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LETTER

China’s power transformation may drastically change employment patterns in the power sector and its upstream supply chains

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Abstract

China’s power sector, as the major CO2 emitter, has experienced significant restructuring that has had profound impacts on employment in both power and its upstream sectors. Combining input–output and structural path analysis, we quantified the direct and indirect impacts of power transformation on employment in China between 2012 and 2017. Direct employment in the power generation sector witnessed a net growth of 0.12 million, while over 10 times that number of jobs (1.40 million) have been lost in the upstream sectors, mainly in coal mining and washing, finance, oil and gas extraction and transportation. Among the top 10 critical paths, the share of employment driven by solar and wind power increased to 12.31% in 2017, more than nine times that in 2012. Furthermore, three scenarios have been set up to evaluate the employment patterns in 2030 and 2050. Under the 1.5 °C scenario, projection shows that the power sector could support over 5 million jobs in 2050, with more than 80% of these being related to renewable energy. Policy suggestions for a just transition, such as resettlement of laid-off workers and job transfer in upstream industries, are comprehensively discussed.

1. Introduction

A power system dominated by coal-fired power plants (CFPPs) consumed more than half of the fossil fuels and contributed about a third of China’s CO2 emissions (Shan et al. 2021). To alleviate the environmental pollution associated with the power sector and achieve climate mitigation targets, China has implemented comprehensive energy conservation and emission reduction policies (China Xinhua News Network 2020a, 2020b, Guo et al. 2021). Therefore, the power sector in China has undergone tremendous transformation in recent years (Lu et al. 2019), including the shutdown of small units, development of renewable energy and upgrading of energy technology (Liu et al. 2019, Cao et al. 2020). For instance, small 63.02 GW units with capacity under 300 MW were decommissioned between 2011 and 2020 (Sili et al. 2019) and the total wind power capacity reached 281.53 GW in 2020, which is more than 20 times that in 2005.

Such a drastic transformation of the power sector has successfully reduced various emissions, including carbon emissions, sulfur dioxide and heavy metals (Liu et al. 2019, Zhou et al. 2019). Meanwhile, power transformation has also reshuffled the employment pattern in the power sector (Patrizio et al. 2018), as more than 2.8 million jobs were provided by the production and supply of electric power and heat in 2018 (National Bureau of Statistics 2013–2020). With
further advancement of the coal reduction policy, shutdown of CFPPs may lead to a wave of unemployment in the power sector without proper placement of laid-off workers (Heinrichs et al. 2017, Burke et al. 2019). By contrast, the capacity of renewable energy, including wind power and solar power, has grown rapidly in recent years and created plenty of new jobs (Bohlmann et al. 2019) that may provide opportunities to compensate for the job losses resulting from closure of CFPPs (Pai et al. 2021).

Furthermore, the employment patterns in other sectors along the upstream supply chains can also be contemporaneously influenced by the low carbon transition of the power sector due to the inter-sectoral linkages between the power sector and other industrial sectors. For instance, more than 1 million jobs would be lost in coal mining (National Bureau of Statistics 2020) if all CFPPs were to be decommissioned in the future because the power sector is the largest downstream market for coal. However, the transformation to low-carbon energy can provide a large number of new jobs in upstream industries in the renewable energy sector, such as the manufacture of wind turbines and solar panels. A quantitative analysis of direct and indirect impacts on employment may help us to understand how the entire economy is affected by power transformation through the industrial supply chains to inform advance planning for future industrial development.

By applying input–output (IO) analysis and structural path analysis (SPA) this study aims to evaluate the direct and indirect impacts of power transformation on employment in China between 2012 and 2017. Moreover, China will continue to vigorously promote a clean transformation in the power sector, and the capacity of wind power and solar power will be over 1200 GW in 2030, indicating a significant growth of over four times. Therefore, it is important to understand the job implications of rapid development of renewable energy in the future. Here, we set up three scenarios for power transition in China, and evaluate the possible changes in employment pattern in the future. Thus, this study not only reveals the impacts on employment caused by energy transition but also provides valuable insights for preventing potential social conflicts and transition barriers caused by unemployment in the power sector so as to achieve a just transition and plan the industrial situation in advance according to the power transformation.

2. Method and data

Power transformation has significant impacts not only on direct employment in operation and maintenance in the power sector but also on indirect employment along the upstream supply chains, including raw material extraction, manufacturing and transportation for power sectors (O’Sullivan and Edler 2020). There are two widely used methods for estimating indirect employment, namely, the employment factor approach and IO analysis. The former method calculates indirect employment using the employment factors of different energy types, namely the employment per unit of installed capacity (Cameron and van der Swaan 2015, Garrett-Peltier 2017), however, it cannot trace the flow of elements between different sectors so does not meet the requirements for formulating refined policies for managing power transformation. Environmentally extended IO analysis is often used to evaluate the indirect and supply chain effects of final demand using different indicators, such as pollutant emissions, employment, land and water resources (Su et al. 2017, Mi et al. 2018, Faturay et al. 2020, Wang et al. 2020). Consequently, we evaluated the indirect employment along the power sector’s upstream supply chains by IO analysis to reveal the interaction between different industrial sectors.

2.1. Direct employment in the power sector

Direct employment can be calculated using equation (1)

\[ J_i = EI_i \times C_i \]  

(1)

where \( J_i \) is direct employment in the power generation sector \( i \), \( EI_i \) (in units of jobs MW\(^{-1}\)) is the employment intensity of sector \( i \) and \( C_i \) (in MW) is the total capacity of sector \( i \).

2.2. Environmentally extended IO analysis

To reveal the employment impacts along the supply chain, we evaluated the indirect employment based on the intermediate inputs from other sectors into the power sector using equation (2)

\[ ME = e \times (I - A)^{-1} \times X \]  

(2)

where \( ME \) (in units of jobs) is a vector of the employment driven by the intermediate inputs of the power sector (excluding the flows within the sector), \( e \) (in units of jobs/yuan) is a vector of employment coefficient for all sectors, which is calculated by direct employment in each sector divided by the sector’s total output, \((I - A)^{-1}\) is the Leontief inverted matrix \((L)\), in which \( A \) is a direct input coefficient matrix, and \( X \) (in yuan) is a vector of intermediate inputs to the power sector.

2.3. SPA

SPA is applied to analyze the production network through inter-sector flows, which reveal the crucial paths for employment driven by the power sector along the supply chains (Li et al. 2019). According to Taylor series approximation, the domestic Leontief inverse can be expanded as

\[ (I - A)^{-1} = I + A + A^2 + \cdots + A^n. \]  

(3)
Therefore, equation (1) can be expressed as
\[
ME = e^* (I - A)^{-1} * X = e1X + eAX + eA^2X + \cdots + eA^nX
\]
where \(eA^nX\) represents the employment associated with the \(n\)th production layer (PL\(^n\)). The zeroth production layer (PL\(^0\)) represents direct element flows driven by the output while PL\(^n\) represents material flows from the \(n\)th PL, which is a set of supply chain paths with \(n\) steps (Zhen et al. 2018, Zhang et al. 2020). The first-order production layer (PL\(^1\)) from sector \(i\) into sector \(j\) is represented by \(e_iA_{ij}X_j\), for example the embodied employment flow from the coal mining and washing industry to CFPPs. The second-order production layer (PL\(^2\)) from sector \(i\) via sector \(k\) into sector \(j\) is represented by \(e_iA_{ik}A_{kj}X_j\), and the same pattern continues for all tiers.

### 2.4. Scenario analysis
In this study, we set up three scenarios to analyze future direct employment in the power sector and indirect employment that can be attributed to it, namely the baseline scenario (under current policies), the 2 °C scenario and the 1.5 °C scenario; the capacities of different power generation sectors are summarized in table S1 (available online at stacks.iop.org/ERL/17/065005/mmedia). The baseline scenario assumes that China maintains its current policy for the power sector, and the proportion of CFPPs will remain at approximately 20% of the total capacity of the power sector in 2050. To guarantee full access for electricity generated by renewable sources, the 2 °C scenario assumes that construction of new CFPPs will be prohibited after 2030, and the average annual number of power generation hours will decrease to 3500 by 2050. The 1.5 °C scenario assumes that construction of new CFPPs will be prohibited after 2025, and the reserved CFPPs will be used for backup units of peak-shaving and frequency modulation. Therefore, the average annual number of power generation hours of CFPPs will gradually decrease in the 1.5 °C scenario, and will be less than 2000 in 2050. By contrast, the average annual number of power generation hours of renewable energy will increase with technological progress, to 2500 h for wind power and 1500 h for solar power in 2050. For the three scenarios, we assumed that total electric power generation will reach 9 000 terawatt-hours by 2030 and 11 000 terawatt-hours by 2050. Owing to the wide use of intelligent equipment and new technologies, we assume that the employment intensity of different energy types will decline in the future, as summarized in table S2.

### 2.5. Data sources
We collected the IO tables from 2012 and 2017 from the National Bureau of Statistics of China and converted them into 2012 constant prices by the double deflation method. Moreover, the original power sector has been disaggregated to power transmission and distribution, coal power, nature gas power plants (NGPPs), hydroelectric power, nuclear power, wind power and solar power (the detailed methods of disaggregation can be found in a previous study (Li et al. 2019)), while the changes in power sector employment in this study do not include jobs in the power transmission and distribution sector. The total employment in all sectors in 2012 and 2017 was collected from the China Population and Employment Statistics Yearbook (National Bureau of Statistics 2013–2020). The number of workers for the six types of power generation sectors is calculated based on the jobs in specific sectors and the corresponding employment intensity collected from previous studies and reports (IRENA 2013–2018, National Bureau of Statistics 2013–2020); the detailed information is summarized in table S2.

### 2.6. Limitations
When calculating direct employment in the power sector, the employment intensity of solar power was assumed as 1.5 times that of wind power, based on the average employment intensity of OECD countries summarized in IRENA (2013–2018). However, the rates of employment intensity in solar and wind power in China are not exactly the same as that in OECD countries, leading to a certain degree of bias in the estimate. Furthermore, we assumed that the employment intensity in China’s power sector will gradually decline in the future, while the changes in employment intensity and economic structure of upstream supply chains were not considered. Thus, the 2017 IO table was used for evaluating the indirect employment driven by the power sector in 2030 and 2050, which could create uncertainties in scenario analysis. As the employment intensity will also drop in upstream suppliers, the estimates represent the upper bound of possible employment effects in the future. Additionally, the disaggregation of the power sector in the IO table was derived from the national output weight of each power generation sector, and the method only considers the specificity of five upstream sectors, including coal mining, water production and supply, gas production and supply, petroleum, and oil and gas exploration. Thus, the disaggregation of the power generation sector may not fully conform to the actual situation, which can also lead to a certain degree of uncertainty (Li et al. 2019).

### 3. Results

#### 3.1. Direct employment in the power sector
As shown in figure 1, total employment in China’s power sector increased from 1.13 million in 2012 to 1.25 million in 2017. Although 155 500 direct jobs were lost in CFPPs due to the shutdown of small
Figure 1. The changes in employment in the power sector between 2012 and 2017.

units, the new jobs from solar and wind energy development largely exceeded the jobs lost, leading to a net increase of 120,000 jobs. It is worth noting that the average employment intensity of decommissioned small CFPPs is much higher than that of the newly built large CFPPs; thus, the total capacity of CFPPs can keep growing while jobs continue to decline in CFPPs. On the contrary, over 200,000 new jobs were provided by the development of wind and solar power, accounting for 79.06% of all newly added jobs in power sector between 2012 and 2017.

Furthermore, the growth in employment brought by solar power (150,190) is more than twice that of wind power (69,180), as solar power plants have a higher employment intensity than wind power. As the second largest job creator in the power sector, hydroelectric power plants provided 31,570 new jobs with a newly installed capacity of 110.61 GW during this time period, and the total employment in hydroelectric power (256,410) ranks only second to CFPPs. Compared with renewable energy power plants, there were relatively few new jobs contributed by nuclear power plants due to the low employment intensity (0.61 jobs MW$^{-1}$) and production expansion, because nuclear power plants are mainly dominated by at least two units with capacity of 100 MW, which can reduce the employment intensity by shared management and maintenance personnel between different units.

3.2. Impact of power transition on employment of upstream suppliers

The embodied jobs witnessed a net loss of 1.27 million between 2012 and 2017, while the indirect jobs in upstream sectors decreased by 1.4 million, as illustrated in figure 2. Furthermore, the decline of indirect jobs in upstream suppliers is 10 times the growth of direct jobs in the power sector, indicating that power transition has more significant impacts on employees of upstream sectors than the power generation sector. In 2012, there were 3.17 million jobs in upstream sectors related to the power sector, and more than one-third of the indirect employment driven by CFPPs was concentrated in the coal mining and washing industry (CMWT). After a series of policies on power transformation were implemented between 2012 and 2017, over 630,000 jobs in the supply chain (indirect employment) would be lost due to the small unit shutdown campaign without considering newly built CFPPs. Hydroelectric power takes the second position in factors driving indirect new employment in other sectors (420,000) in 2012, decreasing to 310,000 in 2017.

Compared with CFPPs, indirect employment related to solar and wind (90,000 jobs) was very inconspicuous in 2012, but quickly climbed to 190,000 in 2017 as the total capacity increased by more than three times during the same period. However, the net effect related to renewable energy tends to be lower than the gross effects, as the expansion of renewable energy may crowd out investment in and budgets of other economic sectors. According to the Renewable Energy and Jobs Annual Review issued by the International Renewable Energy Agency (IRENA), the total employment in China’s wind and solar industry reached 2.7 million in 2017, which is much higher than the results (480,000 jobs) in this study. This discrepancy can be explained by the different research boundaries; this study only calculated the direct and indirect employment driven by China’s power sector, while the annual IRENA study evaluates the total employment in the renewable energy
industry in China, including the jobs driven by export of photovoltaic panels and wind turbines.

Apart from CMWI, the indirect new employment in finance, transportation, electrical machinery and equipment manufacturing (EMEM) fields is the most relevant to transition of the power sector. As a capital-intensive industry, the construction of power stations requires huge amounts of financial support, which means that transformation of the power sector has significant impacts on finance. In this study, the total indirect employment flow from finance to the power sector was reduced by 98,860, while the indirect employment driven by solar and wind power in 2017 was approximately twice that in 2012. In addition, the power sector created 11,390 new indirect jobs in EMEM between 2012 and 2017, and more than three-quarters of new jobs were attributed to solar and wind power, resulting in the proportion of indirect employment driven by solar and wind power increasing from 2.98% to 10.98%. Owing to the elimination and postponement of CFPPs, the contribution of paths involved with CFPPs also decreased from 42.69% to 32.05%.

3.3. Critical paths of jobs driven by the power sector

Compared with the critical paths in 2017, the paths of employment driven by the power sector were apparent at deeper layers along the supply chain in 2012, with the largest path of job shifts being from PL$^1$ (32.55%) in 2012 to PL$^0$ (34.96%) in 2017. From the PL perspective, the job opportunities driven by the power sector are mainly concentrated in the first three PLs (PL$^0$–PL$^3$), accounting for 56.47% and 59.69% of total indirect employment in 2012 and 2017 respectively, as summarized in table 1.

Among all the power sectors, CFPPs can drive more employment in upstream sectors, such as CMWI, EMEM and SRTS. CMWI → CFPPs was the critical path (856,530 jobs) in 2012, while the largest driver of jobs (636,290) occurred along the path of CFPPs in 2017, followed by the paths of CMWI → CFPPs and hydroelectricity. Comparison reveals that the loss of jobs driven by the CMWI → CFPPs path dropped from 17.71% to 10.69% between 2012 and 2017, and the contribution of paths involved with CFPPs also decreased from 42.69% to 32.05%. The loss of indirect jobs in CMWI is mainly attributed to the application of mechanized technology in coal mining, resulting in the total production of one miner per year increasing by more than 20% between 2012 and 2017, and over 1.3 million workers lost their jobs in CMWI. Furthermore, the indirect jobs driven by the finance → CFPPs path decreased from 81.59 thousand jobs in 2012
Table 1. Top 10 structural paths in terms of employment.

| Year | Rank | PL | Indirect jobs | Contribution | Paths |
|------|------|----|---------------|--------------|-------|
| 2012 | 1    | 1  | 856 530       | 17.71%       | CMWI → CFPPs |
|      | 2    | 0  | 791 790       | 16.37%       | CFPPs    |
|      | 3    | 0  | 224 840       | 4.65%        | Hydroelectricity |
|      | 4    | 2  | 136 830       | 2.83%        | CMWI → CFPPs → CFPPs |
|      | 5    | 1  | 117 100       | 2.42%        | Hydroelectricity → Hydroelectricity |
|      | 6    | 2  | 103 040       | 2.13%        | CMWI → CFPPs → CFPPs |
|      | 7    | 1  | 95 250        | 1.97%        | CFPPs → CFPPs |
|      | 8    | 1  | 81 600        | 1.69%        | Finance → CFPPs |
|      | 9    | 0  | 61 420        | 1.27%        | Wind |
|      | 10   | 2  | 60 990        | 1.26%        | Hydroelectricity → Hydroelectricity → Hydroelectricity |

| Year | Rank | PL | Indirect jobs | Contribution | Paths |
|------|------|----|---------------|--------------|-------|
| 2017 | 1    | 0  | 636 290       | 17.83%       | CFPPs |
|      | 2    | 1  | 381 400       | 10.69%       | CMWI → CFPPs |
|      | 3    | 0  | 256 410       | 7.19%        | Hydroelectricity |
|      | 4    | 0  | 155 300       | 4.35%        | Solar |
|      | 5    | 0  | 130 600       | 3.66%        | Wind |
|      | 6    | 1  | 83 990        | 2.35%        | Solar → Solar |
|      | 7    | 1  | 70 600        | 1.98%        | Hydroelectricity → Hydroelectricity |
|      | 8    | 1  | 69 210        | 1.94%        | Wind → Wind |
|      | 9    | 1  | 66 070        | 1.85%        | CFPPs → CFPPs |
|      | 10   | 2  | 59 600        | 1.67%        | CMWI → CMWI → CFPPs |

to 41.21 thousand jobs in 2017, which confirms the postponement and suspension of coal-fired power projects during the studied period.

On the contrary, renewable energy was not the main driver of indirect employment in 2012, because the total capacity of wind power and solar power was less than 5% of that of CFPPs. With the continuous advancement of power transformation, the installed capacity share of wind power and solar power increased to 11.43% in 2017, leading to the drivers of indirect employment shifting from CFPPs to renewable energy between 2012 and 2017, especially for wind power and solar power. The jobs related to paths driven by solar and wind power increased by more than seven times to 0.44 million in the top 10 paths, accounting for 12.31% of total embodied jobs. Moreover, the share of hydroelectricity in the top 10 paths ranked second only to CFPPs, and grew from 5.91% in 2012 to 9.17% in 2017.

3.4. Scenario analysis of future employment in power and its related sectors

Figure 3 shows that total employment would range from 1.17 million to 1.67 million in the three scenarios. As employment intensity will decline further with the advance of intelligent management technology, total employment in the power sector will rise first and then fall. Under the three different scenarios, solar power always creates the most employment, followed by wind power and hydroelectricity. For example, renewable energy will provide more than 80% of jobs in the power sector as predicted in the 1.5 °C scenario, especially in solar power (41.25%) and wind power (23.91%). Moreover, solar can drive more employment with the same installed capacity because solar power (0.3 jobs MW\(^{-1}\)) has a higher employment intensity than wind power (0.2 jobs MW\(^{-1}\)). Meanwhile, the average output of employees in the wind sector is higher than in solar, as the former (2500 h) has higher average annual power generation hours than the latter (1500 h). It is interesting to note that nuclear power could produce nearly 20% of electricity with only 5% of workers in the power sector; this is because nuclear power can produce much more electricity with the same capacity, as its average annual power generation hours is highest among all types of power plants.

From the perspective of sectors, there will be more than three times as many jobs provided by solar power than provided by CFPPs in the 2.0 °C scenario, and this ratio will be increased by over 20 times in the 1.5 °C scenario, despite the employment intensity (0.4 jobs MW\(^{-1}\)) of CFPPs being higher than solar power (0.3 jobs MW\(^{-1}\)), by 2050. On one hand, the proportion of large coal-fired units with capacity over 600 MW has increased from 40.15% in 2012 to 47% in 2019, and will continue to rise in the future. On the other hand, more intelligent management systems will be applied in CFPPs, which can significantly reduce staff requirement in power plants. With the decline in both employment intensity and installed capacity of CFPPs, only 4.78% of direct jobs (80 000) are driven by CFPPs in the 1.5 °C scenario. Compared with the employment provided by CFPPs in 2017, approximately 0.6 million workers will lose their jobs by 2050 in the 1.5 °C scenario.
Furthermore, the indirect jobs driven by the power sector will also undergo dramatic changes during power transformation along the supply chain. Results reveal that approximately 2.10 million new jobs will be created in power-related sectors under the 1.5 °C scenario, mainly attributed to EMEM (345,530), the financial industry (320,530) and transportation (209,300). In contrast to the CFPPs in 2017, renewable energy will be the major driver of indirect employment along the supply chain in 2050, especially wind power (1.44 million) and solar power (1.38 million). However, the upstream industries of CFPPs and renewable energy are quite different, and the impacts on job losses caused by decommissioning CFPPs cannot be avoided by the development of renewable energy. For example, CMWI is highly dependent on CFPPs, and 0.36 million jobs could be lost in CMWI if the capacity of CFPPs is reduced to 200 GW as predicted in the 1.5 °C scenario. Furthermore, total employment in EMEM related to the power sector will increase by more than five times, while workers in CFPPs will witness a drop of more than 1 million. Therefore, power transition will not only affect workers in the power sector but will also lead to the transfer of workers in other industries.

4. Discussion

4.1. Employment in the power sector shift from coal to renewable energy

To achieve the ambitious goal of carbon neutrality, most of the CFPPs in China will be decommissioned by 2050 and only large units with flexible transformation for peak-shaving and frequency regulation will remain. Power transformation may bring potential risks to socio-economic systems, with conflict between environmental protection and job creation. Our results have verified that the strategy of developing large units to replace small ones could cause job losses in the power sector, and approximately 0.68 million workers will lose their jobs as CFPPs are phased out. Furthermore, there may be a risk of massive unemployment for coal-dependent cities if all CFPPs are decommissioned in a short time. For
instance, the total capacity of CFPPs in Jining City, Shandong reached 10.17 GW in 2018, which means that over 10,000 workers may lose their jobs under the power transition. Fortunately, there is enough time to compensate for this through training and regional support of new industries before 2050. To manage the conflicts between socio-economic and environmental systems, the regional differences in unit capacity and industrial structure should be taken into consideration when formulating the strategies for power transformation.

A few types of renewable power plant have similar devices to those used in CFPPs, for instance, solar thermal power stations also have turbines and generators. Therefore, some of the workers laid off from CFPPs can be absorbed by those renewable power plants through vocational education and skills training, which can promote just transition in the power sector. For example, China Energy Investment Corporation, one of the China’s five major power generation groups, owns the largest installed capacity of CFPPs (184.65 GW) and wind power (41.16 GW) concurrently. To alleviate the pressure of relocating unemployed workers, this power generation giant can shift employees from CFPPs to renewable power plants within itself. Furthermore, monetary compensation is also a feasible way to promote just transition in the power sector, and the government could set up a special resettlement fund to help unemployed workers. Under the 1.5 °C scenario, the total amount of monetary compensation would be more than 50 billion RMB if the unemployment compensation for one unemployed worker is 10 months’ salary.

4.2. Promote just transition in power-related sectors along the supply chain

Our results have revealed that power transformation not only affects workers in the power generation sector but also brings substantial changes to its upstream sectors, such as coal mining, electrical machinery and equipment, finance and instrumentation manufacturing. Coal mining, as the raw material supplier for CFPPs, will lose approximately 1 million workers if there are no other emerging industries to take up the reduced coal consumption of CFPPs. Although wind and solar power will provide a large number of jobs directly and indirectly, the skills of the unemployed coal miners will mismatch with the skill requirements of new jobs related to renewable energy. However, a considerable number of coal mines could still be retained, as environmental innovations could offer an alternative means of coal consumption. For example, the coal chemical industry is regarded as a solution for efficient and clean utilization of coal in the future, including coal gasification and liquefaction. In recent years, China’s coal chemical industry has witnessed a series of major breakthroughs in terms of scale and technological advancement, and the production of coal-to-oil increased from 1.32 million tons in 2015 to 7.46 million tons in 2019 (Xie et al 2010, Li and Hu 2017, Yang et al 2020). Moreover, the production of coal chemicals will continue to increase with technological progress, and the coal chemical industry is expected to play an important role in providing new jobs and reduce unemployment of coal miners.

In addition, the demand for products from CFPPs’ upstream sectors, such as boilers and turbines, will be significantly reduced owing to the CFPP shutdown campaign, while more fan blades, gearboxes, photovoltaic panels and inverters will be produced along with the fast-growing renewable energy sector. Therefore, the power generation sector’s upstream manufacturing enterprises need to adjust their product lines in time, which will also affect employment patterns. Shanghai Electric, a leader in the thermal power equipment industry, has gradually shifted its focus from boilers and steam turbines to solar energy, wind energy and energy storage in recent years, resulting in a shift of employment from coal-related industries to renewable energy-related industries simultaneously. Therefore, the impacts of upstream and downstream sectors need to be fully considered when formulating policies for energy transition. Similarly, all the upstream enterprises should consider environmental innovations for future development routes to keep up with the turbulent changes in the power sector.

4.3. Potential job opportunities driven by power transformation

Owing to the instability and intermittency of power generation from new energy sources, the rapid growth of new energy not only has significant impacts on the generation side but also poses great challenges to the stability and security of the power grid. Therefore, additional equipment is required to maintain the balance of the power grid (Shirazi and Mowla 2010, Gu et al 2016, Guelpa et al 2017), such as peak-shaving power plants and related equipment, which can also bring new job opportunities in the power sector and related industries.

Pumped-storage hydroelectricity is considered to be an excellent option for peak-shaving (Pérez-Díaz et al 2015, Jurasz et al 2018), and provided more than 40,000 jobs with a capacity of 40 GW in 2020, while the workers will increase to more than 100,000 in 2050. Moreover, electrochemical energy storage is another important solution to peak-shaving in China, and not only works in conjunction with power plants on the generating side but can also be arranged separately on the user side. In 2018, the total installed capacity of electrochemical energy storage reached 1.02 GW, and more than two-thirds of the market share is taken by lithium-ion batteries. The large-scale application of energy storage batteries in the future will bring plenty of new job opportunities in
battery production, lithium mining and the chemical industry.

Furthermore, carbon capture, utilization and storage (CCUS) technology is a new technology which could be another option for carbon reduction without decommissioning CFPPs (Gibbins and Chalmers 2008, Boot-Handford et al 2014, Wilberforce et al 2019). It can not only provide new jobs for operation and maintenance of CCUS, but can also avoid a large amount of unemployment in the coal power shutdown campaign. However, cost and efficiency are the main factors hindering the large-scale commercial application of CCUS, and potential employment in CCUS needs to be further evaluated. If CCUS technology could be successfully commercialized in half of CFPPs in the future, more than 200,000 jobs will be retained, and the employment pattern in the power sector will also change accordingly.

5. Conclusion

In this study we have evaluated the impact of power transformation on jobs directly and along the supply chains, and a quantitative analysis of the structural paths of employment has been conducted. Results show that power transformation not only leads to large numbers of workers being transferred in the power sector but also in upstream sectors. From 2012 to 2017, embodied jobs driven by the power sector decreased from 4.84 million to 3.57 million, although direct jobs in the power sector increased by 0.12 million. For upstream suppliers, the biggest indirect job losses occurred in CMWI (736,370), followed by finance (98,860), transportation (50,400) and instrumentation (44,590). However, renewable energy has gradually become the main driver of employment growth in power transformation, and the embodied jobs driven by renewable energy increased by more than four times during the studied period.

Moreover, this study set up three scenarios to estimate the impacts on employment caused by power transformation in the future. By the end of 2050, most power-related jobs will be driven by renewable energy, while many workers in CFPPs and its related sectors will lose their jobs. Under the 1.5 °C scenario, less than 5% of direct employment in the power sector will be provided by CFPPs, and more than 1 million jobs will be reduced owing to the shutdown of CFPPs. To promote just transition in the power sector and its upstream suppliers, the socio-economic impacts and policy implications have been fully discussed in this study. On the one hand, government and enterprises could develop a series of resettlement plans to help unemployed workers find new jobs, including skills training for re-employment and monetary compensation. On the other hand, the commercial application of CCUS and the coal chemical industry may be a solution to reduce unemployment of workers in coal mines and CFPPs. This study demonstrates that unemployment caused by power transformation may lead to potential conflicts and risks, and employment transfer will occur not only in the power sector but also in its upstream suppliers. Moreover, targeted strategies have been proposed for laid-off workers and power-related industries, which can provide valuable insights for promoting just transition in China and worldwide.

Data availability statement

All data that support the findings of this study are included within the article and any supplementary files (Sili et al 2022).

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Conflict of interest

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

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