, D.L., et al., 2015. Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. Technol. Forecast. Soc. Change 90, 89−102. https://doi.org/10.1016/j.techfore.2014.02.028.

Kim, J.H., Yoo, S.H., 2021. Comparison of the economic effects of nuclear power and renewable energy deployment in South Korea. Renew. Sustain. Energy Rev. 135, 110236. https://doi.org/10.1016/j.rser.2020.110236.

Li, Z., Chen, S.Y., Dong, W.J., et al., 2021. Low carbon transition pathway of power sector under carbon emission constraints. Proc. CSEE 41 (12), 3978−4001. https://doi.org/10.13334/j.0258-8013.pcsee.210671.

Lin, B.Q., 2021. The problem and solution of Chinese carbon neutrality. New Finance 2021 (7), 26−29 (Chinese).

Lin, J., Kahrl, F., Yuan, J., et al., 2019. Economic and carbon emission impacts of electricity market transition in China: a case study of Guangdong province. Appl. Energy 238, 1093−1107. https://doi.org/10.1016/j.apenergy.2019.01.128.

Liu, Y., Tong, D., Chen, J., et al., 2021. Role of climate goals and clean-air policies on reducing future air pollution deaths in China: a modelling study. Lancet Planet. Health 6, 92−99. https://doi.org/10.1016/S2542-5196(21)00326-0.

Luo, F., Guo, Y., Yao, M.T., et al., 2020. Carbon emissions and driving forces of China's power sector: input−output model based on the disaggregated power sector. J. Clean. Prod. 268, 121925. https://doi.org/10.1016/j.jclepro.2020.121925.

Mu, Y.Q., Cai, W.J., Evans, S., et al., 2018. Employment impacts of renewable energy policies in China: a decomposition analysis based on a CGE modeling framework. Appl. Energy 210, 256−267. https://doi.org/10.1016/j.apenergy.2017.10.086.

NBSC (National Bureau of Statistics of China), 2020. National Bureau of Statistics of China Input-Output Tables of China. http://data.stats.gov.cn/ifnormal.htm?u=/files/html/quickSearch/trcc/trcc01.html&h=740.

NEAC (National Energy Administration of China), 2021. List of National Electric Power Industry Statistics. http://www.nea.gov.cn/2021-01/20/c_139683739.htm.

NRDC (Natural Resources Defense Council), 2017. Research on Employment Issues Associated with Coal Industry Transition. http://www.nrdc.cn/information/informationinfo?id=288&cook=2 (Chinese).

Su, J., Liang, Y.B., Ding, L., et al., 2021. Research on China's energy development strategy under carbon neutrality. Bull. Chin. Acad. Sci. 36 (9), 1001−1009. https://doi.org/10.16418/j.issn.1000-3045.20210727001 (Chinese).

Tang, R., Zhao, J., Liu, Y., et al., 2022. Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. Nat. Commun. 13, 1008. https://doi.org/10.1038/s41467-022-28672-3.

Wang, C., Zhang, W.S., Cai, W.J., et al., 2013. Employment impacts of CDM projects in China's power sector. Energy Pol. 59, 481−491. https://doi.org/10.1016/j.enpol.2013.04.010.

Wang, X.X., Lo, K., 2022. Political economy of just transition: disparate impact of coal mine closure on state-owned and private coal workers in Inner Mongolia, China. Energy Res. Social Sci. 90, 202585. https://doi.org/10.1016/j.erss.2022.102585.

White, D., 2020. Just transitions/design for transitions: preliminary notes on a design politics for a green new deal. Appl. Econ. Lett. 31 (2), 20−39. https://doi.org/10.1080/10455752.2019.1583762.

Yu, D.F., 2015. Research on the regional low carbon scenario analysis and macro-economic impacts based on MAC and IO models in China. Tsinghua University (Chinese).

Zhang, C., He, G., Johnston, J., et al., 2021. Long-term transition of China's power sector under carbon neutrality target and water withdrawal constraint. J. Clean. Prod. 329, 129765. https://doi.org/10.1016/j.jclepro.2021.129765.

Zhang, S.F., Chen, Y., Liu, X.L., et al., 2017. Employment effects of solar PV industry in China: a spreadsheet-based analytical model. Energy Pol. 109, 59−65. https://doi.org/10.1016/j.enpol.2017.06.058.

Zhang, X.L., Huang, X.D., Zhang, D., et al., 2022. Research on the pathway and policies for China's energy and economy transformation toward carbon neutrality. Manage. World 38 (1), 35−66. https://doi.org/10.19744/j.cnki.11-1235/f.2022.0005.

Zhu, P.Y., Ling, W., 2020. Study on the impact of different peak carbon emission scenarios on industrial structure: an analysis based on dynamic CGE model. Financ. Theor. Pract. J 41 (5), 110−118. https://doi.org/10.16339/j.cnki.hdxbcjb.2020.05.015 (Chinese).