Paper ID APEN-MIT-2019_078
Applied Energy Symposium: MIT A+B
May 22-24, 2019 • Boston, USA

The water-CO_2 trade-offs driven by energy demand in China

Xi Liu
College of Management and Economics
Tianjin University
Tianjin 300072, China
liuxitju@tju.edu.cn

Huibin Du
College of Management and Economics
Tianjin University
Tianjin 300072, China
duhuibin@tju.edu.cn

Xin Zhang
Appalachian Laboratory,
University of Maryland Center for Environmental Science
Frostburg, MD 21532, United States
Xin.Zhang@umces.edu

Abstract—The virtual water and CO_2 along with the energy trade has reshaped the water resources utilization and CO_2 emissions, making the energy, water and carbon emission management more complicated. We employed the multi-regional input-output analysis to examine the virtual water-CO_2 trade-offs driven by energy demand among Chinese regions in 2010. We observe different spatial distribution for water and CO_2 footprints, which have high intensity in south and north China respectively, though most coastal provinces have high water and CO_2 footprints than inland provinces. The virtual water and CO_2 are transferring from central and west provinces to the coast, consistent with the energy transmission network, but at the risk of aggravating the water stress and CO_2 emissions in especially Yellow River region (including Shanxi, Shaanxi, Henan, Inner Mongolia). By paying attention to different energy sectors, the major exporters are different, indicating the higher water pressure in Yangtze River region (including Anhui, Hunan, Hubei, Jiangxi), higher CO_2 emission increase in Yellow River region induced by electricity sector, while the northeast region in both aspects induced by oil refining sector. To mitigate water consumption and CO_2 emission both directly and indirectly, the sector interactions between energy and others highlight the upstream water use by agriculture, and the electricity sector's water use and CO_2 emissions. The environmental impacts driven by the same energy demand in each province are examined. Finally, policy implications are discussed based on the findings.

Keywords— water-CO_2-energy nexus; trade-offs; input-output analysis; China

I. INTRODUCTION

Energy consumption accounts for 60% of world greenhouse gas emissions, therefore policymakers, researchers worldwide are making efforts to curb CO_2 emissions [1]. Meanwhile, energy sector relies on water resources for production, and puts increasing pressures on water resources in many places around the world [2,3]. The CO_2 emission and water consumption associated with the energy sector are considered to be closely coupled rather than independent because when actions are taken for one aspect, there maybe negative impacts on the other [4].

With the growing recognition of the importance of the energy-water nexus and water-carbon nexus, the existing studies has been conducted in mainly two ways. Many researchers have quantified the water use for specific energy types, e.g. life cycle water use of fossil fuel or renewable based electricity [5,6] or bioenergy based on crops [7]. Meanwhile, some researchers, taking a dynamic view, are projecting the impacts of low carbon energy system on water uses under climate mitigation policy [8], or trying to identify the energy system's adaption strategy (like efficiency improvement, cooling system switch) to water resource changes (e.g. streamflow and water temperature change under climate change) [9]. The above studies focus on energy system on a local scale, however, the energy could be easily transformed and transported between areas of production and consumption, resulting in the distributed sources of the inputs for energy production and final demand. The movement of energy resources around the regions, nations or world, coupled with the "virtual water/CO_2" trade, added complexity to the policies and options for the energy, water security and the CO_2 mitigation management.

For China, the interregional energy trade frequently occurred among provinces. For example, the West-to-East Electricity transmission Project was launched in 1990s, aiming to relieve electricity shortages in China's developed regions by exploiting resources in the west [10]. As a result, the spatial distribution of China's electricity system has been changed, with 24% of the total thermoelectric capacity (46 gigawatt, GW to 222GW) in China located in the northwestern regions (Shanxi, Inner Mongolia, Shaanxi, Gansu, Ningxia and Xinjiang) [11]. However, the electricity-export northwestern regions were suffering from water shortages, indicating the geographic mismatch between the water resources and energy resources. And such energy trade activities, coupling with the virtual water and CO_2 trade, would pose extra challenge for the energy resource management in different regions facing both water security and CO_2 mitigation challenges in China.

So far, few studies have examined the water impacts associated with energy across regional boundaries for China, and even less for water-CO_2 impacts together. In the few existing studies for energy-water analysis, virtual water embodied in electricity transmission has been investigated at grid or region level by Zhang et al. (2017a), Guo et al. (2016) and Zhu et al. (2015) [12-14], concluding that the virtual water flows from the inland regions to the coastal parts. From a different view, the work by Wang et al. (2017) and Wang et al. (2018) [15,16], employed the "hybrid water" concept to include the direct and energy-related water for all economic sectors to identify the regional water transfer or core sectors in the transfer network. Similar work has been done by Fang and Chen (2017) [17]. For the very limited analysis for addressing the water-CO_2 trade-offs, Fang and Chen (2018) employed linkage analysis to identify the roles of economic sectors and provinces considering water resources utilization and CO_2 emissions in China [18]. And Peng et al., (2018) developed a optimization model for the electricity system addressing multiple environmental objectives like water, CO_2 emission and air pollution considering the provincial transmission [19].

However, existing studies examined the virtual water and CO_2 trade-offs driven by energy demand only in electricity sector. The different impacts regions have on the overall water-CO_2 performance are not well understood considering different water intensity and CO_2 emission intensity among them. To better understand the impacts of the energy demand on the water resources and CO_2 emissions, this study makes contributions in three ways: (1) quantify the freshwater use and CO_2 emission driven by different types of energy demand in Chinese regions in 2010, including five major energy sectors. (2) identify the role of provinces in water and CO_2 transfer. (3) describe the interactions between energy and other sectors from the whole supply chain regarding water and CO_2 emission and understand the differences among provinces and energy types.

II. MATERIALS AND DATA SOURCES

A. *Methodology*

The multi-regional input-output analysis (MRIO) approach is popular in water footprint studies, tracing the supply chain environmental impacts embodied in trade activities from a consumption based perspective. In the MRIO framework, different regions are connected through inter-regional trade. The intermediate use coefficient between sectors among regions can be calculated directly as $A^*=[A^{rs}]$, composed of $a_{ij}^{rs}=z_{ij}^{rs}/x_j^s$ elements, where z_{ij}^{rs} is the intermediate input from *i*th sector in region *r* to *j*th sector *s* and x_j^s is the total output of *j*th sector in region *s*. The final consumption matrix $Y^*=[Y^{rs}]$, where y_j^{rs} is the trade from *j*th sector in region *r* to region *s* as final consumption. The export matrix, $E^*=[E^r]$, with E_{ij}^{rs} indicating the export of *i*th sector in region *r*.

Then, the basic equilibrium in the MRIO framework is:

$$\begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \cdots \\ x^n \end{bmatrix} + \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1n} \\ y^{21} & y^{22} & \cdots & y^{2n} \\ \cdots & \cdots & \cdots & \cdots \\ y^{n1} & y^{n2} & \cdots & y^{nn} \end{bmatrix} + \begin{bmatrix} e^1 \\ e^2 \\ \cdots \\ e^n \end{bmatrix} \quad (1)$$

The equation could be expressed as $X^*=A^*X^*+Y^*+E^* = (I-A^*)^{-1}(Y^*+E^*)=L^*(Y^*+E^*)$, where, L^* is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary value.

Taking into account of the environment impacts multiplier-direct water use intensity matrix (W^*) and direct CO_2 emission intensity matrix (C^*), we could derive the virtual water flow or CO_2 emission from region *s* to region *r* could be calculated as:

$$VF^{sr}=\begin{bmatrix} D^{s1} & D^{s2} & \cdots & D^{sn} \end{bmatrix} \begin{bmatrix} y^{1r} \\ y^{2r} \\ \cdots \\ y^{nr} \end{bmatrix} \quad (2)$$

Where, D^{rs} is the row vector whose elements D_j^{rs} denotes the total water supplied by region *r* to generate one monetary unit of final demand in *j*th sector of region *s*.

Besides the virtual water or CO_2 emission import from other regions, provinces could also import from other countries, which could be decomposed into virtual water or CO_2 emission associated with intermediate goods import VF^{iimr} and final goods import VF^{fimr}. Thus, we could obtain the water or CO_2 emission footprint of one province.

Based on the virtual water or CO_2 emission inflows and outflows related to energy, we could obtain the virtual water or CO_2 emission trade balance (VTB) as

$$VTB^r=\sum_s^n VF^{sr}-VF^{rs} \quad (3)$$

where, when the VBT is positive for region *r*, it is a net virtual water or CO_2 emission importer (mitigating water stress or CO_2 emission), and the negative VBT shows a net virtual water or CO_2 emission exporter (aggregating water stress or CO_2 emission).

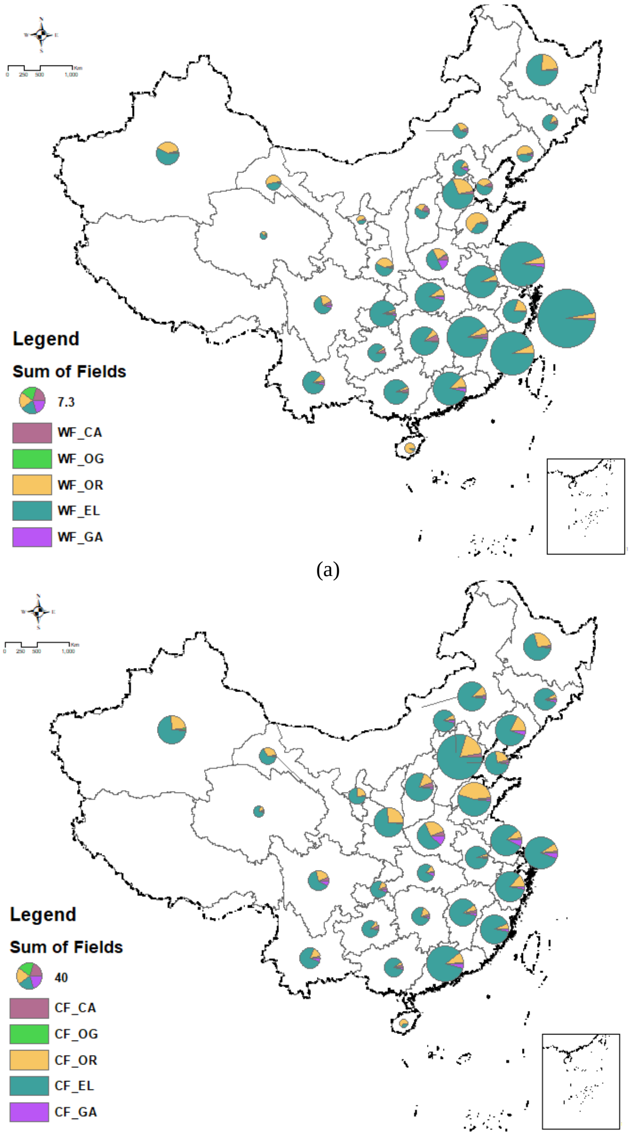
B. *Data Sources*

The MRIO table in 2010 was from School of International Development, University of East Anglia, which included monetary transactions among 30 sectors across 30 provinces. Our analysis focused mainly on the blue water uses to evaluate the impacts of the interprovincial trade on provincial and national water uses, similar to other studies. The water-related data were mainly extracted from Chinese Statistical Yearbook 2011 [20] and China Urban-Rural Construction Statistical Yearbook 2010 [21], Chinese Economic Census Yearbook 2008 [22]. For the CO_2 emission-related data, we mainly refer to the China Emission Accounts and Datasets, CEADs, including fossil fuel combustion (20 energy types, e.g. coal, coke, oil, etc.) and process CO_2 emission.

III. RESULTS

A. *Energy driven freshwater uses, CO_2 emissions*

The national water footprint of all energy sectors was 24 billion million m^3 in 2010, accounting for 16% of the total industrial water uses; while national CO_2 footprint was 1,210 million tonnes, about 15% of the national CO_2 emissions (including industry, primary and tertiary industry and industrial process). For the provincial footprints (Fig.1), the results showed that, the developed provinces driven by large amount of energy demand, e.g. Shanghai, Jiangsu, Guangdong, were in the top in water and CO_2 footprint. The distribution of water and CO2 footprints had different pattern: the provinces in the South (e.g. Jiangxi, Hubei, Hunan) were attached with larger water footprints, while provinces in the North (e.g. Hebei, Shandong, Liaoning, Shaanxi) tended to have higher CO_2 footprint. The difference is mainly shaped by the provincial water intensity and CO_2 intensity difference. The provinces in South China, with a greater penetration of once-through cooling technology [23], leads to large water withdrawal, for example, the water intensity of electricity generation in Shanghai (453 $m^3/10^4$CNY) is 2.8 times of national average level (162 $m^3/10^4$CNY). However, the CO_2 emission intensity of electricity in the North China is higher which is related to the higher thermal electricity structure, for example, when generating one unit, Inner Mongolia would emit much higher CO_2 emission than national average level (15 *vs* 10 tonne/10^4 CNY).



(a)

(b)

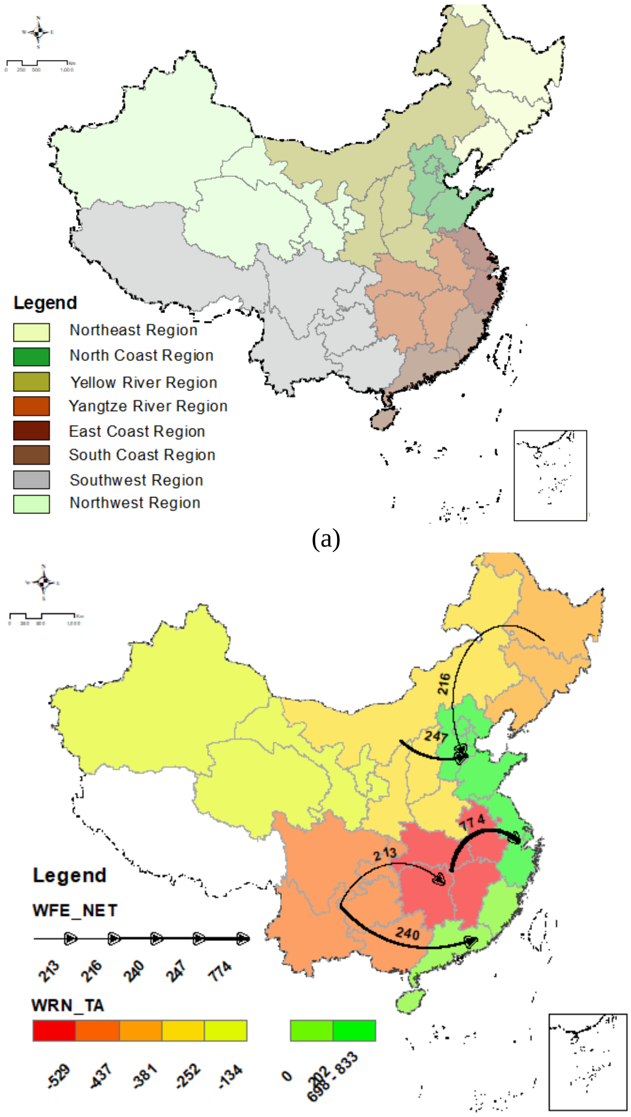
Fig.1 The provincial water footprint (a), CO_2 footprint (b) and energy composition driven by different types of energy demand.

Note: The pie indicates the water footprint and CO_2 footprint driven by each energy sector (by color, CA: coal mining; OG: oil & gas extraction; OR: oil refining; EL: electricity; GA: gas) and the size shows the magnitude of provincial water footprint and CO_2 footprint (million m^3, million tonnes).

For the national water footprint by energy types, electricity (75.2%) is the major one, followed by oil refining, coking, nuclear processing (19.6%, oil refining for short), coal mining (2.3%), gas (2.3%) and oil as gas extraction (0.5%). The major contribution of electricity sector in water uses is due to its more water intensive process for cooling process than other energy sectors, which is more than ten times of other energy types from the national average level. Similar ranking of energy sector has been observed for CO_2 footprint, where electricity and oil refining sector make the largest contribution by 77.3% and 16.6%, respectively due to the higher contribution in total final energy demand (52.9% and 32.3% of the total final energy demand in monetary units) and higher carbon intensity than other sectors.

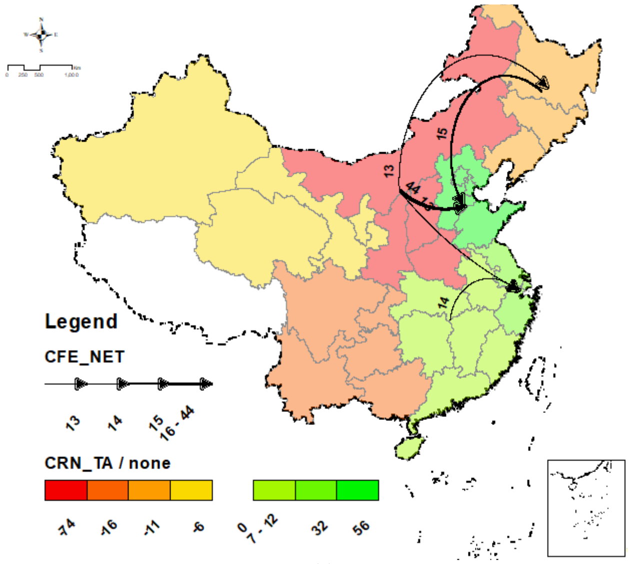
B. Regional trade network for water use and CO_2

The reallocation of water resources and CO_2 emissions through inter-provincial energy trade shows similar pattern, consistent with the energy flow direction from resource rich and less developed region to less resource but developed coastal regions (Fig.2). Coastal provinces are saving local water resources by importing energy from the west and north China. The imported virtual water resources accounts for 54%, 13% and 7% of provincial water footprint in north coast, east coast and south coast region. Similarly, the imported CO_2 shares 30%, 23% and 7% of provincial CO_2 footprints in the three regions, respectively.



(a)

(b)



(c)

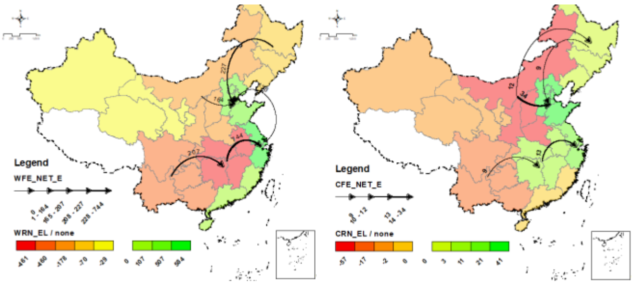
Fig.2 The regional classification (a), water transfer (b) and CO_2 transfer (b) driven by total energy demand.

Note: the color indicates the net virtual water transfer and CO_2 transfer situation in each region (import, green; export, red), and the lines indicate the five top water or CO_2 flows among regions (million m^3, million tonnes).

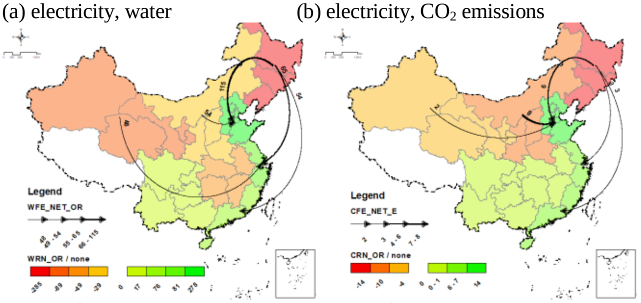
However, the dominate flows and regions for water use and CO2 emissions are different. For water uses, due to the higher water intensity of energy (electricity) production in Yangtze River region, the largest virtual water flows from Yangtze River region to east coast (Fig. 2b), followed by Yellow River Region to north coast and Southwest Region to south coast. In contract, for CO_2 emissions, the Yellow River region, as the largest exporter, would export CO_2 for north coast and east coast. The current trade network implies that the Yellow River Region, which is an energy resource abundance region but with higher water stress level, would face a big challenge for the energy planning and associated water use and CO_2 emission impacts.

Under the current regional trade network, the same region may have different performance in the water and CO_2 emissions. For example, Yangtze River region, as a virtual CO_2 importer but virtual water exporter. This could be caused by the higher water intensity but lower CO_2 intensity for electricity in this region. For such regions, the environmental impacts driven by energy demand should be considered in an integrated way rather than only one aspect.

In addition, in terms of different energy types, similar trade pattern as the total energy is observed for electricity (Fig.3a, 3b), which shares 76% and 72% in the total water and CO_2 transfer. In comparison, for oil refining sector (Fig.3c, 3d), the role of northeast and northwest region for exporting water or CO_2 is the most important, consistent with “North oil to south” trade scheme in China. Therefore, the associated water resources and CO_2 export in the northern China should not be neglected in the energy planning.



(a) electricity, water (b) electricity, CO_2 emissions



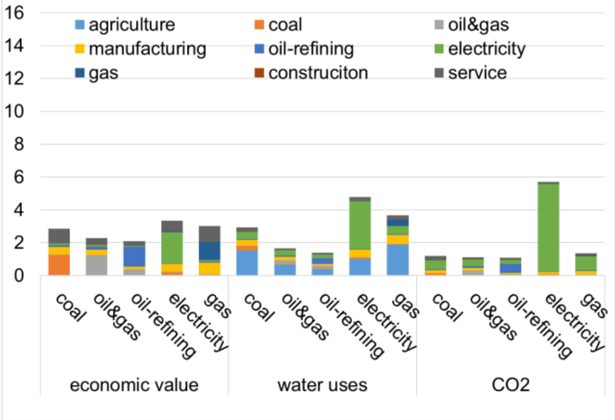
(c) oil refining, water (d) oil refining, CO_2 emissions

Fig.3 The regional water transfer (a, c) and CO2 transfer (b, d) driven by electricity and oil refining demand.

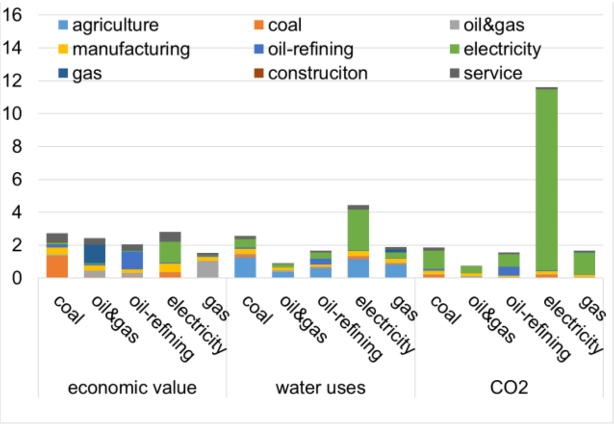
Note: the color indicates the net virtual water transfer and CO_2 transfer situation in each region (import, green; export, red), and the lines indicate the five top water or CO_2 flows among regions (million m^3, million tonnes).

C. Sector performance in the water and CO_2 emission

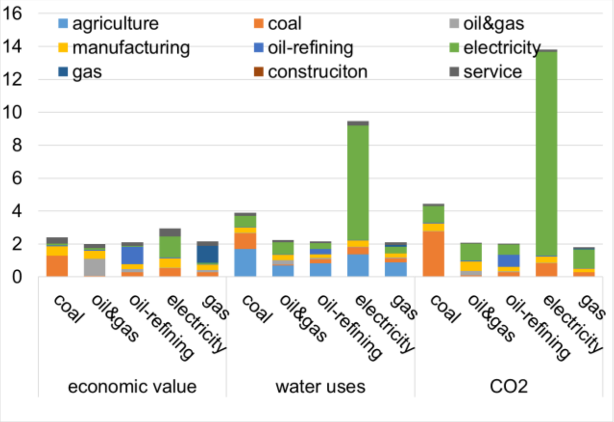
The consumption-based water use/CO_2 emission metric, water footprint of energy sectors, traces both the direct and indirect water uses/CO_2 emissions (i.e. water used to produce to materials, energy, labor, and the rest of non-water inputs) throughout the full supply chain of finished goods and services to the final consumers. Here, we used four provinces in the north coast as examples to demonstrate the sector interactions between energy and others in terms of water or CO_2 emissions (Fig.4).



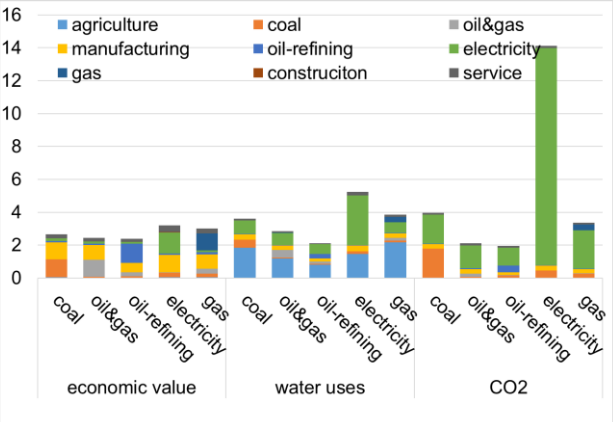
(a)Beijing



(b)Tianjin



(c)Hebei



(d)Shandong

Fig.4 The economic value (10000CNY), water uses (100m^3) and CO_2 emission (tonne) driven by one unit increase of different energy demand (10000CNY).

First, the different types of energy are associated with different upstream sectors for water uses or CO_2 emissions. For example, in terms of the water uses, majority of the water uses for electricity sector takes place in the electricity itself, i.e. Beijing (61%), Tianjin (56%), Hebei (73%), Shandong (57%). While, for oil refining sector, besides the sector itself, we observe other sectors like, the agriculture (28%, 36%, 39% and 36% for Beijing, Tianjin, Hebei and Shandong), manufacturing sector (9%, 9%, 10% and 9% for Beijing, Tianjin, Hebei and Shandong) and electricity (16%, 23%, 16%, 27% in Beijing, Tianjin, Hebei and Shandong).

Second, for the water uses and CO_2 emissions, the sector interactions show different feature. The agriculture sector contributes to the water uses much higher than in the CO_2 emissions, and electricity sector itself would induce large CO_2 emissions, e.g. accounting for 93%, 95%, 90% and 93% for generating electricity demand and 23%, 46%, 30% and 55% for generating oil products, in Beijing, Tianjin, Hebei and Shandong.

Third, to meet one unit of energy demand, different provinces will induce different amount of water use and CO_2 emission . Taking electricity sector as an example, water uses amount is much lower in Beijing, Tianjin, Shandong than in Hebei province (Fig.4). This difference could be caused by the higher technology efficiency in Beijing and Tianjin's electricity sector, and the uses of sea water for cooling in Shandong. CO_2 emissions induced by additional electricity demand is the lowest among all four provinces, which could be contributed by Beijing's higher level of technology development in CO_2 abatement.

IV. CONCLUSION AND POLICY IMPLICATOINS

This paper investigates the virtual water and CO_2 transfer driven by energy demand in China. The major findings and policy implications are:

First, the coastal provinces are importing water resources CO_2 from central and west provinces, which aggregates the water scarcity, CO_2 emissions in these regions. Especially for Yellow River region, which shows higher level of water stress and air pollution, should pay more attention to the environmental impacts associated with the energy transfer. To reduce the impacts induced by the energy transfer, two measures could be considered: 1) improve the demand-side management in the energy import province, like Jing-Jin-Ji area, to release the water uses and CO_2 pressure in Yellow River region; 2) increase the water use and fossil fuel use efficiency in the Yellow River region to reduce the negative environmental impacts.

Second, when we focus on the specific energy sector planning, the major exporters are different, which reminds us different prioritize regions with large mitigation potential in water uses and CO_2 emission. For example, for the electricity sector, the Yangtze River region to east coast and the Yellow River region to north coast could do more for reducing the water uses and CO_2 emissions. While in terms of oil refining sector, the northeast region to north coast and Yellow River region to north coast are the most dominate one in reducing water uses and CO_2 emissions.

Third, the energy demand generates a long chain of interactions in its production process because the material feedstock, energy inputs, infrastructure requirements (such as factories, machinery), transportation, the financial services and so on, need to be "produced" and themselves also require numerous inputs. The MRIO analysis thus provides us a perspective on water resources utilization and CO_2 emission along the whole supply chain for energy production. For example, our MRIO analysis suggests that the agriculture sector contributes to water uses in energy production (Fig. 4), therefore, water savings in agriculture sector can contribute to water savings for energy production indirectly. Also, the different provincial performance in water uses and CO_2 emission for generating the same energy demand shows us that, improving the technology development level, using alternative water sources for cooling (e.g. sea water) would be effective for reducing the water uses. To mitigate water uses and CO_2 emissions at the same time, technology adoption should be carefully considered for its trade-off in water-CO_2

performance, and renewables such as wind power, solar PV may be potentially considered [5].

REFERENCES

[1] International Energy Agency. Excerpt from: CO_2 Emissions from Fuel Combustion 2016, 1-15.

[2] Liu, Y., Hejazi, M., Kyle, P., Kim, S.H., Davies, E., Miralles, D.G., Teuling, A.J., He, Y., Niyogi, D., 2016. Global and Regional Evaluation of Energy for Water. Environ Sci Technol 50, 9736-9745.

[3] Water in the West, 2013. Water and Energy Nexus: A literature review, pp. 1-136.

[4] Zhang, C., Anadon, L. D., Mo, H., Zhao, Z., & Liu, Z. 2014. Water–carbon trade-off in China’s coal power industry. Environ Sci Technol, 48(19), 11082-11089.

[5] Feng, K., Hubacek, K., Siu, Y.L., Li, X.J.R., Reviews, S.E., 2014. The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. 39, 342-355.

[6] Xin, L., Feng, K.S., Siu, Y.L., Hubacek, K., 2015. Challenges faced when energy meets water: CO2 and water implications of power generation in inner Mongolia of China. Renew. Sust. Energ. Rev. 45, 419-430.

[7] Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H., 2009. The water footprint of bioenergy. Proceedings of the National Academy of Sciences 106, 10219-10223.

[8] Huang, W., Ma, D., Chen, W.J.A.E., 2017. Connecting water and energy: Assessing the impacts of carbon and water constraints on China’s power sector. 185, 1497-1505

[9] Van Vliet, M.T., Wiberg, D., Leduc, S., Riahi, K., 2016. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Climate Change 6, 375

[10] Lin, B., Wu, W.J.E.P., 2017. Cost of long distance electricity transmission in China. 109, 132-140

[11] Editorial Board of China Electric Power Yearbook, 2014. China Electric Power Yearbook, Beijing, China, pp. 1-691

[12] Zhang, C., Zhong, L., Liang, S., Sanders, K.T., Wang, J., Xu, M., 2017a. Virtual scarce water embodied in inter-provincial electricity transmission in China. Applied Energy 187, 438-448.

[13] Guo, R.P., Zhu, X.J., Chen, B., Yue, Y.L., 2016. Ecological network analysis of the virtual water network within China's electric power system during 2007-2012. Applied Energy 168, 110-121.

[14] Zhu, X.J., Guo, R.P., Chen, B., Zhang, J., Hayat, T., Alsaedi, A., 2015. Embodiment of virtual water of power generation in the electric power system in China. Applied Energy 151, 345-354.

[15] Wang, S., Cao, T., Chen, B.J.A.e., 2017. Urban energy–water nexus based on modified input–output analysis. 196, 208-217.

[16] Wang, S., Liu, Y., Chen, B.J.A.e., 2018. Multiregional input–output and ecological network analyses for regional energy–water nexus within China. 227, 353-364

[17] Fang, D., Chen, B.J.A.e., 2017. Linkage analysis for the water–energy nexus of city. 189, 770-779.

[18] Fang, D., & Chen, B. 2018. Linkage analysis for water-carbon nexus in China. Applied energy, 225, 682-695.

[19] Peng, W., Wagner, F., Ramana, M. V., Zhai, H., Small, M. J., Dalin, C., ... & Mauzerall, D. L. 2018. Managing China’s coal power plants to address multiple environmental objectives. Nature Sustainability, 1(11), 693.

[20] China National Bureau of Statistics, 2011. China Statistical Yearbook. China Statistics Press, Beijing.

[21] Ministry of Housing and Urban-Rural Development, P.s.R.o.C., 2011. China Urban-Rural Construction Statistical Yearbook 2010. China Planning Press, Beijing, pp. 1-215.

[22] The State Council 's second national economic census leading group office, 2010. China Economic Census Yearbook 2008. China Statistics Press: Beijing.

[23] Zhang, X., Liu, J., Tang, Y., Zhao, X., Yang, H., Gerbens-Leenes, P. et al. 2017. China’s coal-fired power plants impose pressure on water resources. Journal of cleaner production, 161, 1171-1179