Renewable Energy 208 (2023) 356–366

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Internal spillover effect of carbon emission between transportation sectors and electricity generation sectors

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ARTICLE INFO

Keywords:
Spillover effect
Transportation electrification
Electricity generation mix
Physical CO_2 flow
Virtual CO_2 flow

ABSTRACT

The exact carbon reduction potential of transportation electrification has not been answered directly from the coupled view of electric power transmission and transportation. To address this issue, the multi-regional input-output model and quasi-input–output model are used. Through simulation results comparison between the baseline scenario and transportation electrification scenario, we can observe that transportation electrification scenario would finally reduce 403 million tons, while the increase of 302 million tons of CO_2 from the electricity generation sector due to the spatial spillover effect offsets the reduced 705 million-tons decarbonization benefits of the traffic transportation sector, as well as the decarbonization benefits of cleaner electricity generation. The total reduced CO_2 emissions under the combined scenario are 1997 million tons, which is 94 million tons larger than the overall effect of the separate implementation of transportation electrification scenario and cleaner electricity generation scenario. We conclude that to reduce carbon emission transfer, much greater attention needs to be paid to cleaner generation mix construction.

1. Introduction

The 2015 Paris Climate Agreement set the goal that the increase in global average temperature should not exceed 2 °C compared with preindustrial levels [1]. An increasing number of countries have announced their objectives of carbon neutrality and their timeline, including the US, China, Europe, Japan, and South Africa [2]. Transportation electrification is viewed as an effective way to realize Greenhouse Gas (GHG) reduction goals [3,4]. The electricity generation of power plants and transportation have been widely recognized as the two main carbon emission sources [5–7]. Cleaner electricity generation and transportation electrification (TE) are becoming the pursuits to alleviate the carbon emission amount. Transportation electrification can be recognized as having zero GHG emissions during vehicle operation using electricity [8].

Researchers have been conscious of the influence of electricity generation structure on the carbon emissions of transportation electrification in different countries [9]. The electricity generation mix is recognized as a key factor influencing the GHG emission intensity of electric vehicles (EV) [10]. Actually, as the two main carbon emission sources, the electricity generation sector and transportation sector have closed linkages. The linkages have become more and more complex due to the developed power transmission line, especially in China. The existed research focused on isolated region or single industry chain can not answer the question of carbon reduction potential of TE clearly.

[11] considered that the carbon reduction potential of new energy transportation (NET) is underestimated. It is still lack of direct support of data and methods to support the view. The blind spot is that the carbon reduction potential of TE is still unknow under the background of various electricity generation mix and complex transmission lines from the view of the whole economic system, the internal interaction of carbon transfer between electricity generation sector and transportation sector has not either been discussed directly. The current research considers only the influence of the local electricity generation mix and

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https://doi.org/10.1016/j.renene.2023.03.052
Received 14 April 2022; Received in revised form 7 March 2023; Accepted 9 March 2023
Available online 21 March 2023

ignores the impact of holistic tele-transfer of electricity generation mix networks among the different power grids. The spatial spillover effect caused by the transfer between different power grids would not only influence the life cycle GHG emission amount but would also induce carbon emission transfer. Furthermore, the combined effect of virtual carbon flow in economic systems and physical flow in power grids may aggravate or offset the carbon emission amount for a certain region [5, 6]. researched the physical and virtual carbon metabolism effects of global cities as isolated points. Discussing the decarbonization potential of transportation electrification and electricity generation mix improvement from the view of networks is an urgent matter, especially in China, which is world's second largest economy, and has the largest amount of carbon emission, electricity consumption, motor vehicle population and electric vehicles [12]. The research results can reveal the spatial flow pattern of physical carbon and virtual carbon, indicate carbon reduction contribution of transportation electrification and electricity generation, and can support for the sectoral and regional carbon reduction measures implementation to realize carbon neutrality goals in China.

2. Literature review

The current research progress related to transportation electrification and electricity generation can be concluded into two types: (1) the isolated regional research of carbon mitigation benefits of EVs through the sectoral linkages analysis of carbon emission using lifecycle assessment method and well-to-wheel emission analysis [13,14], (2) the spatial pattern of carbon emission through multi-regional input-output model (MRIO).

The isolated regional study of carbon mitigation benefits of EVs under different cleaner level of electricity mix has been done by many researchers. Multiple research scales have been developed, including global, nationwide and regional scales [15]. [16] explain the GHG emissions difference for electric vehicles through international comparison [17]. calculated the climate benefits of EVs in typical cities in China, the United States, and Germany [18]. discuss the relationship between the GHG emissions of EVs and the electricity generation mix in China [19]. took Beijing city as the case to analyse the energy consumption and GHG emission reduction status [20]. revealed that the carbon emissions of grid powered battery electric vehicles varied according to the power source through case study in Malta [21]. identified the carbon benefits through transitioning from conventional to hybrid and battery electric light-duty in China. Thus, carbon emissions from upstream electricity generation cannot be ignored [22]. [23] found that EVs can obtain significant carbon reduction effect compared with the conventional fuel vehicles through well-to-wheel assessment in the premise that the electricity mix is clean [24]. proved that due to the clean electricity mix, compared to conventional vehicles, EVs can reduce carbon emissions up to 29%. While in Australia, due to the high-carbon intensity of electricity generation, the carbon emission reduction potential of EVs is low [25].

Various approaches have been used to address carbon flows, such as life-cycle analysis [26], material flow analysis [27], input-output table [28,29]. Life-cycle analysis and material flow analysis are often used to reveal the flow in a single industrial chain, while input-output table, especial multi-regional input-output model (MRIO) is a better way to describe the whole industrial landscape and spatial industrial linkages [30]. However, few researchers have discussed the carbon reduction benefits research of EVs using MRIO. In the few existed research, MRIO is always supported as a tool to reveal the environmental effect from the view of the whole industry chain with consideration the spatial difference [31]. assessed the carbon footprints throughout the supply chain of alternative delivery trucks [32]. analysed the provincial difference of life cycle environmental rebound effect of EVS in China [33]. used MRIO to identify the spatial pattern of environmental and economic performance of an Li-Ion Battery Pack from the global way [34]. analysed the circular economy effect for EVs batteries through reducing reliance on raw materials. The current research mainly concerns the spatial differences of carbon emission [4,35].

According to above literature review, the deficiencies in the current research of carbon emission reduction potential of transportation sectors could be concluded as two main points: (1)the carbon reduction potential of TE is still unknow under the background of various electricity generation mix and complex transmission lines from the view of the whole economic system, the internal interaction of carbon transfer between electricity generation sector and transportation sector has not either been discussed directly. The diversity linkage between transportation sectors and electricity generation sectors is dissevered. The electricity generation sources mix of transportations sectors would finally determine the carbon emission reduction potential through the complex transmission lines; (2) it is still lack of a suitable method to identify the carbon reduction potential through separation of new energy transportation (NET) and conventional fuel transportation (CFT) because that the transportation sector in Chinese input-output (IO) table is a very aggregate sector.

To resolve the above deficiencies, this study improve the IO table and establish a coupled carbon flow framework. The main improvements include: (1) the spatial and sectoral linkages between electricity generation sector and transportation sector is established and revealed from the view of the whole economic system based on MRIO and quasi-input–output model (QIO). MRIO is used to assess the virtual CO_2 flow level embodied in the transportation sector and other sectors. To make more accurate physical CO_2 flow through different power grids, QIO is used to calculate physical CO_2 flow between electricity generation sectors. China has become the largest EV producer and consumer [36], while has quite complex power grids and diverse power structure [37]. These conditions make China become an ideal place to research the carbon emission reduction benefits of new energy transportation with consideration the difference of electricity generation sources. The physical CO_2 flow through electricity trade and virtual CO_2 flow through all other types of economic trade are quantified at the provincial scale of China in 2017. Then, the spatial effect linkages between TE and electricity generation structure can be revealed. (2)The exact carbon emission reduction potential of transportation electrification can be answered through scenarios simulation wish consideration of the ratio relationship between NET and CFT based on the energy balance formula.

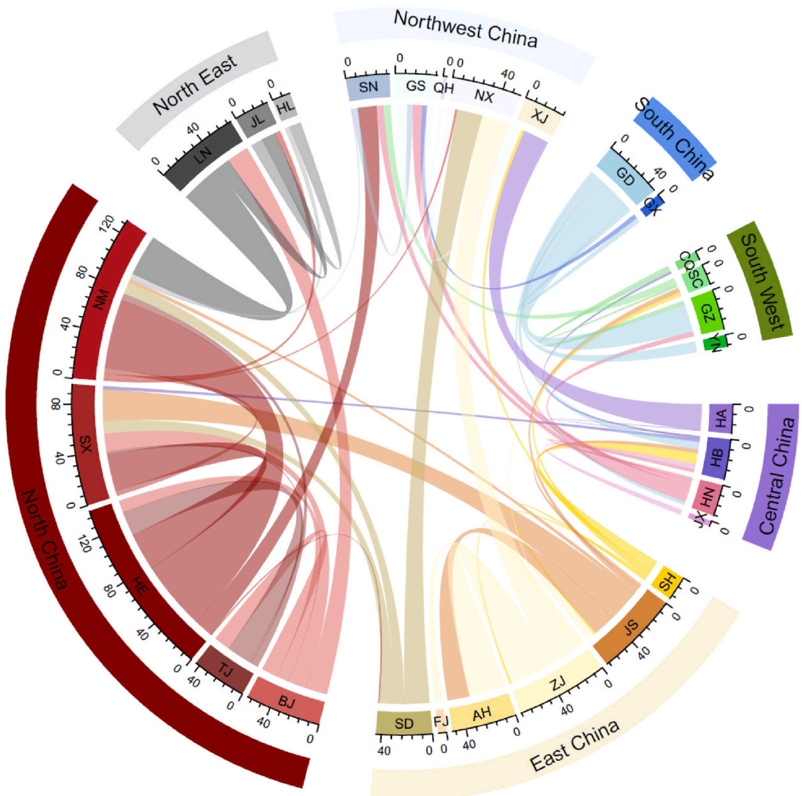
3. Data sources and study area

The study focused on 30 provincial-level administrative regions (names are shown in Table 1, and locations are shown in Fig. 1) in mainland China where data were available. The provincial-level administrative regions of Tibet, Hong Kong, Macao and Taiwan were

Table 1
Abbreviation of the provinces in this study.

Provinces	Abbreviation	Provinces	Abbreviation
Beijing	BJ	Hubei	HB
Tianjin	TJ	Hunan	HN
Hebei	HE	Guangdong	GD
Shanxi	SX	Guangxi	GX
Inner Mongolia	NM	Hainan	HI
Liaoning	LN	Chongqing	CQ
Jilin	JL	Sichuan	SC
Heilongjiang	HL	Guizhou	GZ
Shanghai	SH	Yunnan	YN
Jiangsu	JS	Tibet	XZ
Zhejiang	ZJ	Shaanxi	SN
Anhui	AH	Gansu	GS
Fujian	FJ	Qinghai	QH
Jiangxi	JX	Ningxia	NX
Shandong	SD	Xinjiang	XJ
Henan	HA		

(A) Physical CO_2 flow based on QIO



(B) Physical CO_2 flow based on IO

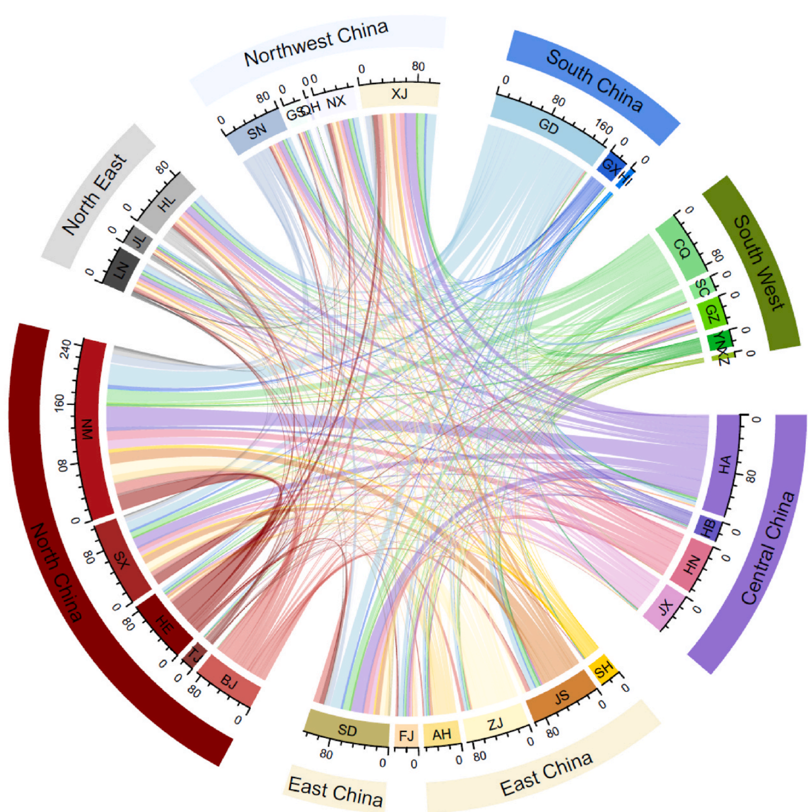


Fig. 1. Physical CO_2 transfers. (A) Net physical CO_2 flow among different grids based on QIO and (B)Net physical CO_2 flow based on electricity input data of IO data (Unit: Mt).

excluded due to insufficient data. The data used for QIO calculation were obtained from the editorial board of the China Power Yearbook [38] and the China Electricity Council [39], and the energy consumption structure in electricity generation was obtained from the National Bureau of Statistics [40]. The multiregional input–output data were obtained from Zheng et al. [41].

4. Methods

The CO_2 flow through electricity trade is recognized as the physical CO_2 flow to identify the CO_2 flow of the largest carbon emission sector, electricity generation sector, and CO_2 flow through all other types of economic trade is recognized as the virtual CO_2 flow.

4.1. Quasi-input–output model

In conventional input-put methods, the carbon emissions embodied in products and services can be tracked, and electricity is also a kind of product. In this study, given that the electricity generation process has a close relationship with primary energy, such as coal, oil, natural gas, and hydropower, and is the main carbon emissions source, accounting for 48% of the total carbon emissions, electricity generation has been separately recognized as the physical flow. The IO table cannot correctly quantify the flow amount due to the relatively coarse data collection and it cannot identify the life cycle process of electricity transfer between multiple grids [42]. The QIO model is used to calculate the CO_2 physical flow embodied in electricity transfer in this study [43]. We assess the CO_2 emissions and physical flow based on the electricity trade and based on the real electricity consumption and transfer data among the 30 provincial subgrids. The QIO model can assess the CO_2 physical flow, including direct and indirect processes, from the whole network view. The electricity transfer relationship is shown as follows:

$$F_i^e = g_i + \sum_1^n f_{ji} = c_i + \sum_1^n f_{ij} \tag{1}$$

where F_i^e indicates the total electricity transfer of province i, g_i and c_i indicate the electricity production and consumption amount of province i, f_{ij} indicates the electricity transfer amount from province i to province j, and n indicates the number of provincial subgrids.

According to the local electricity generation mix of local grids, the physical CO_2 flow embodied in the electricity transfer can be calculated as follows:

$$PF_i^{CO_2} = pfg_i^{CO_2} + \sum_1^n pf_{mn} = pfc_i^{CO_2} + \sum_1^n pf_{nm} \tag{2}$$

where $PF_i^{CO_2}$ indicates the total CO_2 transfer of province i, $pfg_i^{CO_2}$ and $pfc_i^{CO_2}$ indicate the CO_2 emission amount through electricity production and consumption of province i, pf_{mn} indicates the physical CO_2 flow amount from province i to province j, and n indicates the number of provincial subgrids.

4.2. Improved Input–Output model

The interprovincial virtual CO_2 flow is calculated with the MRIO model. The Leontief matrix is used to quantify the embodied virtual CO_2 flow ($vf_{ij}^{CO_2}$) between provinces [44]. The equation is as follows:

$$VF_{m\times m}^{CO_2} = (I - D)^{-1} \times E_{m\times m}^d \tag{3}$$

where $(I - A)^{-1}$ is the Leontief matrix, I is the identity matrix, D is the direct requirement matrix, and $E_{m\times m}^d$ is the diagonal matrix transformed from CO_2 emission status [45,46]. To obtain accurate results of the physical CO_2 flow, the electricity trade between different provinces is excluded in the IO model and is identified specifically in the QIO model.

The sectoral CO_2 emission amount of each province in 2017 which used to calculate CO_2 flow is obtained from the research of [47].

As the research purpose of this study is to explain the influence of the transportation and electricity sectors on CO_2 emissions, and these have been included in the IO table for each province, their economic sectors are classified into the following three types: transportation sector, electricity sector, and other sector. As QIO can provide more accurate data related to electricity production and trade information, the related electricity production information in the IO is excluded to avoid double counting.

4.3. Scenario simulation methods

There are four scenarios in this study: the baseline scenario (BAS), transportation electrification scenario (TES), cleaner electricity generation scenario (CEGS) and their combined scenario (CS). To observe the CO_2 emission reduction potential of these two policies, extreme ideal situations are hypothesized.

For the TES, we assumed that all the conventional fuel transportation are replaced by new energy transportation. All we know that, the transportation sector in Chinese IO table is a very aggregate sector, which not only include vehicle transport, but also include train, airplane, and subway. Even for the vehicle transport, there are different types of vehicles such as truck, bus, and light-duty vehicles. It is not easy to model the transportation electrification from bottom to top. Therefore, in this study, we established the energy balance formula between electricity consumption of new energy transportation (NET) and conventional fuel transportation (CFT) in each province.

$$\mathrm{CFTeneC}_i = \frac{\mathrm{CFTC}_i}{\mathrm{ACFTC}_i} \tag{4}$$

where CFTC_i is the CO_2 emission amount of conventional fuel transportation in province i, ACFTC_i is the average CO_2 emission intensity of fossil energy used by the CFT in province i. $\mathrm{CFTeneC}_i$ is the energy usage amount of the CFT in province i.

$$\mathrm{NETeleC}_i = \mathrm{CFTeneC}_i \times \frac{\mathrm{NETECE}}{\mathrm{CFTECE}} \times \mathrm{eneTeleECE} \tag{5}$$

where NETECE is the energy conversion efficiency of NET, CFTECE is the energy conversion efficiency of CFT, eneTeleECE is the transfer coefficient of energy to electricity, $\mathrm{NETeleC}_i$ is the electricity consumption amount if all of CFT change into NET in the TES.

The electricity required by NET would be satisfied by the local electricity generation grids and other grids that have relevant electricity trade relationships. The required electricity amount will be allocated according to the ratio of the electricity surplus amount through comparison of the local current electricity generation and consumption amount.

$$\mathrm{NETeleCP}_{ij} = \mathrm{NETeleC}_i \times \frac{\mathrm{eleS}_{ij}}{\sum_1^n \mathrm{eleS}_{ij}} \tag{6}$$

where eleS_{ij} is the electricity surplus amount of province j which has electricity trade relationship with province i, $\sum_1^n \mathrm{eleS}_{ij}$ is the total electricity surplus amount of provinces energy which have electricity trade relationship with province i. $\mathrm{NETeleCP}_{ij}$ is the provided electricity amount of province j to province i for NET.

For CEGS, all the provinces in which the renewable energy ratio for electricity generation is lower than 50% are set to 50%. The input from other sectors would not be changed during the process. For CS, the integrated effects of the two policies are observed.

4.4. Spillover effects at the sectoral level

The spillover index (SPI) indicates the ratio of CO_2 emissions in other influenced provinces caused by the transportation electrification process in a targeted region. The formula is shown below.

$$CE_{ij} = \frac{NETeleCP_{ij}}{eneTeleECE} \times FR_{ij} \times CI \tag{7}$$

$$SPI = \frac{CE_{ij}}{CFTeneC_i} \tag{8}$$

where FR_{ij} is the ratio of fossil energy in the total energy consumption for electricity generation. CI is the CO_2 emission intensity of the fossil energy, CE_{ij} is the CO_2 emission of province j which has electricity trade relationship with province i.

In this study, the SPI of the physical CO_2 flow is first observed, and then the coupled SPI of physical and virtual CO_2 flow is comprehensively assessed.

5. Results and discussion

5.1. Comparison of QIO- and IO-based physical CO_2 transfers

Fig. 1 vividly presents the physical CO_2 transfer difference based on QIO and IO. The physical CO_2 flow based on the QIO has a relatively simple relationship, fewer flow linkages and a larger amount of CO_2 flow. The physical CO_2 flow is based on IO is similar to the complex economic system, whereby nearly any pair of provinces have a flow relationship, and the flow amount is small. Based on real electricity statistics, electricity trade is restricted by grids and electricity lines, and it does not easily flow as complex as in the economic system. It is necessary to replace the IO-based CO_2 flow with QIO-based flow.

5.2. Physical and virtual CO_2 transfers

Fig. 2A shows the spatial pattern of electricity production and consumption and the whole CO_2 emission. In 2017, electricity contributed nearly half of the total CO_2 emissions, accounting for 48%. The electricity consumption of all the developed provinces is larger than that of the undeveloped provinces, which are mostly located in northwestern and southwestern China. CO_2 emissions present the same pattern: Economically developed provinces and resource- and energy-based provinces release more CO_2 than the undeveloped provinces. An interesting phenomenon is that in the core of the regional development of two metropolitan regions, BJ-TJ-HE and the Yangtze River Delta, the cities of BJ and SH have relatively low levels of CO_2 emissions and are surrounded by provinces with high levels of CO_2 emissions; this is especially true for BJ.

Fig. 1A shows the physical CO_2 transfers among the provinces. Net physical CO_2 flows between provincial subgrids amounted to 600.23 million tons (Mt), accounting for 6.1% of national CO_2 emissions and 12.1% of total electricity sector emissions. A significant interregional flow community can be found in the physical CO_2 flow circle. The largest physical flow is from HE to NM, accounting for 60.06 Mt. Some long-distance physical CO_2 flow through electricity trade of high-voltage power transmission projects can also be found, such as from SD to NX, from HE to SN, from JS to SX, and from HA to XJ [48]. also found a similar phenomenon for as early as 2012.

The magnitude of virtual CO_2 flows was relatively smaller than that of physical CO_2 transfers. The total amount of virtual CO_2 flows was 579.81 Mt in 2017, accounting for 5.87% of national CO_2 emissions in China. Fig. 2B shows the net virtual CO_2 flow and illustrates the major virtual CO_2 flows between seven districts. There are virtual CO_2 flows from developed provinces such as GD, ZJ, JS and BJ to relatively poor and undeveloped provinces such as HE. HA is a relatively undeveloped province, and it has nearly equal CO_2 input and output amounts. It is a typical transit point located at the centre of China. Through economic activities, it transfers a large amount of CO_2 to undeveloped provinces such as HE, NM, SX, and SN and then suffers from CO_2 emissions from developed provinces such as GD, ZJ, and BJ. It is interesting that SH constitutes the net CO_2 input provincial city through economic trade, although it is a quite developed region. Its net CO_2 input through economic trade is 9.92 Mt. The results indicate that SH does not benefit from carbon transfer benefits through economic trade, which is quite different from other developed provincial regions. The main flow destination regions are the other developed provincial districts, including GD, BJ, ZJ and JS.

5.3. Spillover and coupled effects

Fig. 3A shows the spillover effect of physical CO_2 flow under the TE scenario. Although transportation electrification can reduce the CO_2 emissions of the targeted regions, it can enhance the CO_2 emission amount in the other regions through electricity transfer between different grids. BJ, TJ, HE, SD and LN have the highest SPI values, larger than 0.6, and these high values are mainly caused by the high ratio of coal power generation to electricity generation in their imported provinces. In contrast, most of the provinces in southern China have a relatively low SPI due to the cleaner electricity generation mix of their imported provinces. The SPI value of all provinces is lower than 1, indicating the CO_2 reduction ability of transportation electrification. This ability mainly results from the high energy usage efficiency of electric vehicles compared with that of conventional gasoline-powered vehicles [49].

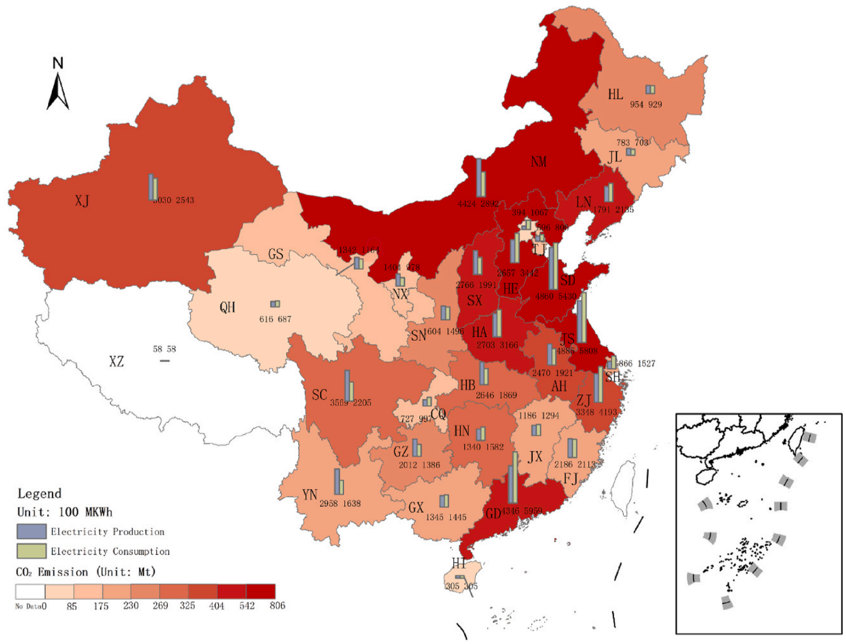
The top four net virtual output provinces (ZJ, GD, BJ, JS) accounted for 79.09% of the net virtual CO_2 output, whereas 60.82% of the net virtual CO_2 input was from four provinces (HE, SX, NM, and LN, which were all located in northern China). The top six net physical output provinces (HE, ZJ, BJ JS, GD, and SD) accounted for 75.60% of the net physical CO_2 output, while 79.32% of the net physical CO_2 input was from six provinces (NM, SX, AH, NX, XJ and GZ which are mostly located in northern and western China). NM is the largest importer of CO_2 emissions through the north channel electricity trade of the West-East electricity transmission project.

The integrated emissions effect can be observed in Fig. 3B. The most developed provinces benefited most from virtual and physical CO_2 flows, including GD, ZJ, JS, and BJ, while some resource-based or heavy industry dominated provinces (NM, SX, XJ, and GZ), which are mostly in North and West China, did not benefit from virtual and physical CO_2 flows. Some provinces benefit through virtual flow but lose any net benefit through physical flow, such as HB, YN, and SC, while other provinces benefit through physical flow but lose any net benefit through virtual flow, such as HE, SD, SH, LN and HN and HA. FJ, HI, QH and XZ have low flow linkages with other provinces. It is found that, provinces always maintain their different statuses in the same large regional district, some resource-based or heavy industry dominated provinces always support as CO_2 producer for the consumption of other developed countries through physical of virtual CO_2 flows. BJ released 118 Mt of CO_2 through coupled transfer, indicating that although it had low direct CO_2 emissions, its total emissions would increase vastly through indirect emissions. For SH, the net input amount of CO_2 through virtual flow is compensated by the net output through physical flow. A large amount of electricity is transferred to SH to support high-intensity economic activities along with physical CO_2 flow. The final CO_2 transfer status of SH is “net output region”, and its CO_2 net output amount is 19.33 Mt.

5.4. Scenarios simulation

Through scenario simulations, we find that the electricity generation cleaner level has a significant influence on carbon emissions in both provincial regions and all of China, which is consistent with our intution due to the dominant ratio of total carbon emissions. Transportation electrification can directly eliminate CO_2 emissions from traffic transportation. The CO_2 emissions of the traffic transportation sector contributed only 705 Mt, accounting for 7.15% of the total emissions.

(A) Electricity production and consumption



(B)Virtual CO_2 flow without electricity sector larger than 5 Mt

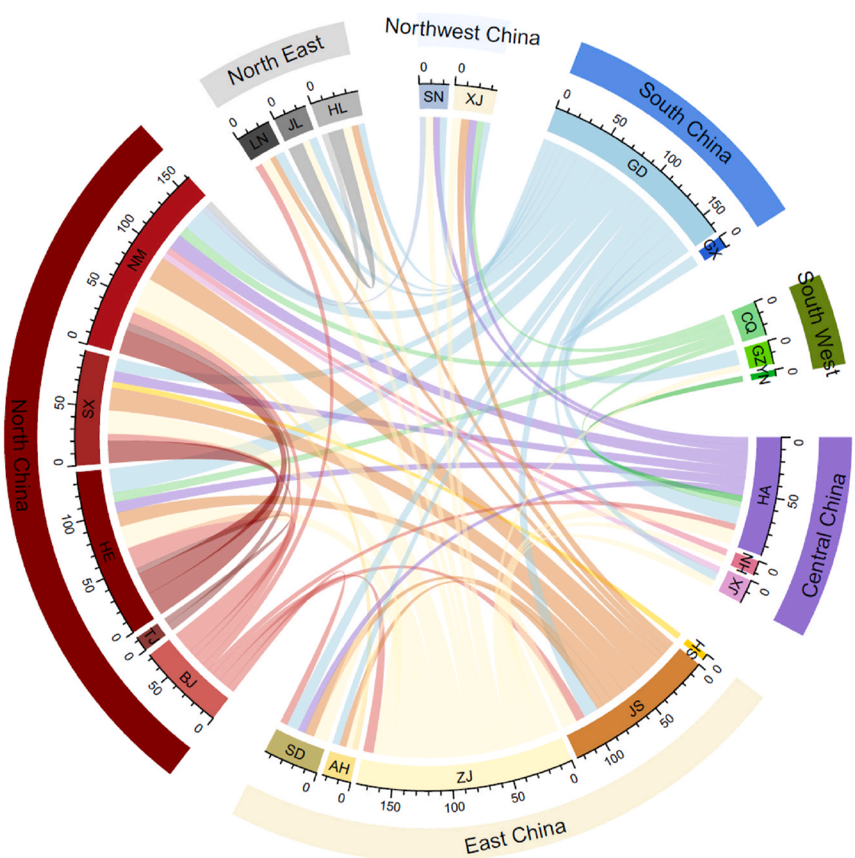


Fig. 2. (A) Spatial pattern of electricity production, consumption and CO_2 emissions. (B) Net virtual CO_2 flow larger than 5 Mt in the economic system.

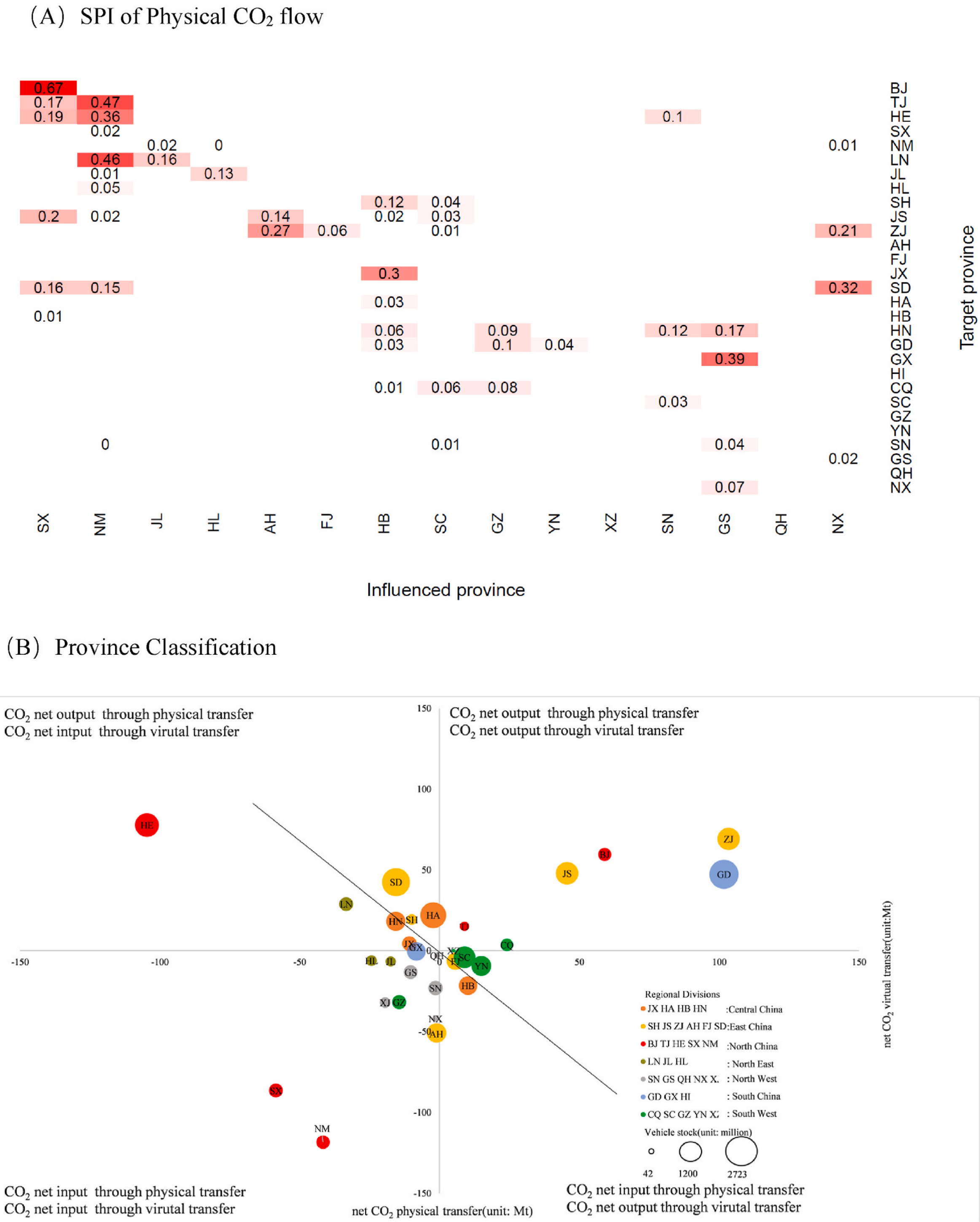


Fig. 3. (A) CO_2 spillover effect of a specific province to the other provinces.(B) Province classification according to the net input and output of physical and virtual CO_2 transfer.

Therefore, the emission reduction effect of transportation electrification in the economic system without the electricity generation sector is relatively limited.

Fig. 4A and B shows the direct and indirect CO_2 emissions in the economic system without the electricity generation sector. We find that CEGS has no impact on direct and indirect CO_2 emissions. TE has an obvious direct CO_2 emission impact for all of the provinces, at 705 Mt, and all of the CO_2 emissions from the transportation sector are eliminated (Fig. 4A), but it has the opposite indirect impact for the provinces due to the function of the spatial spillover effect (Fig. 4B). Due to economic trade, SH inputs 15 Mt of CO_2 through transportation, followed by 11 Mt from LN and 9 Mt from JN. This indicates that transportation is a main sector in SH that inputs CO_2. GD, JS, and ZJ amplify the CO_2 reduction benefit of TE through the virtual CO_2 flow of economic trade caused by cross-provincial transportation. The indirect CO_2 reduction of GD, JS, and ZJ is 17 Mt, 16 Mt and 15 Mt, respectively.

When we focused on the emissions of the electricity generation sector (Fig. 4C and D), we find that TE and CEGS have opposite effects on CO_2 emissions. From the view of direct CO_2 emissions (Fig. 4C), CEGS would reduce 1499 Mt of the total CO_2 emissions of the electricity

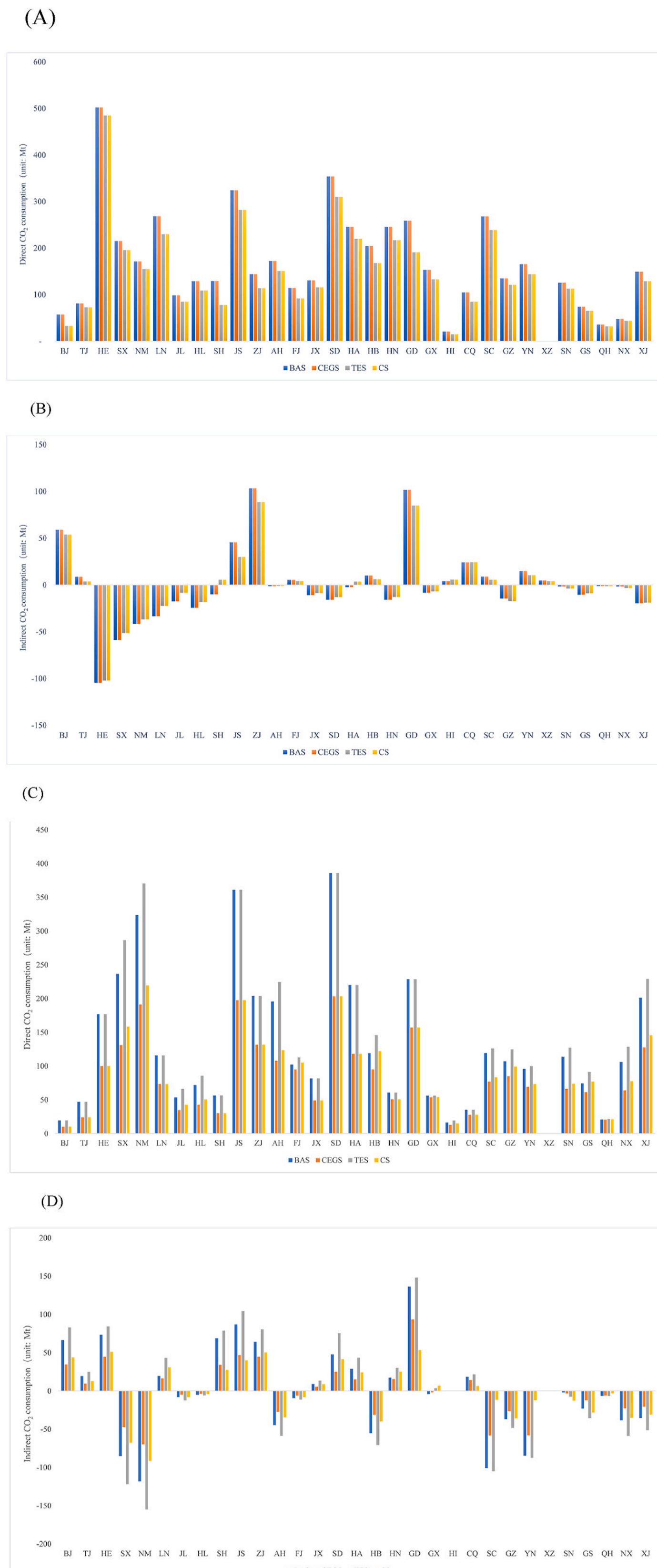


Fig. 4. CO_2 emission reduction effect of the four scenarios, including TES, CEGS, and CS, in the virtual system and physical system. (A) Direct CO_2 emissions in the economic system without the electricity sector, (B) indirect CO_2 emissions in the economic system without the electricity sector, (C) direct CO_2 emissions in the electricity sector, and (D) indirect CO_2 emissions in the electricity sector.

generation sector. SD, JS, NM and SX decreased their emissions significantly, and the reduced amounts were 182 Mt, 164 Mt, 132 Mt and 106 Mt, respectively. TES would increase CO_2 emissions by 302 Mt due to the spatial spillover effect between the transportation sector and electricity generation sector. The top three provinces with the greatest increases are SX, NM and AH, increasing by 50 Mt, 47 Mt and 29 Mt, respectively. From the view of indirect CO_2 emissions (Fig. 4D), due to clean energy improvements, the physical CO_2 flow caused by electricity trade is alleviated. GD, JS, SH and BJ would transfer less CO_2 to other provinces, reducing by at least 32 Mt under the CEGS, while NM, SC and SX would input less CO_2 from other provinces, reducing by at least 38 Mt. TE enhanced the CO_2 output amount for some provinces, such as SD, LN and JS, and it enhanced the CO_2 input for electricity generation provinces, such as SX, NM and NX.

From the view of the total CO_2 emission change in China (Table 2), CEGS would reduce 1499 Mt totally from the electricity generation sector. TE would finally reduce 403 Mt, while the increase of 302 Mt of CO_2 from the electricity generation sector due to the spatial spillover effect offsets the reduced 705 Mt decarbonization benefits of the transportation sector, as well as the decarbonization benefits of cleaner electricity generation. CE would reduce 1291 Mt of CO_2 emissions from the electricity generation sector and 705 Mt of CO_2 emissions from other economic sectors. The total reduced CO_2 emissions under the CS are 1997 Mt, which is 94 Mt larger than the overall effect of the separate implementation of CEGS and TE. The main reason is that the electricity generation mix cleaner improvement would weaken the spatial spillover effect of TE under the CS.

The results support the idea that enhancing the ratio of clean energy is important for electricity generation [50]. NM, SX and other provinces that were coal power generation-based support the development of a large number of provinces in China, and they also contribute a significant amount of CO_2 emissions. Due to CO_2 emissions from coal power generation, the spatial spillover effect of transportation electrification offsets the decarbonization benefits of cleaner electricity generation and causes a reduction in the combined measures of TE and CEG. If cleaner energy was selected for electricity generation, then the CO_2 reduction amount would increase. Developing photovoltaic power generation to enhance the emission reduction effect of transportation electricity, especially to decrease the spillover effects of BJ, TJ, HE, SD and LN, which are located in northern China is still an urgent matter. We can also encourage the net CO_2 output provinces, such as BJ, ZJ, JS and GD, to import more electricity from provinces that have affluent hydropower resources and cleaner electricity generation mixes, such as SC and YN.

6. Conclusions and policy implications

6.1. Conclusions

The results of TES show that the full CO_2 reduction potential of transportation electrification is 403 Mt, only accounted for 4.41% of the total emission. The cleaner electricity generation would reduce more 94 Mt of transportation electrification due to the spatial spillover effect in CS. Cleaner electricity generation is the basic way to decrease CO_2 emission through CEGS simulation, which could not only reduce the CO_2 emission of the electricity generation sector, accounted for 16.41% while the renewable energy ratio for electricity generation in all the provinces is higher than 50%in the CEGS, but could also enhance the effect of CO_2 reduction efforts of other economic sectors, such as transportation electrification efforts in CS.

As a large carbon dioxide emitter, the electricity sector is quantified specifically based on QIO in this study, and the virtual and physical CO_2 flows are further distinguished with a combination of the IO and QIO methods. Their coupled effects are assessed, as is the spillover effect of transportation electrification. The results show that transportation electrification measures may offset the decarbonization benefits of cleaner electricity generation due to the coupled CO_2 flow, especially in northern China, which has a coal-based electricity generation mix. An interesting phenomenon was found: that SH is the only net CO_2 virtual exporter provincial district in a totally developed region, and the main flow destination regions are the other developed provincial regions. BJ transfers a large amount of CO_2 emissions through coupled physical and virtual CO_2 flows, although it has low local direct emissions. HA acts as a transit point that links northern and southern China. Through economic activities, HA transfers much CO_2 to undeveloped provinces, such as HE, NM, SX, and SN, and it then suffers from CO_2 emissions from developed provinces such as GD, ZJ, and BJ.

The scenario simulation results further strengthen the spillover effect of transportation electrification. Transportation electrification can reduce the CO_2 emissions from the transportation sectors, and it also increases the CO_2 emission amount of the electricity generation sector of local provinces and other provinces through electricity lines. To some extent, transportation electrification induced CO_2 emission transfer while realizing CO_2 emission reduction. The simultaneous implementation of transportation electrification and cleaner electricity generation improvement can reduce CO_2 emissions by 94 Mt compared with the overall effect of the separate implementation of transportation electrification and cleaner electricity generation improvement. The main reason is that cleaner electricity generation improvement would weaken the spatial spillover effect of transportation electrification. Cleaner improvement of electricity generation mix is the basic solution for reducing total CO_2 emissions, and it can also enhance the emission effect of transportation electrification.

6.2. Policy implications

Some policy implications may be obtained from the research results. Firstly, China announced its goal to achieve carbon neutrality in 2060 [51], and many provinces have proposed their action scheme to achieve their own goals. Cleaner electricity generation mix is the basic pursue to realize significant and long-term improvement of CO_2 emission reduction. Under the precondition, the CO_2 emission reduction effect of all other economic sectors efforts can be strengthened, so as transportation electrification. A special point we should pay attention to is that provincial carbon neutrality may be realized through local carbon emission reduction and carbon transfer. Carbon transfer would not help to achieve the country's carbon neutrality goal. For a certain province, carbon transfer may reduce local carbon emissions; however, total carbon emissions may still remain the same and even grow for the country as a whole. From the aspect of physical CO_2 flow, a cleaner electricity generation mix should be pursued, including renewable energy technology such as wind and solar resources and conventional hydropower. Clean coal technology should also be further strengthened. It will supply adequate electricity for the economic activities of other provinces with less carbon emissions and transfer. Coupled with the virtual CO_2 flow, the cleaner electricity generation mix can make a greater contribution to the whole CO_2 emission reduction of the economic system. More high-voltage power transmission projects should also be developed between electricity consumption provinces and hydropower-based electricity generation provinces such as YN and SC.

Transportation electrification is always recognized as the common way to realize decarbonization of the transportation sector [52], and it can reduce sectoral emissions [53]. This study showed that

Table 2
Total CO_2 emissions for the electricity generation sector and other economic sectors in China (unit: Mt).

	Scenarios			
Sectors	BAS	CEGS	TES	CS
Electricity generation sector	4006	2507	4307	2714
Other economic sectors	5130	5130	4425	4425
Total	9136	7637	8732	7139

transportation electrification indeed reduced the local CO_2 emissions, as well as the total emissions of the whole country. However, the spillover effect of transportation electrification through replacement of oil with electricity offsets the decarbonization benefits, and the spillover effect is more significant between the targeted province and the electricity supply province with a coal-dominated electricity generation mix. The spillover effect and emission transfer among the economic sectors and regions cannot be ignored. Total carbon emission reduction through the cooperation of sectors and regions should be considered. Some industrial sectors have been required to consider their carbon emissions from electricity consumption during product production [54] (Shuang et al., 2020). The electricity generation mix should be traced to realize accurate calculation, and the double counting problem should be avoided, as in the case of the transportation sector. Totally, the carbon reduction potential of transportation electrification is limited and is determined by the electricity consumption structure, to reduce carbon emission and transfer, much greater attention needs to be paid to cleaner generation mix construction, such as the development of photovoltaic and wind power and the construction of high-voltage power transmission projects from hydropower-based provinces.

Another issue that needs to be noted is that although the cleaner electricity generation mix can theoretically make EVs zero emission of carbon, other materials such as the metallic elements including Lithium and Nickel, which are the key raw materials for EVs battery production, will be the limited factors that suppress the development of EVs industry [55,56]. The circular economy of the raw materials and recycling of the urban mines should be strengthened in the future development of EVs industry.

Data availability

The datasets in the study can be found in the supplementary materials.

CRediT authorship contribution statement

Xi-Yin Zhou: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Zhicheng Xu:** Writing – review & editing. **Jialin Zheng:** Data curation, Writing – review & editing. **Ya Zhou:** Writing – review & editing. **Kun Lei:** Conceptualization. **Jiafeng Fu:** Writing – review & editing. **Soon-Thiam Khu:** Conceptualization, Formal analysis. **Junfeng Yang:** Conceptualization, Formal analysis.

Declaration of competing 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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51907036), which is dedicated to researching the capacity value of renewable energy considering temporal and spatial uncertainty characteristics.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.03.052.

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