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Shift in a national virtual energy network

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HIGHLIGHTS

- Virtual energy transferred from energy-scarce to energy-abundant provinces in China increased.
- Changes in flow pattern of China's virtual energy network since the financial crisis were revealed.
- Most provinces had more distant virtual energy trade than nearby virtual energy trade.
- Virtual energy flowing from west China to east China was greater than physical energy through the WTEETP.

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ABSTRACT

Energy is one of the most fundamental resources for humans and nature. Virtual energy transfer is considered one potential mechanism to alleviate energy shortages and support socioeconomic development in energy-scarce regions. However, little research has explored the change in flow pattern of national virtual energy trade since the 2008 global financial crisis. To fill this knowledge gap, we choose China's interprovincial virtual energy transfer network as a demonstration, since China is the world's biggest energy consumer and features a starkly uneven spatial distribution of energy resources. Surprisingly, the total virtual energy transferred from energy-scarce to energy-abundant provinces increased from 43.2% to 47.5% from 2007 to 2012. In particular, the virtual oil which transferred from energy-scarce to energy-abundant provinces grew from 51.5% in 2007 to 54.0% in 2012. The percentage of provinces that transferred a greater amount of total virtual energy than was consumed internally increased from 23.3% in 2007 to 36.7% in 2012. Unexpectedly, the total virtual energy flowing from west China to east China was much greater than physical energy transferred through the West-To-East Electricity Transmission Project (WTEETP). This study suggests that it would be interesting to study patterns of interactions of virtual energy networks in other countries.

1. Introduction

Global economic development and population growth place large demands on natural resources and contribute to environmental degradation [1,2]. The sustainability of natural resources and the environment attracts global attention, particularly with regards to topics concerning energy availability and production since energy is a fundamental natural resource sustaining human activities (e.g., industry, irrigated agriculture) [1,3]. Many regions face severe energy shortages, posing threats to their sustainable development. More than one billion people lack access to electricity [4].

Due to persistent energy shortages, the virtual consumption and transfer of energy has attracted widespread attention in recent years [5]. Virtual energy is energy consumed during the production process of commodities [6,7,8]. Virtual energy is considered a potential mechanism critical to avoiding regional energy crises since commodities traded from one location to another include virtual energy. This means the importing area can avoid expending the energy to produce the imported commodities. In contrast, physical energy is transferred by energy transmission projects such as China's West-To-East Electricity Transmission Project (WTEETP) to alleviate energy shortages in energy-scarce regions [9].

Many studies have explored the spatial structure and impact of virtual energy or other virtual materials like embodied emissions/pollution transfer [10,11,12,13,14,15,5,16]. For example, Tang et al. (2013) analyzed the virtual energy embodied in the UK's international trade and found that the UK's virtual energy imports had surpassed its virtual energy exports every year since 1997 [10]. Wu et al. (2015)

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assessed the spatial pattern of virtual energy flow between provinces in China in 2007 and revealed that huge amounts of virtual energy went from western provinces to eastern provinces [11]. Sun et al. (2017) studied the energy implications of China's booming regional economic development. They found that China's three major economic circles (Pearl-River-Delta, Yangtze-River-Delta, and Jing-Jin-Ji) had large demands for virtual energy trade and more than 50% of interregional trade of virtual energy was induced by the three economic circles [14]. Mi et al.(2017) studied changes in China's CO_2 emission flow network between 2007 and 2012, and found that the CO_2 flow pattern had changed substantially since the financial crisis [13]. Kan et al. (2019) applied multi-regional input-output (MRIO) analysis to assess the natural gas embodied in international trade, and showed that the total amount of natural gas embodied in the international trade accounted for 2722.1 bcm in 2011 [16]. Chen et al. (2018) used MRIO and complex network analysis to study the structure of embodied energy flow network across multiple scales [15]. Their results indicated the existence of small-world nature and heterogeneity in the network. Xu et al. (2019) employed MRIO and Multiplexity approach to assess evolution of multiple global virtual material flows and interactions between multiple virtual material networks [5]. They found that the total amount of most of virtual materials transfer increased over time except for the global virtual land network, and different global virtual material networks tended to enhance each other.

Based on the integrated framework of metacoupling (environmental and socioeconomic interactions within and across borders [17]), we identified the following research gaps: (1). little research has assessed the changes in flow pattern of China's interprovincial virtual energy network considering different types of virtual energy (e.g., coal, oil, natural gas and others) since the global financial crisis; (2). few studies have investigated the changes in patterns of types (e.g., coal, oil, natural gas and others) of virtual energy transferred between energy-scarce and energy-abundant areas; (3). little research has compared virtual energy transfer to physical energy transfer such as the West-To-East Electricity Transmission Project which aims at solving energy shortages. (4). comparisons between internal energy consumption (internal energy consumption here refers to the internal energy footprint, which encompasses all local energy use (direct and indirect) associated with the final consumption in the studied area), nearby virtual energy trade and distant energy trade have not been undertaken [17]. Such information is urgently needed given the high energy demand and severely uneven distribution of global energy resources. Addressing these gaps can also illuminate the hidden network linkages of interregional virtual energy flows. Assessing the change in flow pattern of virtual energy network since the global financial crisis will result in more updated and accurate information about China's virtual energy transfer. Assessing the changing patterns of virtual energy flows from energy-scarce to energy-abundant provinces will help to clarify the role of virtual energy trade in alleviating regional energy shortages. Comparing interactions between distant provinces and nearby provinces can reveal potential key partners in cooperation. This comparison may also demonstrate socioeconomic and environmental impacts from trade with distant and nearby provinces (e.g., distant trade often consumes more energy for transport and therefore emits more CO_2).

To fill these knowledge gaps, we focused on China's interprovincial virtual energy networks over time. With the country's economic growth, the national energy consumption and environmental pollutant emissions are growing rapidly. In 2013, nearly 22% of global energy consumption occurred in China [18]. Consequently, China has surpassed the United States to be the world's largest energy consumer and the largest source of CO_2 emissions [19,18]. China's uneven energy resource distribution has negative impacts on its own development [20]. As China is still in the industrialization and urbanization process, energy consumption and pollutant emissions will increase in the near future [21]. Developing strategies to maintain energy supplies while achieving economic and social sustainable development will be important issues for policy makers.

We proposed the following hypotheses. First, more virtual energy was transferred from energy-scarce to energy-abundant provinces since the 2008 global financial crisis. Second, provinces tended to have more cross-border (including nearby and distant) virtual energy trade since the global financial crisis. Third, provinces depended more on distant rather than nearby virtual energy trade and this dependence increased over time. Fourth, net virtual energy transferred from the west of China to the east of China was greater than the physical energy transferred through the WTEETP. To test these hypotheses, we investigated China's interprovincial virtual energy networks in 2007 and 2012.

2. Methods

2.1. Data sources

We applied the recent multiregional input-output table for China: the Chinese 2007 and 2012 interprovincial input-output table. The data source of China's MRIO table is the same as that in the paper by Mi et al. (2017) which explored changes in China's interprovincial CO_2 network between 2007 and 2012 [13]. The CEADs (China Emission Accounts & Datasets) have published China's Multi-Regional Input-Output Table 2012 on the website (http://www.ceads.net/data/input-output-tables/). The energy consumption data for sectors within provinces were obtained from the energy balance table of the China Energy Statistical Yearbook 2008 and 2013 [22].

2.2. Construction of virtual energy trade network

We constructed the interprovincial virtual energy transfer network by applying multi-region input-output analysis and direct energy consumption coefficients. We considered each trading province as one node, therefore all trading provinces constructed one interprovincial virtual energy trade network. A direct link existing between any pair of nodes represents a virtual energy flow between provinces. The weight of the link represents the volume of virtual energy flow.

First, we used multi-region input-output analysis to assess interdependencies between different provinces' economies by tracking capital flow. By using this method, we showed the contribution from production sectors within provinces to intermediate and final consumption of all sectors in all provinces in the form of monetary value. Intermediate consumption is reflected by the monetary value of goods and services consumed as inputs by a process of production, while final consumption is reflected by the monetary value used for direct satisfaction of individual needs or collective needs of members of a community.

Assuming the number of provinces is m, and each province possesses n sectors, the output in sector i of province R can be calculated by Eq. (1) as follows:

$$x_i^R = \sum_{S=1}^{m}\sum_{j=1}^{n} x_{ij}^{RS} + \sum_{S=1}^{m} y_i^{RS} \tag{1}$$

where x_{ij}^{RS} is the intermediate consumption in sector j of province S provided by sector i of province R. The y_i^{RS} represents the final consumption in province S directly provided by sector i of province R.

The direct input coefficient a_{ij}^{RS} can be calculated by Eq. (2):

$$a_{ij}^{RS} = x_{ij}^{RS}/x_j^S \tag{2}$$

where x_j^S is the total output in sector j of province S. a_{ij}^{RS} is the amount of input in sector i of province R to increase one monetary output in sector j of province S.

Based on Eq. (2), we can transform Eq. (1) into a matrix as follows:

$$X^* = A^*X^* + Y^* \tag{3}$$

$X^* = [x^1, x^2, \cdots, x^m]^T$ is the vector of total output for all m provinces.

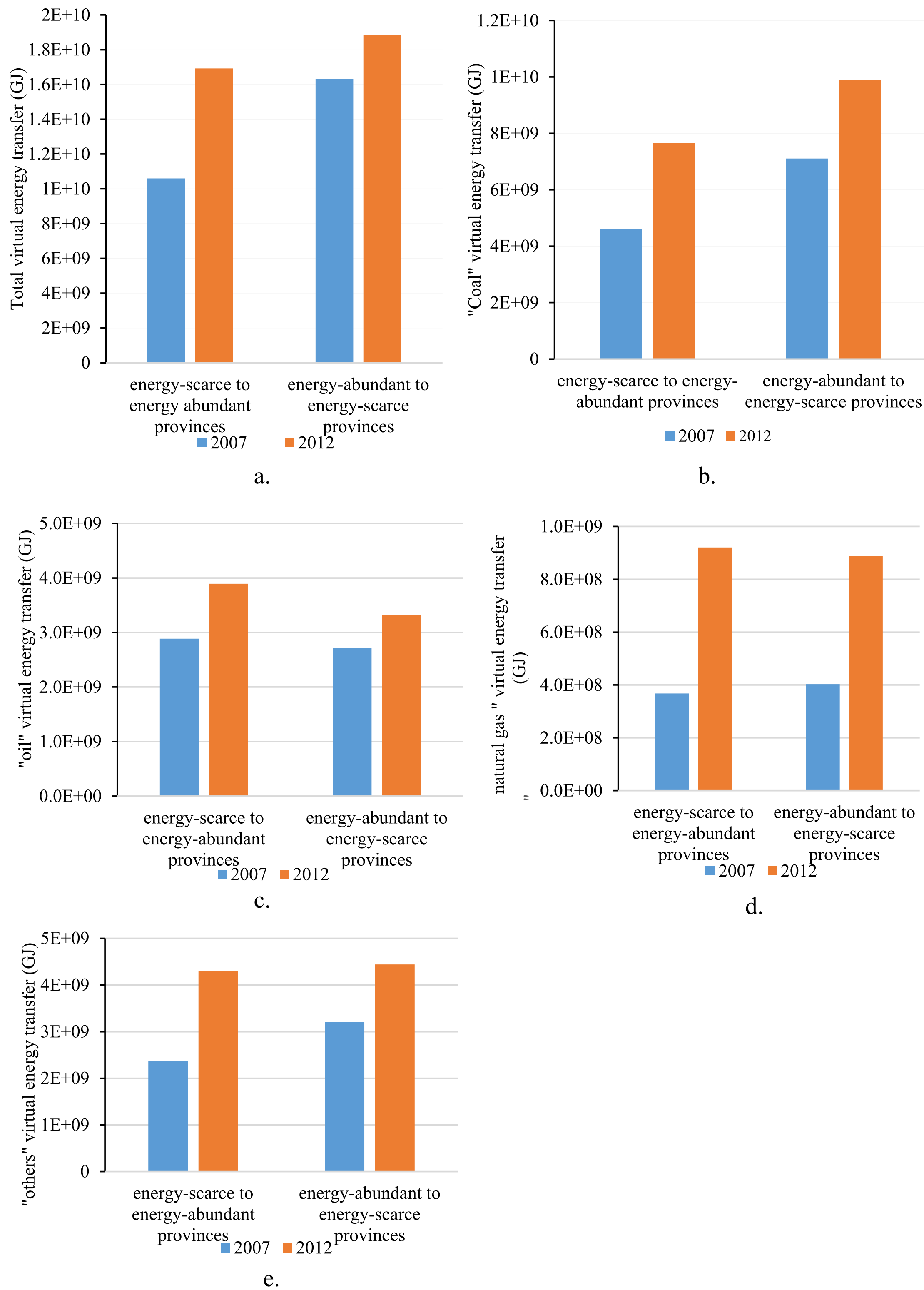

Fig. 1. Different types of virtual energy transferred from energy-scarce to energy-abundant provinces: (a) total virtual energy; (b) virtual coal; (c) virtual oil; (d) virtual natural gas; (e) other virtual energy types.

A represents a matrix for direct input coefficient. Y^* represents the vector of final consumption in all provinces.

Then we transformed Eq. (3) into a consumption driven format as follows:

$$X^* = BY^*, B = (I - A)^{-1} \tag{4}$$

The$(I - A)^{-1}$ is the Leontief inverse matrix indicating how much output from other provinces is required to meet one unit of final consumption in monetary value.

To link monetary transfer with virtual energy transfer, the direct energy consumption coefficients are defined and applied. The direct energy consumption coefficient of sector j in province R can be calculated as Eq. (5):

$$e_j^R = \frac{w_j^R}{x_j^R} \tag{5}$$

where w_j^R is the total energy consumption for a particular type of energy in sector j of province R, and x_j^R represents the output of sector j of province R. e_j^R is the amount of energy used to produce one monetary unit of output in sector j of province R. Here, we divided the virtual energy into different types based on energy sources that were used to produce the virtual energy. Based on the available data in China provinces' Energy Balance table in 2007 and 2012, we divided virtual energy into virtual coal, virtual oil, virtual natural gas and other virtual energy.

For a particular province R, the total energy footprint WF^R,which is equal to the sum of net virtual energy import and internal energy consumption [23], can be expressed by Eq. (6):

$$WF^R = E.\ B.\ Y^R \tag{6}$$

where $E = [e^1, e^2, \cdots, e^N]$ represents a 1 × n × m vector of all provincial sectors' direct energy consumption coefficients, Y^R is the final consumption in province R. Our analyses' calculation is based on the multiregional input-output analysis which captures both the direct and indirect energy use embodied in commodity trade [16]. Our internal energy consumption refers to the internal energy footprint, which refers to all local energy use (direct and indirect) associated with final consumption in the studied area.

Provincial energy production data were obtained from the China Energy Statistical Yearbook for the years 2008 and 2013 to identify whether or not virtual energy flowed from energy-scarce to energy-abundant provinces. If the virtual energy flowed from a province with comparably less energy production to another province with comparably more energy production, the virtual energy trade would be classified as a flow from an energy-scarce to an energy-abundant province, and vice-versa.

China is geographically divided into east, central and west areas. In this paper, 30 provinces were analyzed. Liaoning, Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan belong to the eastern area. Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan are located in the central area. Inner Mongolia, Chongqing, Guangxi, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang are all western provinces. Tibet, Hong Kong, Macau and Taiwan were not analyzed due to data acquisition problems.

We also classified interprovincial virtual energy trade into "nearby virtual energy trade" and "distant virtual energy trade" based on the geographical relationship between provinces. For example, virtual energy trade between provinces that share land borders was deemed as nearby virtual energy trade. In all other cases, virtual energy trade between two provinces was deemed as distant virtual energy trade.

3. Results

More virtual energy was transferred from energy-scarce to energy-abundant provinces over time (Figs. 1–2). The total virtual energy transferred from energy-scarce to energy-abundant provinces grew by 63.8% from 2007 to 2012, while the total virtual energy transferred from energy-abundant to energy-scarce provinces grew by only 38% during the same period (Fig. 1a). The virtual energy transferred from energy-scarce to energy-abundant provinces of coal, oil, natural gas and other energy sources grew by 66%, 34.8%, 150% and 81.5%, respectively (Fig. 1b–e). Conversely, the virtual coal, virtual oil, virtual natural gas and other virtual energy transferred from energy-abundant to energy-scarce provinces grew by 39.3%, 22.2%, 120% and 38.4%, respectively. The ratio of the amount of virtual energy trade – that flowing from energy-scarce to energy-abundant provinces – to the total amount of virtual energy trade increased from 43.2% to 47.5% over time (Fig. 2). For virtual coal, this ratio increased from 39.4% to 43.6%

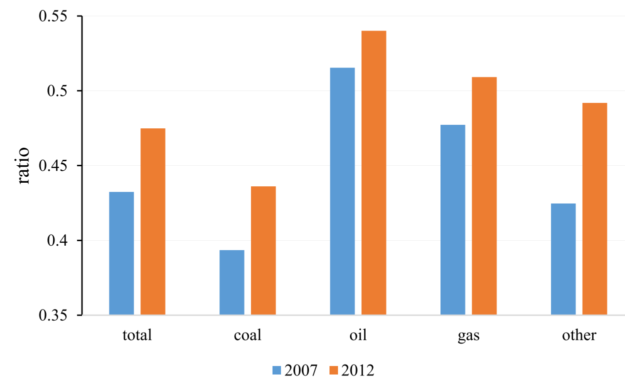

Fig. 2. Ratio of the different types of virtual energy, which transferred from energy-scarce to energy-abundant provinces, to the total amount of the corresponding type of virtual energy transfer.

(Fig. 2). For virtual oil, this ratio increased from 51.5% to 54%. For virtual natural gas, this ratio increased from 47.7% to 50.9%. For other virtual energy, this ratio increased from 42.5% to 49.2%.

A majority of the provinces inspected had more imported virtual energy than internal energy consumption over time (Fig. 3). The percentage of provinces that imported more total virtual energy than total energy consumed internally increased from 23.3% in 2007 to 36.7% in 2012. For virtual coal, virtual oil, virtual natural gas and other virtual energy, this percentage increased by 6.67%, 20%, 6.67% and 6.67%, respectively. The provinces that depended most on imported total virtual energy in 2012 were Beijing, Hainan and Shanghai. However, for specific types of virtual energy, the provinces that depended most on the imported virtual energy varied (Fig. 3). The provinces that depended most on imported virtual coal in 2007 and 2012 were Hainan, Beijing and Shanghai. For virtual oil, the top provinces in 2007 were Anhui, Jiangsu and Hebei, while in 2012 the top provinces were Anhui, Inner Mongolia and Jilin. Concerning virtual natural gas, the provinces that depended most on imported virtual energy in 2007 were Guangxi, Fujian and Jiangxi, and in 2012 were Yunnan, Guangxi and Guizhou. For other virtual energy types, the provinces that depended most on imported virtual energy in 2007 were Shanghai, Hainan and Anhui, and in 2012 were Hainan, Shaanxi and Shanghai. The imported total virtual energy in all provinces was equal to 58% and 71% of internal energy consumption in 2007 and 2012, respectively. For specific types of virtual energy, the ratio was 55.2%, 60.6%, 49.8% and 57.3% in 2007, and was 77.3%, 60.5%, 68.6% and 67.5% in 2012, for virtual coal, virtual oil, virtual natural gas and other virtual energy, respectively.

Distant virtual energy trade became more common than nearby virtual energy trade over time (Fig. 4). Eighty percent of provinces had more distant virtual energy trade over time. In 2007, 73.3% of the provinces had more distant total virtual energy trade than nearby total virtual energy trade (Fig. 4), and this ratio increased to 100% in 2012. In particular, 83.3% of the provinces in 2007 had more distant virtual oil trade than nearby virtual energy trade, and this ratio increased to 100% in 2012. The provinces with the most distant total virtual energy trade were Xinjiang, Fujian and Yunnan in 2012 (Fig. 4). In 2007, the top provinces dominated by distant total virtual energy trade were Guangdong, Xinjiang and Beijing. The provinces least dominated by distant total virtual energy trade were Hebei, Jilin and Shaanxi. These results varied by the virtual energy type being traded (Fig. 4). The top provinces dominated by distant virtual coal trade in 2007 were Xinjiang, Guangdong and Shanghai, and in 2012 were Xinjiang, Fujian and Shanghai. The top provinces dominated by distant virtual oil trade in 2007 Beijing, Shandong and Xinjiang, and in 2012 were Xinjiang, Yunnan and Heilongjiang. The top provinces dominated by distant virtual natural gas trade in 2007 were Guangdong, Fujian and Beijing, and in 2012 were Guangdong, Xinjiang, Fujian and Yunnan. Finally, the top provinces dominated by distant trade of other virtual energy in

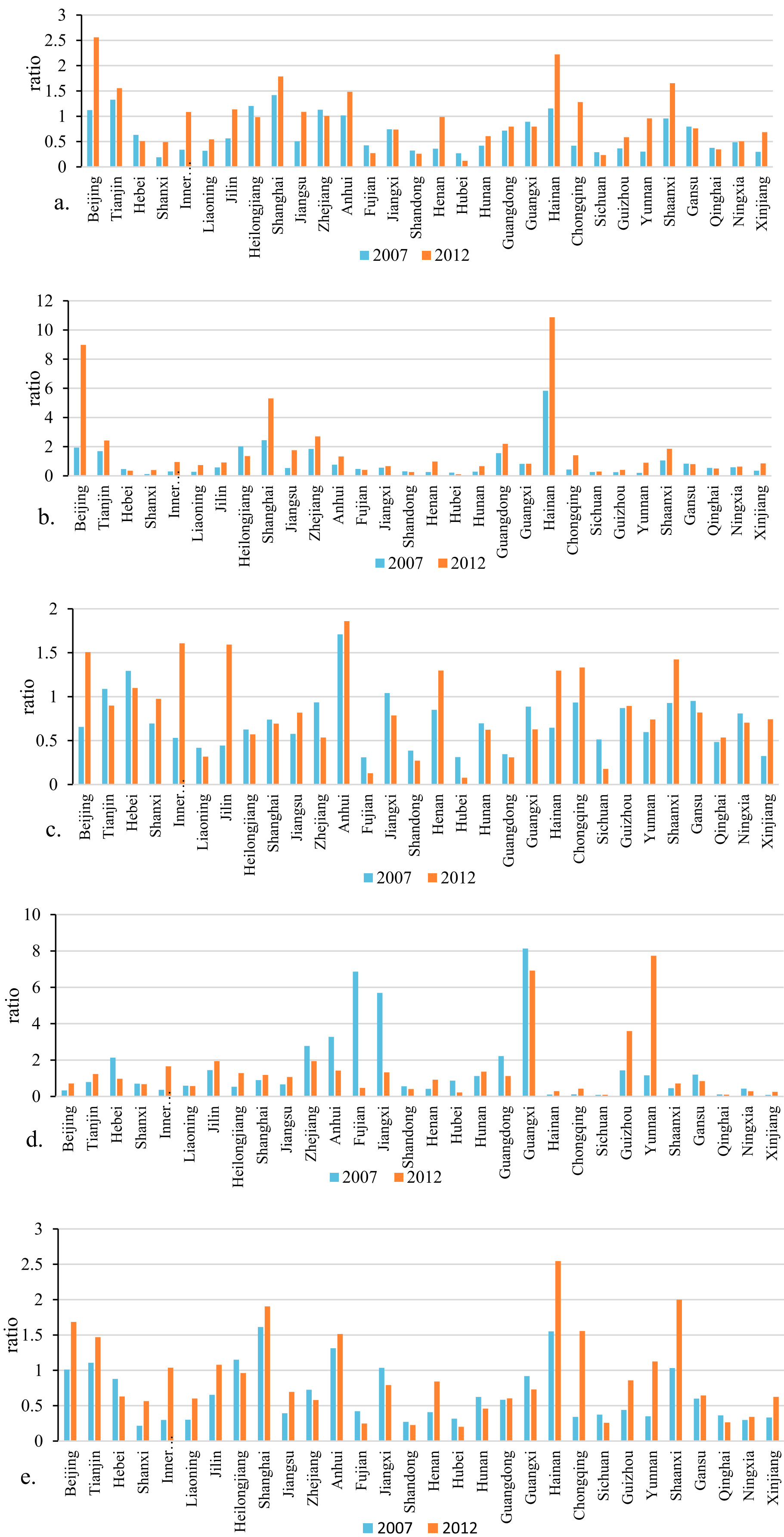

Fig. 3. Ratio of imported virtual energy to internal energy consumption in each province in 2007 and 2012: (a) total virtual energy; (b) virtual coal; (c) virtual oil; (d) virtual natural gas; (e) other virtual energy types.

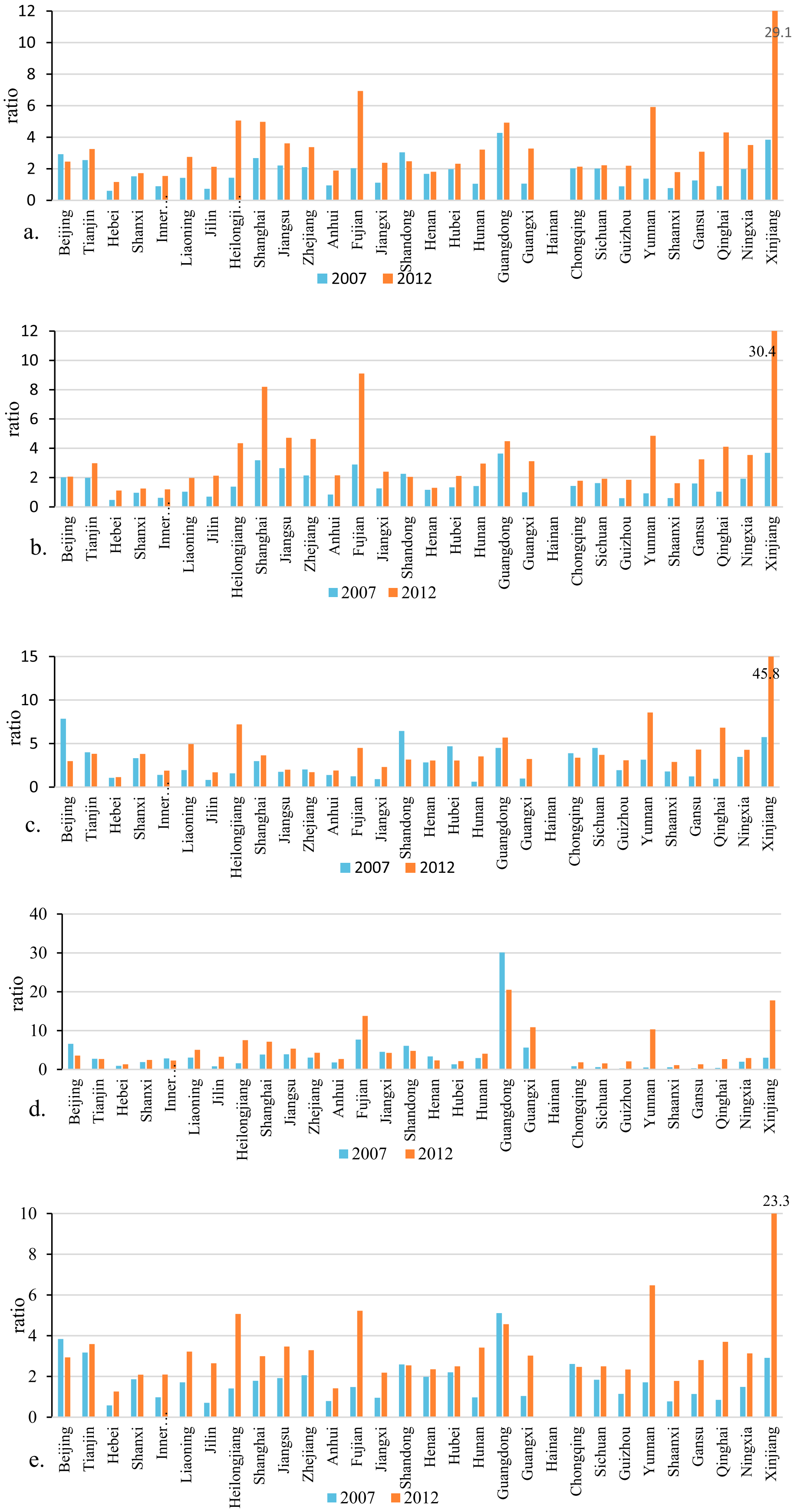

Fig. 4. Ratio between distant and nearby virtual energy trade in each province in 2007 and 2012: (a) total virtual energy; (b) virtual coal; (c) virtual oil; (d) virtual natural gas; (e) other virtual energy types.

Table 1a
Total virtual energy transferred between different parts of China.

Total virtual energy transferred (GJ)		Receiving systems					
		2007			2012		
		East China	West China	Central China	East China	West China	Central China
Sending systems	East China	2.76×10^{10}	1.67×10^{9}	3.42×10^{9}	2.78×10^{10}	4.05×10^{9}	5.02×10^{9}
	West China	1.99×10^{9}	1.17×10^{10}	1.05×10^{9}	4.27×10^{9}	1.70×10^{10}	2.49×10^{9}
	Central China	3.17×10^{9}	1.08×10^{9}	1.38×10^{10}	4.76×10^{9}	2.55×10^{9}	1.76×10^{10}

Table 1b
Virtual coal transferred between different parts of China.

Virtual coal transferred (GJ)		Receiving systems					
		2007			2012		
		East China	West China	Central China	East China	West China	Central China
Sending systems	East China	1.23×10^{10}	6.37×10^{8}	1.54×10^{9}	1.10×10^{10}	1.72×10^{9}	2.10×10^{9}
	West China	1.03×10^{9}	6.04×10^{9}	5.34×10^{8}	2.27×10^{9}	8.34×10^{9}	1.31×10^{9}
	Central China	1.86×10^{9}	6.7×10^{8}	8.35×10^{9}	2.71×10^{9}	1.46×10^{9}	9.41×10^{9}

2007 were Guangdong, Beijing and Tianjin, and in 2012 were Xinjiang, Yunnan and Fujian.

More total virtual energy moved from west to east China than the physical energy that flowed from west to east China through the WTEETP (Tables 1a–1e). In 2007, the total virtual energy from west to east China was 236% as much as the physical energy transferred through the WEETP. This percentage was 160% in 2012. The flow pattern of virtual energy varied for different types of virtual energy. For both virtual coal and virtual natural gas, more virtual energy was transferred from west China to east China than the virtual energy transferred in the opposite direction in both 2007 and 2012. But more virtual oil was flowed from east China to west China than the virtual oil that flowed in the opposite direction in both 2007 and 2012.

4. Discussion

This study explored the shift in national virtual energy transfer patterns since the global financial crisis. In particular, considering the potential differences in the flow pattern of different virtual energy types, this paper analyzed the virtual coal, virtual oil, virtual natural gas and other virtual energy types based on the available data. Based on our analysis of these flow patterns in China's virtual energy in 2007 and 2012, we found that more total virtual energy flowed from energy-scarce to energy-abundant regions since the global financial crisis, especially for the virtual oil. The reason for this may be that virtual energy transfer does not aim to alleviate regional energy shortages; rather, it is motivated by commodity trade which seeks to promote economic growth since the financial crisis. After the "reform and opening up" policy, China's GDP grew about 10% annually from 1979 to 2013 [24], with associated growth in energy demand across provinces. The geographical separation between production and consumption of products across provinces continues to drive this virtual energy transfer embodied in commodity trade [16].

Provinces depend more on cross-border trade, especially trade taking place over great distances. Based on our analyses in 2007 and 2012, the proportion of provinces with imported virtual energy exceeding the internal consumption increased over time, and the growth rate of total imported virtual energy in China exceeded the internal consumption. Among them, the ratio of virtual oil to the internal oil consumption greatly exceeded other types of virtual energy. In 2012, the amount of distant trade of all types of virtual energy was greater than their respective nearby trade. For local governments, looking to distant suppliers within trading networks helps them find "hidden" energy resources. In the case of virtual energy networks, our results demonstrate that distant areas have greater impacts on focal areas than adjacent areas. More cooperation with distant provinces should be encouraged since they play more important roles in meeting resource demands. In the case of virtual energy networks, our results demonstrate that distant areas have greater impacts on focal areas than adjacent areas. As China's economic development, population growth and technological progress continue, we hope the government to guide the development of long-distance virtual energy trade, strengthen effective cooperation among different regional provinces to satisfy people's demand, support economic development and further shape the regional environmental mechanism. Especially for Xinjiang which greatly depends on distant energy transfer, it is important for Xinjiang to develop cooperation with trading partners.

In this study, we found virtual energy transfer to have a greater impact on sending and receiving systems than physical energy transfer. The virtual energy flowing from west to east China is much greater than the physical energy transferred through the WTEETP. Currently, energy policy primarily focuses on physical supplies, not virtual energy. This

Table 1c
Virtual oil transferred between different parts of China.

Virtual oil transferred (GJ)		Receiving systems					
		2007			2012		
		East China	West China	Central China	East China	West China	Central China
Sending systems	East China	7.57×10^{9}	5.68×10^{8}	9.45×10^{8}	8.1×10^{9}	1.03×10^{9}	1.37×10^{9}
	West China	3.46×10^{8}	1.91×10^{9}	1.79×10^{8}	6.44×10^{8}	3.07×10^{9}	3.82×10^{8}
	Central China	6.65×10^{8}	1.82×10^{8}	2.49×10^{9}	8.08×10^{8}	3.95×10^{8}	3.34×10^{9}

Table 1d
Virtual natural gas transferred between different parts of China.

Virtual natural gas transferred (GJ)		Receiving systems					
		2007			2012		
		East China	West China	Central China	East China	West China	Central China
Sending systems	East China	5.96×10^8	3.72×10^7	6.6×10^7	1.2×10^9	2.02×10^8	2.39×10^8
	West China	1.47×10^8	1.05×10^9	8.29×10^7	2.89×10^8	1.46×10^9	1.84×10^8
	Central China	4.85×10^7	2.12×10^7	2.66×10^8	1.69×10^8	9.08×10^7	6.19×10^8

Table 1e
Other virtual energy transferred between different parts of China.

Other virtual energy transferred (GJ)		Receiving systems					
		2007			2012		
		East China	West China	Central China	East China	West China	Central China
Sending systems	East China	7.11×10^9	4.25×10^8	8.69×10^8	7.56×10^9	1.1×10^9	1.32×10^9
	West China	4.69×10^8	2.66×10^9	2.52×10^8	1.06×10^9	4.17×10^9	6.07×10^8
	Central China	5.99×10^8	2.06×10^8	2.72×10^9	1.08×10^9	6.05×10^8	4.19×10^9

may overlook the important influence that virtual energy has on the regional energy mechanism, thus leading to less efficient policy management. If the government only applied physical energy transmission projects to alleviate the energy scarcity, it would overlook the virtual energy's function and therefore the efficiency of policy for saving energy shortage in focal areas may not be maximized. Therefore, besides physical energy transmission projects, government agencies can also consider managing virtual energy trade to alleviate energy shortages in energy-scarce areas. For example, they can consider applying a virtual energy subsidy to motivate virtual energy trade from energy-abundant areas to energy-scarce areas for alleviating energy scarcity [25]. The interregional results provide a quantitative basis to assign sound reduction targets for specific regions and help facilitate binding commitments of interprovincial cooperation for energy conservation. According to our results, the eastern regions such as Guangdong should take more responsibility for energy production and consumption due to the large share of virtual energy this province uses. The eastern regions can play an important role in energy saving and emission reduction by leveraging its favorable economic conditions and advanced technologies. In addition, future analyses using enhanced energy monitoring and updated input–output tables at the national and sub-national levels are encouraged in order to gain a more robust understanding of the implications energy transfers may have on China's resource consumption, expanding economy and population.

Energy management should target specific types of virtual energy, since the flow patterns of different types of energy differed from each other. This was especially true for virtual oil as more than half of the virtual oil was flowed from energy-scarce to energy-abundant provinces. Therefore, the government should consider policies (e.g., applying virtual oil export tax) that may regulate the virtual oil flows to change their spatial patterns [25].

By placing this study under the metacoupling framework, the temporal patterns of interaction between trading provinces across the virtual energy network at the national scale are further revealed, contributing to a more holistic understanding of virtual resource studies. Future research should extend this study by applying complex network analysis to study typologies of national virtual resource transfer networks [15], and assessing the interactions across multiple types of virtual resource/material flows beyond virtual energy, for example, to include virtual water, land and carbon across spatial and temporal scales [26]. This could further reveal the relationship (e.g., trade-offs, synergies) between more virtual resource/material transfer networks and their impacts on national sustainability and thereby result in a more in-depth understanding of the mechanism of interactions within and between adjacent and distant systems. By utilizing the metacoupling framework, we believe a series of metacoupling studies could improve our understanding of cross-border interactions across multiple scales and multiple organizational levels, and help uncover hidden problems which give rise to national and global sustainability challenges [[27]]. These studies could also facilitate an increased understanding of the importance of adjacent and distant interactions as well as their associated implications for policy, thereby aiding efforts to improve human well-being and ensure the sustainability of coupled human and natural systems [[28]].

5. Conclusions

We conducted the assessment concerning the changes in flow pattern of national virtual energy trade in China since the financial crisis. And flow patterns of different types of virtual energy (coal, oil, natural gas and others) were compared. We demonstrated a persistent flow of total virtual energy from energy-scare to energy-abundant provinces as the percentage of total virtual flows between such provinces increased from 43.2% in 2007 to 47.5% in 2012. Especially for virtual oil, its transfer from energy-scarce to energy-abundant provinces grew from 51.5% in 2007 to 54.0% in 2012. Further, net total virtual energy flowing from west China to east China greatly exceeded physical energy transferred by way of the West-to-East Electricity Transmission Project. Provinces were also increasingly trading with distant locations as 73.3% of all investigated provinces had more distant than nearby total virtual energy trade in 2007; yet, in 2012, this ratio increased to 100%. We hope these findings will assist policymakers in crafting more efficient energy policy since the current focus on physical energy supplies may overlook potential solutions virtual energy trade can offer in addressing regional energy deficits.

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Author Contributions

Z.X. designed the research; M.G. contributed the data; Z.X., D.Z., P.M., and J.L. provided comments on the manuscript; Z.X. and D.Z. analyzed the data and wrote the manuscript. All authors reviewed the manuscript.

Conflict of interest

The authors declare no competing financial interests.

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