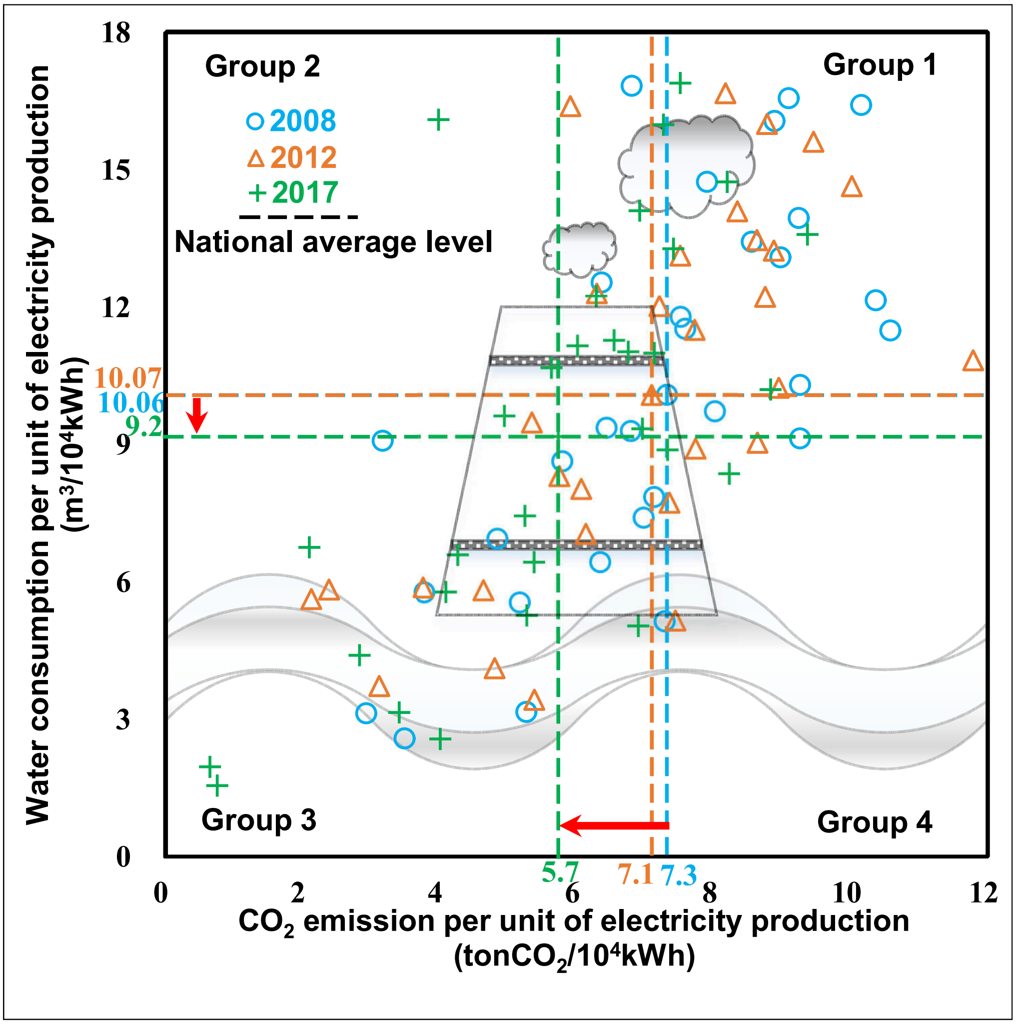
iScience

CellPress
OPEN ACCESS

Article

Water-saving co-benefits of CO_2 reduction in China's electricity sector



Xu Peng, Hong Chen, Honglin Zhong, ..., Pengbang Wei, Pengfei Zhang, Jindao Chen

hongchenxz@163.com (H.C.)
longruyin@163.com (R.L.)
chao_zhang@tongji.edu.cn (C.Z.)
zdd0212@gmail.com (D.Z.)

Highlights

Accounting CO_2 emission and virtual water with Quasi-Input-Output model

Water-saving through energy substitution, efficiency improvement, and electricity trade

Quantifying water-saving by comparing the baseline scenario with hypothetical scenario

Water use from surface water, ground water, mine water, and municipal wastewater

Peng et al., iScience *26*, 106035
February 17, 2023
https://doi.org/10.1016/j.isci.2023.106035

iScience

CellPress
OPEN ACCESS

Article

Water-saving co-benefits of CO_2 reduction in China's electricity sector

Xu Peng,[1] Hong Chen,[1,*] Honglin Zhong,[2] Ruyin Long,[1,*] Chao Zhang,[3,11,*] Dandan Zhao,[4,*] Guangfei Yang,[5] Jingke Hong,[6] Cuncun Duan,[7] Xinxian Qi,[8] Pengbang Wei,[9] Pengfei Zhang,[2] and Jindao Chen[10]

SUMMARY

Electricity sector is the largest CO_2 emitter and water user in China's industrial sectors. The low-carbon transition of China's electricity sector reduces its cooling water consumption. Here we firstly quantify CO_2 emission and virtual water embodied in electricity trade with Quasi-Input-Output model. Then, we analyze the impacts of energy substitution, efficiency improvement, and electricity trade on water-saving co-benefits of CO_2 reduction with the differences between the baseline scenario and counterfactual scenario. Results show that the low-carbon transition contributes to water-saving in China's electricity sector. Virtual water and embodied CO_2 have relatively decoupled from electricity trade since 2012. Water-saving (+10.4% yr^{-1}) outweighed CO_2 reduction (+8.4% yr^{-1}) through energy substitution and efficiency improvement in the 'new normal' stage. Our work emphasizes the need to integrate water-saving co-benefits of CO_2 reduction into electricity system planning and highlights the challenges to facilitate co-ordinated development of the electricity-water nexus in China.

INTRODUCTION

Electricity sector is the largest CO_2 emitter, accounting for ~50% of the global CO_2 emissions from fuel combustion in 2017.[1] China's electricity sector has undergone a pronounced low-carbon transition since 2012.[2] This rapid decarbonization is vital for achieving China's carbon neutrality target by 2060.[3] Meanwhile, the coal-based thermal power generation requires large volumes of water for cooling purposes in China.[4–6] The thermal power generation is thirsty for water, especially in the arid northwestern regions where large coal mines are located.[7–9] Water scarcity has become one of the important environmental constraints for deploying thermal power plants in catchments under high water stress.[10,11] In this context, achieving water-saving co-benefits when reducing CO_2 emissions could be a win-win strategy to cope with multiple challenges facing China's electricity sector.

A pronounced decarbonization of China's electricity sector has begun since 2012.[2] The substitution of non-fossil electricity for thermal power could reduce water consumption and CO_2 emission per unit of electricity production.[2,12] In addition, China produces electricity with less input of water resource and fossil fuel per unit of electricity output because of efficiency improvement.[13] Notably, China has an unequal spatial distribution of electricity production and consumption. Western regions have less electricity demand, and they export excess electricity to satisfy the growing electricity demand of eastern regions. Thus, eastern regions reduce local CO_2 emission and water use at the expense of increasing that in western regions through electricity trade. Meanwhile, the electricity trade from low water (CO_2) intensity regions to high water (CO_2) intensity regions could achieve water-saving co-benefits of CO_2 reduction (see Figures 4 and 5).[14–17] As a result, the large-scale interregional electricity trade changes the virtual water and embodied CO_2 in grid-connected regions because of their differences in water (CO_2) intensity of electricity production (see Figures 3, 4, and 5).[9,18–23] Overall, energy substitution, efficiency improvement, and electricity trade have reduced the water consumption and CO_2 emission per unit of electricity output and achieved water-saving co-benefits of CO_2 reduction in China's electricity sector (see Figures 1, 2, and 4).[2,12,13]

The water consumption and CO_2 emission of electricity production within the local jurisdictional boundaries refer to the production-based accounting.[24,25] However, not all electricity production is consumed locally, a part of it is traded through electric grids to supply electricity for other regions. In comparison, water consumption and CO_2 emission embodied in purchased electricity driven by the local economic activities

[1]School of Business, Jiangnan University, Wuxi 214122, China

[2]Institute of Blue and Green Development, Weihai Institute of Interdisciplinary Research, Shandong University, Weihai264209, China

[3]School of Economics and Management, Tongji University, Shanghai200092, China

[4]Water & Development Research Group, Department of Built Environment, Aalto University, PO Box 15200, 00076Espoo, Finland

[5]Institute of Systems Engineering, Dalian University of Technology, Dalian116024, China

[6]School of Management Science and Real Estate, Chongqing University, Chongqing400045, China

[7]Beijing Key Laboratory of Urban Hydrological Cycle and Sponge City Technology, College of Water Sciences, Beijing Normal University, Beijing100875, China

[8]School of Geography and Ocean Science, Nanjing University, Nanjing210023, China

[9]School of Management, Zhengzhou University, Zhengzhou450001, China

[10]School of Civil Engineering & Engineering Management, Guangzhou Maritime University, Guangzhou510725, China

[11]Lead contact

*Correspondence:
hongchenxz@163.com (H.C.),
longruyin@163.com (R.L.),
chao_zhang@tongji.edu.cn (C.Z.),
zdd0212@gmail.com (D.Z.)

https://doi.org/10.1016/j.isci.2023.106035

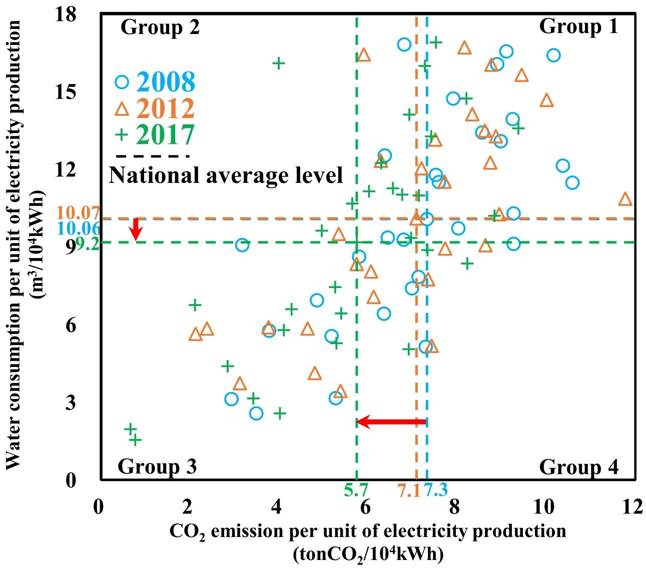


Figure 1. The changes in water consumption and CO_2 emission per unit of electricity production

and household demands represent the consumption-based accounting.[26–28] Consumption-based accounting method attributes a part of electricity producer's environmental impacts to their final consumers.[26] Thus, consumption-based accounting method reveals the actual environmental impacts associated with the local economic growth and reflects the dynamics of energy-water nexus in China's electricity sector.[29–33] Overall, water consumption and CO_2 emission of electricity production differ from those of purchased electricity because of the regional differences in fuel mix, efficiency level, and electricity trade among regions.[2,34] In addition, direct electricity trade method could estimate the resource flow between two regions, but it ignores the complexity of electricity trade network within China.[35,36] The environmental-extended input-output analysis calculates the water consumption (CO_2 emission) embodied in the total supply chain, whereas the Quasi-Input-Output model could quantify the water consumption (CO_2 emission) embodied in electricity trade by considering higher-order electricity transfers in a multi-connected electricity network among regions within China.[20,36,37] To capture the characteristics of electricity trade network, we adopt the Quasi-Input-Output model (QIO) to quantify the virtual water and CO_2 emission embodied in interregional electricity trade and extend environmental protection responsibilities among regions.[37–42]

Previous studies employed production- and consumption-based methods to account virtual water and CO_2 emission.[43–45] However, the existing studies do not evaluate water-saving co-benefits of CO_2 reduction in China's electricity sector. Notably, hypothetical scenario could be used to quantify the net effects of socioeconomic activities (such as international trade and energy policy) on water consumption and CO_2 emission.[46,47] In this study, we quantify the impacts of energy substitution, efficiency improvement, and electricity trade on water-saving co-benefits of CO_2 reduction with the differences in water consumption (CO_2 emission) between the baseline scenario and counterfactual (hypothetical) scenario during financial crisis stage (from 2008 to 2012) and 'new normal' stage (from 2012 to 2017), respectively (see Figure S1 and STAR Methods).[48,49] Investigating water-saving co-benefits of CO_2 reduction could help policymakers to understand the impacts of electricity sector's decarbonization on its water consumption, reveal the energy-water nexus within electricity network, develop targeted strategies in alleviating water stress, and shed light on consumption-side actions to promote water-saving co-benefits of CO_2 reduction toward China's 2060 carbon neutrality target.

RESULTS

The coal-fired electricity accounts for 68% of China's total electricity production.[34] The coal-based thermal power generation consumes a large amount of cooling water and emits a lot of CO_2 emissions. Notably, non-fossil energy substitution and efficiency improvement could reduce both water consumption and CO_2 emission per unit of electricity production and contribute to water-saving co-benefits of CO_2 reduction in China's electricity sector.[2] As a result, the national average CO_2 intensity of electricity production

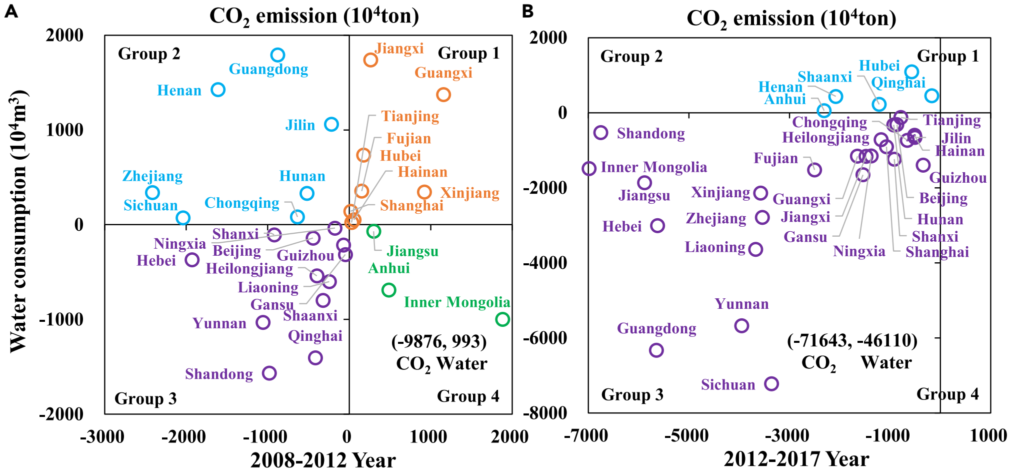


Figure 2. Water-saving co-benefits of CO_2 reduction through energy substitution and efficiency improvement

(A) Annual average water saving and CO_2 reduction during 2008-2012, (B) annual average water saving and CO_2 reduction during 2012-2017.

Note: The positive value indicates the excessive CO_2 emission and water consumption, whereas the negative value indicates the CO_2 reduction and water saving in Figures 2 and 4.

has decreased from 7.3 tonCO_2/10^4kWh in 2008 to 7.1 tonCO_2/10^4kWh in 2012 and 5.7 tonCO_2/10^4kWh in 2017. Meanwhile, the national average water consumption intensity of electricity production slightly increased from 10.06 m^3/10^4kWh in 2008 to 10.07 m^3/10^4kWh in 2012 but decreased to 9.2 m^3/10^4kWh in 2017 (see Figure 1). We found that the decline in water consumption (CO_2 emission) intensity of electricity production in the 'new normal' stage outweighs that of financial crisis stage. In addition, electricity trade could also contribute to water-saving and CO_2 reduction. The interregional electricity trade from low water (CO_2) intensity provinces to high water (CO_2) intensity provinces could achieve water-saving co-benefits of CO_2 reduction (see Figure 4, Tables S1 and S2). For example, provinces in group 1 (with higher resource intensity level) outsourcing electricity to group 3 (with lower resource intensity level) could achieve water-saving co-benefits of CO_2 reduction (see Figure 1). Overall, energy substitution, efficiency improvement, and electricity trade together contributed to water-saving co-benefits of CO_2 reduction in China's 30 provincial electricity sector (see Figures 1, 2, and 4).

Water-saving co-benefits of co_2 reduction through energy substitution and efficiency improvement

Figure 2 shows the impacts of energy substitution and efficiency improvement on water-saving co-benefits of CO_2 reduction in provincial electricity sectors.[50] 30 provinces are divided into four groups according to water-saving and CO_2 reduction. From 2008 to 2012, 16 provinces reduced their shares of thermal power and 19 (14) provinces reduced CO_2 (water) intensity of electricity production in Figure 1. Energy substitution and efficiency improvement reduced CO_2 emission by 99 Mt yr^{-1} but increased water consumption by 9.9×10^6 m^3 yr^{-1} in this period (see Figure 2A). Specifically, 8 provinces in group 1 increased both CO_2 emission and water consumption (for example, Guangxi and Xinjiang). Seven provinces in group 2 could reduce CO_2 emission but increase water consumption (for example, Henan and Zhejiang). 3 provinces in group 4 could save water consumption but increase CO_2 emission, namely, Jiangsu, Anhui, and Inner Mongolia. Notably, 12 provinces in group 3 achieved water-saving co-benefits of CO_2 reduction in electricity sector (for example, Yunnan and Shandong). From 2012 to 2017, 24 provinces reduced their shares of thermal power. 30 (24) provinces reduced CO_2 (water) intensity of electricity production in Figure 1. Energy substitution and efficiency improvement reduced CO_2 emission by 716 Mt yr^{-1} and achieved water-saving by 461 million m^3 yr^{-1} in this period. Specifically, 5 provinces reduced CO_2 emission but increased water consumption (for example, Hubei and Henan). The remaining 25 provinces achieved water-saving co-benefits of CO_2 reduction from 2012 to 2017 (for example, Xinjiang and Inner Mongolia). Compared with financial crisis stage (from 2008 to 2012), more provinces reduced their shares of thermal power which contributed to the water saving and CO_2 reduction in the 'new normal' stage (from 2012 to 2017). Overall, energy substitution and efficiency improvement have achieved pronounced water-saving co-benefits of CO_2 reduction since 2012.

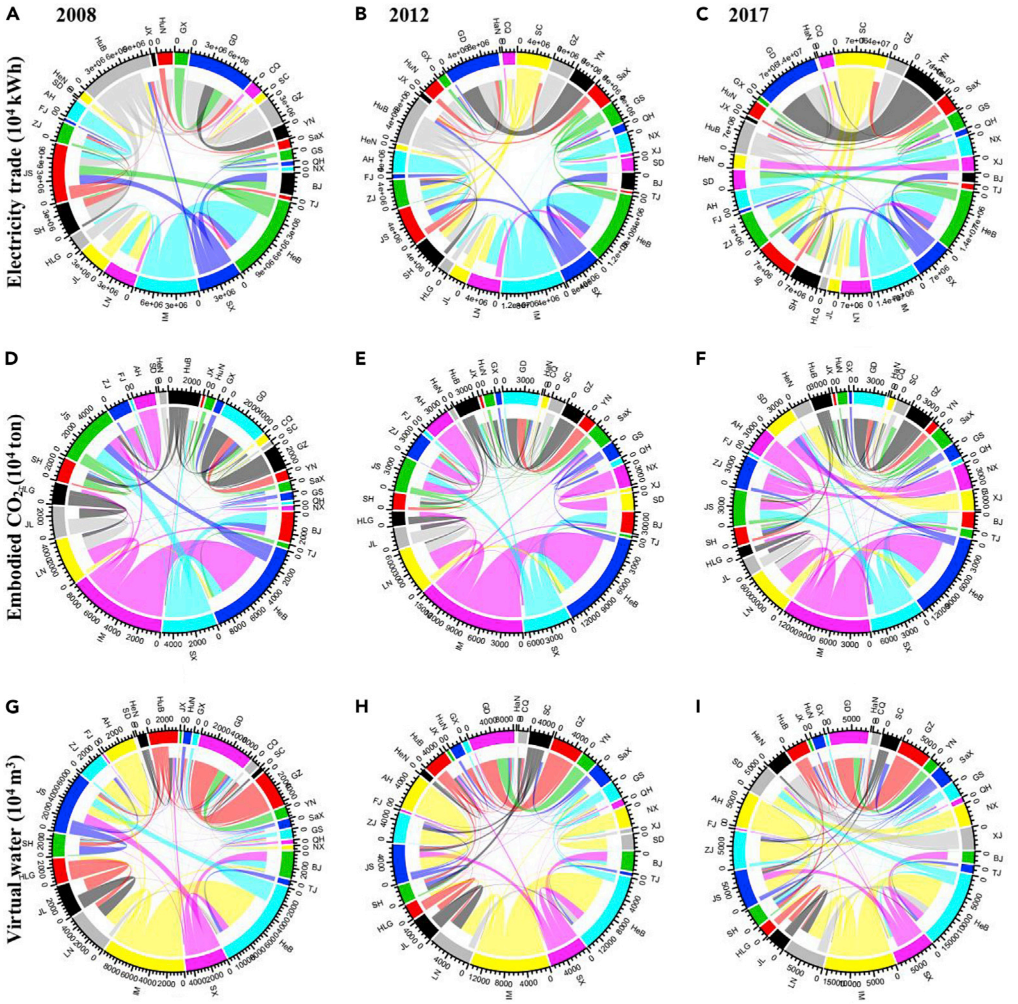


Figure 3. Virtual water and CO_2 emission embodied in electricity trade in 2008, 2012, and 2017

(A–C) Electricity trade, (D–F)embodied CO_2 emission, and (G–I)virtual water. Note: The full names of 30 provinces are shown in Table S1.

Water consumption and co_2 emission embodied in electricity trade

The construction of large-scale ultra-high voltage power transmission lines accelerates interregional electricity trade within China.[34,36] The large-scale electricity trade alleviates the electricity shortage and contributes to the exchanges of virtual water and embodied CO_2 among grid-connected regions within China.[51–54] The inter-provincial electricity trade increased from 485 TWh in 2008 to 727 TWh in 2012 and 1129 TWh in 2017, by 12.5% yr^{-1} and 11.1% yr^{-1} in each period, respectively. Inner Mongolia is one of the nine clusters of large coal-fired power plants and the important cluster of wind power plants with the maximum electricity outflow in the study period.[55,56] In 2008, Inner Mongolia exported electricity to Hebei (30% of Inner Mongolia's total electricity flow), Liaoning (8.6%), and Heilongjiang (2.3%), respectively. In contrast, Guangdong is the maximum electricity inflow region. Guangdong's electricity demand driven by its rapid economic growth is satisfied by outsourcing electricity to Guizhou (8.9% of Guangdong's total electricity flow), Yunnan (4.9%), and Guangxi (4.5%), respectively. In 2012 (2017), Hebei (Guangdong) had the maximum electricity inflow.

The interregional electricity trade has changed the network of virtual water and embodied CO_2 emission within China (see Figure 3D–3I and Figure S4). The CO_2 emission embodied in electricity trade increased from 315 Mt in 2008 to 482 Mt in 2012 and 521 Mt in 2017, by 13.3% yr^{-1} and 1.6% yr^{-1}, respectively. Results show that the growth rate of embodied CO_2 emission (+1.6% yr^{-1}) is slower than that of electricity trade (+11.1% yr^{-1}) in the 'new normal' stage.[2] Figures 3G–3I show that virtual water increased from

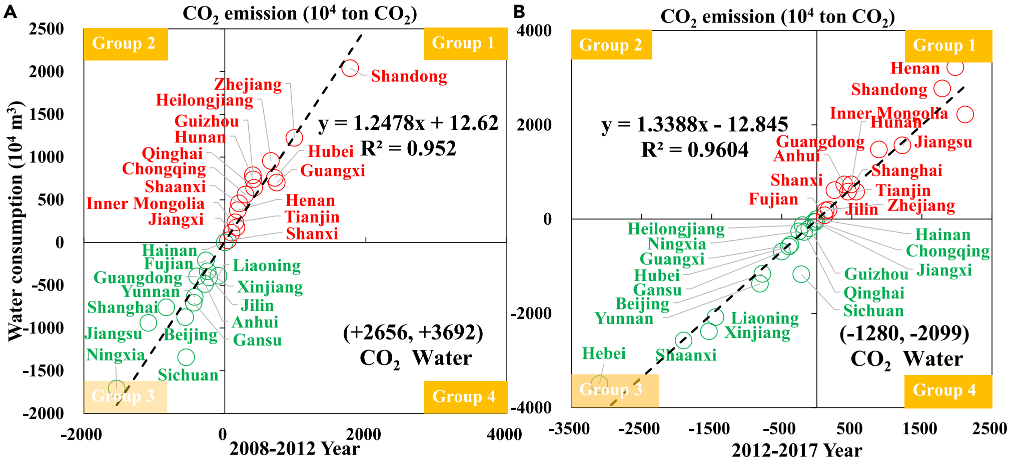


Figure 4. Water-saving co-benefits of CO$_2$ reduction through electricity trade

(A) Annual average water saving and CO$_2$ reduction during 2008-2012, (B) annual average water saving and CO$_2$ reduction during 2012-2017.

405 million m^3 in 2008 to 612 million m^3 in 2012 and 753 million m^3 in 2017, increasing by 12.8% yr^{-1} and 4.6% yr^{-1}, respectively. Overall, the growth rate of virtual water and embodied CO$_2$ has slowed down since 2012. Virtual water (+4.6% yr^{-1}) and embodied CO$_2$ (+1.6% yr^{-1}) relatively decoupled from electricity trade (+11.1% yr^{-1}) through energy substitution, efficiency improvement, and electricity trade in 'new normal' stage. The top 5 and bottom 5 provinces with virtual water and CO$_2$ emission embodied in electricity trade are shown in Figure S3 (see Note S2).

Water-saving co-benefits of co$_2$ reduction through electricity trade

The first number in parentheses is CO$_2$ reduction and the second is water-saving through electricity trade (see Figure 4). The largest water source of electricity production is surface water, accounting for 67.8% (69.3%) in that of electricity trade (production). Moreover, groundwater, municipal wastewater, and mine water account for 17.9%, 12%, and 2.3% in that of electricity trade, respectively; 16.2%, 12.7%, and 1.7% in that of electricity production, respectively (see Figures 3, S2, and S4).

The annual average growth rate of virtual water embodied in electricity trade has slowed down since 2012. Compared with the annual growth rate in financial crisis stage, the biggest decline is surface water (−10.3% yr^{-1}), followed by mine water (−7.4% yr^{-1}), municipal wastewater (−5.7% yr^{-1}), and groundwater (−3% yr^{-1}) in the 'new normal' stage (see Figure S4). Notably, groundwater is the second largest water source in electricity production and plays a central role in sustaining ecosystem.[57] However, groundwater has the least decline rate (−3% yr^{-1}) in the four sources. Mine water has the smallest share of water consumption in electricity production (1.5%) but achieves a pronounced decline (−7.4% yr^{-1}) in the 'new normal' stage.

Figure 4 shows the water-saving co-benefits of CO$_2$ reduction through electricity trade. Outsourcing electricity to regions with lower water (CO$_2$) intensity of electricity could reduce the local water consumption (CO$_2$ emission), vice versa. Compared with the counterfactual scenario, provinces in group 1 (3) consumed more (less) water and emitted more (less) CO$_2$ emission. The increase in water consumption (CO$_2$ emission) in group 1 outweighs the water saving (CO$_2$ reduction) in group 3 through electricity trade (see Figure 4A). As a result, electricity trade increased water consumption (CO$_2$ emission) by 37 million m^3 (27 Mt) yr^{-1} between 2008 and 2012. In contrast, we found pronounced water-saving co-benefits of CO$_2$ reduction through electricity trade between 2012 and 2017 (see Figure 4B). The water saving (CO$_2$ reduction) in group 3 outweighs the increase in water consumption (CO$_2$ emission) in group 1 (see Figure 4B). On the one hand, electricity trade contributed to water-saving (−21 million m^3) and CO$_2$ reduction (−13 Mt) yr^{-1} in the 'new normal' stage. On the other hand, electricity trade increased by 11.1% yr^{-1}, but water saving (CO$_2$ reduction) decreased by 2.8% yr^{-1} (3.5% yr^{-1}) between 2012 and 2017 and water saving and CO$_2$ reduction absolutely decoupled from electricity trade. Compared Figure 4B with Figure 4A, we found that more provinces have achieved water-saving co-benefits of CO$_2$ reduction in group 3 since 2012. 17 provinces reduced both water consumption and CO$_2$ emission through electricity trade in group 3 (see Figure 4B). As a result, water saving (CO$_2$ reduction)

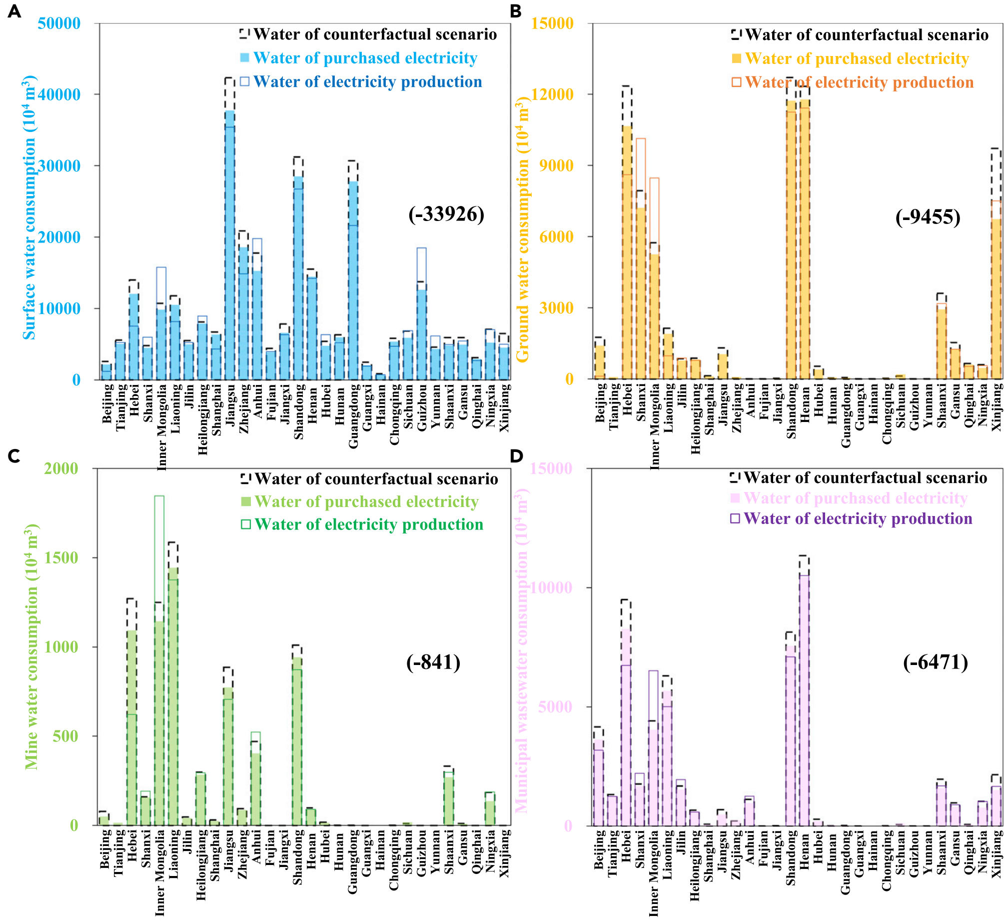


Figure 5. Water consumption in electricity production, purchased electricity, and counterfactual scenario
(A) Surface water, (B) ground water, (C) mine water, and (D) municipal wastewater.

increased by 157% (148%) in the 'new normal' stage compared to that of financial crisis stage. Overall, more electricity is transferred from low water (CO_2) intensity provinces to high water (CO_2) intensity provinces. Meanwhile, more provinces have achieved water-saving co-benefits of CO_2 reduction since 2012.

Four sources of water-saving through electricity trade

The water consumption of electricity production (solid line) and purchased electricity (color-filled bar chart) in the baseline scenario are shown in Figures 5A–5D. In counterfactual scenario (black dotted line), we assume that there are no changes in interregional electricity trade in the study period. The number in parentheses is the annual average water-saving through electricity trade in study period. Overall, electricity trade benefited water-saving for surface water (-339×10^6 m^3), groundwater (-95×10^6 m^3), municipal wastewater (-65×10^6 m^3), and mine water (-8×10^6 m^3) in China's electricity sector. Our results reveal diverse changes in virtual water consumption between electricity production and purchased electricity (see Figures 5 and S4). Here, we used the differences in virtual water consumption between the baseline scenario and counterfactual scenario to investigate the impacts of electricity trade on water-saving for each province in Figures 5A–5D. Compared with the counterfactual scenario (black dotted line), we find that electricity trade might increase or reduce virtual water consumption at province level (see Figure 5). Guizhou increased surface water of electricity production, whereas Jiangsu and Hebei saved surface water from both electricity production and purchased electricity through electricity trade (see Figure 5). Surface water is the biggest cooling water source for thermal power generation in China (see Figure S2). Xinjiang, Beijing, and Tianjin saved surface water by purchased electricity by 31%, 18%, and 10%, respectively. Groundwater is also widely used for cooling needs in several provinces (for example, Hebei, Shanxi, and Inner Mongolia). Yunnan, Guizhou, and Xinjiang saved ground water by 54%, 48%, and 31%, respectively. In contrast, Zhejiang, Sichuan, and Hunan increased ground water by 161%, 55%, and 31%, respectively. Mine water is used in Hebei, Inner Mongolia, Liaoning, Jiangsu, and Shandong provinces. Yunnan, Guizhou, and Fujian saved mine water by 54%, 49%, and 40%, respectively. In contrast, Xinjiang, Sichuan, and Chongqing increased mine water through electricity trade by 118%, 60%, and 36%, respectively. Concerning municipal wastewater, Yunnan, Guizhou, and Fujian saved municipal wastewater by 54%, 48%, and 33%, respectively. In contrast, Sichuan, Hunan, and Zhejiang increased municipal wastewater by 51%, 34%, and 15%, respectively. Overall, water-saving outweighs the increase in water consumption from four sources through electricity trade in China.

DISCUSSION

The electricity sector is the largest water consumer and CO_2 emitter in China's industrial sector. The low-carbon transition of China's coal-dominated electricity system has reduced CO_2 emission and achieved water-saving co-benefits. Building on previous efforts to assess electricity related water consumption and CO_2 emission, we highlight the impacts of energy substitution, efficiency improvement, and electricity trade on water-saving co-benefits of CO_2 reduction in China's electricity sector.[39,55]

First, the rapid expansion of coal, hydro, wind, solar PV, and nuclear power plants have changed the energy mix in China's electricity sector since 2008.[58,59] The technological advancement of newly built high efficiency units and the phase out of low efficiency units have improved the efficiency level of electricity production. Thus, energy substitution combined with efficiency improvement contributed to CO_2 reduction and achieved water-saving co-benefits in China's electricity sector.

Second, the large-scale long-distance ultra-high voltage power transmission grids alleviate the regional electricity shortages (see Figure 3).[34,56] Moreover, electricity trade reduces water consumption in developed regions (for example, Jiangsu and Beijing) at the expense of increasing water consumption in less developed regions (for example, Shanxi and Jilin) (see Figure 3 and Table S1). Notably, the substitution of low water (CO_2) intensity of electricity for high water (CO_2) intensity of electricity could achieve water-saving co-benefits of CO_2 reduction through electricity trade among grid-connected regions within China (see Figures 1 and 4).

Overall, energy substitution and efficiency improvement combined with electricity trade contribute to water-saving co-benefits of CO_2 reduction in China's electricity sector. In the context of global climate change, water-saving co-benefits of CO_2 reduction could alleviate water scarcity risks of thermal power generation in high water-stressed regions in China.

Conclusions

The water resource shortage and excessive CO_2 emission are important climate risks and constraints for thermal power generation in China.[60–62] Despite the small share of water-saving in each province's total water consumption, water-saving co-benefits of CO_2 reduction are still meaningful for the operation of thermal power plants in high-water stressed catchments (for example, the catchments in Xinjiang and the middle reach of the Yellow River Basin). Thus, we should redistribute and reschedule the operation plan of thermal power plants in these high-water stressed regions.

The energy substitution, efficiency improvement, and electricity trade have accelerated the low-carbon transition of China's electricity sector and achieved water-saving co-benefits of CO_2 reduction. In this paper, we compared the water consumption and CO_2 emission of electricity production (purchased electricity) in the baseline scenario with that of the counterfactual scenario to show the differentiated impacts of the energy substitution, efficiency improvement, and electricity trade on water-saving co-benefits of CO_2 reduction in 30 provincial electricity sectors.

The magnitude of decline in the average CO_2 intensity outweighs that of the average water intensity (see Figure 1). In the 'new normal' stage, water-saving (+10.4% yr^{-1}) outweighed CO_2 reduction (+8.4% yr^{-1}) through energy substitution and efficiency improvement. In contrast, CO_2 reduction (−3.5% yr^{-1}) outweighed water-saving (−2.8% yr^{-1}) through electricity trade. Our results show that provinces in group 3 have achieved water-saving co-benefits of CO_2 reduction but not for other groups (see Figures 2 and 4). Meanwhile, more provinces transferred from group 1 to group 3 and achieved water-saving co-benefits of CO_2 reduction through energy substitution, efficiency improvement, and electricity trade in 'new normal' stage (see Figures 2 and 4). Results show that most of the water saving is from surface water, followed by ground water, municipal wastewater, and mine water through electricity trade (See Figure 5). Thus, energy policymakers should address water-saving problems when making electricity system plans in the future. This study could help policymakers to identify strategic opportunities to emphasize water-saving co-benefits of CO_2 reduction toward China's 2060 carbon neutrality target.

Limitations of the study

The water-saving (CO_2 reduction) through electricity trade is determined by the differences in water (CO_2) intensity of electricity among 30 provinces. In a high penetration of renewables scenario, the shrinking water (CO_2) intensity gaps might limit water-saving co-benefits of CO_2 reduction to a large extent in the future. We account water consumption from thermal power generation by the method proposed by Zhang.[55] However, water consumption from solar photovoltaic and wind power was not included in this study because of their relatively small shares in total electricity production (∼6.5% in 2017) and the lower water intensity (∼0.6L/kWh).[30] Natural evaporation of water in hydropower plants was also excluded from this study.[63,64] Notably, the adoption of air-cooling and seawater-cooling technologies could reduce the freshwater consumption in the electricity sector. However, we do not investigate the changes in cooling technologies in greater detail because of their limited impacts.[65]

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Decoupling method
  - Quasi-Input-Output model
  - Water-saving co-benefits of CO_2 reduction
  - Water-saving co-benefits of CO_2 reduction through energy substitution and efficiency improvement
  - Water-saving co-benefits of CO_2 reduction through electricity trade

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106035.

ACKNOWLEDGMENTS

This work is supported by the Major Project of National Social Science Foundation of China (No. 21&ZD166, 21ZDA065), Key Research & Development Project of Qinghai Province (2022-SF-173), National Natural Science Foundation of China (72174111), Shandong Natural Science Foundation of China (ZR2021MG013), and General Project of Philosophy and Social Science Research in Jiangsu Province's Colleges and Universities (2022SJYB0948).

AUTHOR CONTRIBUTIONS

X.P., D.Z., C.Z., and H.Z. wrote, designed, and conceptualized this research. H.C., and R.L. organized the manuscript. G.Y., J.H., C.D., and X.Q. revised the manuscript. P.W., P.Z., and J.C. performed the research and revised the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: June 27, 2022
Revised: October 7, 2022
Accepted: January 18, 2023
Published: January 24, 2023

REFERENCES

1. International Energy Agency (2019). CO2 Emissions from Fuel Combustion 2019 (OECD Publishing).

2. Peng, X., Tao, X., Feng, K., and Hubacek, K. (2020). Drivers toward a low-carbon electricity system in China's provinces. Environ. Sci. Technol. *54*, 5774–5782.

3. P.R. Shukla, J. S., R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

4. Zhang, C., Anadon, L.D., Mo, H., Zhao, Z., and Liu, Z. (2014). Water— carbon trade-off in China's coal power industry. Environ. Sci. Technol. *48*, 11082–11089.

5. (2019). Ministry of water resources of the people's Republic of China. In China water resources bulletinChina water resources bulletin (China Waterpower Press).

6. Zhang, Z., Liu, J., Cai, B., Shan, Y., Zheng, H., Li, X., Li, X., and Guan, D. (2020). City-level water withdrawal in China: accounting methodology and applications. J. Ind. Ecol. *24*, 951–964.

7. Feng, K., Hubacek, K., Siu, Y.L., and Li, X. (2014). The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renew. Sustain. Energy Rev. *39*, 342–355.

8. Jiang, D., and Ramaswami, A. (2015). The 'thirsty'water-electricity nexus: field data on the scale and seasonality of thermoelectric power generation's water intensity in China. Environ. Res. Lett. *10*, 024015.

9. Chini, C.M., Djehdian, L.A., Lubega, W.N., and Stillwell, A.S. (2018). Virtual water transfers of the US electric grid. Nat. Energy *3*, 1115–1123.

10. Liu, L., Hejazi, M., Iyer, G., and Forman, B.A. (2019). Implications of water constraints on electricity capacity expansion in the United States. Nat. Sustain. *2*, 206–213.

11. Zhang, C., Zhong, L., and Wang, J. (2018). Decoupling between water use and thermoelectric power generation growth in China. Nat. Energy *3*, 792–799.

12. Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C., and Breyer, C. (2019). Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nat. Energy *4*, 1040–1048.

13. Zhou, Y., Ma, M., Kong, F., Wang, K., and Bi, J. (2018). Capturing the co-benefits of energy efficiency in China—a perspective from the water-energy nexus. Resour. Conserv. Recycl. *132*, 93–101.

14. Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., and Hubacek, K. (2013). Outsourcing CO2 within China. Proc. Natl. Acad. Sci. USA *110*, 11654–11659.

15. Shao, L., Li, Y., Feng, K., Meng, J., Shan, Y., and Guan, D. (2018). Carbon emission imbalances and the structural paths of Chinese regions. Appl. Energy *215*, 396–404.

16. Fang, D., Chen, B., Hubacek, K., Ni, R., Chen, L., Feng, K., and Lin, J. (2019). Clean air for some: unintended spillover effects of regional air pollution policies. Sci. Adv. *5*, eaav4707.

17. Wang, R., Zimmerman, J.B., Wang, C., Font Vivanco, D., and Hertwich, E.G. (2017). Freshwater vulnerability beyond local water stress: heterogeneous effects of water-electricity nexus across the continental United States. Environ. Sci. Technol. *51*, 9899–9910.

18. Zhang, C., Zhong, L., Liang, S., Sanders, K.T., Wang, J., and Xu, M. (2017). Virtual scarce water embodied in inter-provincial electricity transmission in China. Appl. Energy *187*, 438–448.

19. Wei, W., Hao, S., Yao, M., Chen, W., Wang, S., Wang, Z., Wang, Y., and Zhang, P. (2020). Unbalanced economic benefits and the electricity-related carbon emissions embodied in China's interprovincial trade. J. Environ. Manage. *263*, 110390.

20. Zhang, P., Cai, W., Yao, M., Wang, Z., Yang, L., and Wei, W. (2020). Urban carbon emissions associated with electricity consumption in Beijing and the driving factors. Appl. Energy *275*, 115425.

21. Abrell, J., and Rausch, S. (2016). Cross-country electricity trade, renewable energy and European transmission infrastructure policy. J. Environ. Econ. Manage. *79*, 87–113.

22. Peng, W., Yuan, J., Zhao, Y., Lin, M., Zhang, Q., Victor, D.G., and Mauzerall, D.L. (2017). Air quality and climate benefits of long-distance electricity transmission in China. Environ. Res. Lett. *12*, 064012.

23. Wang, C., Wang, R., Hertwich, E., Liu, Y., and Tong, F. (2019). Water scarcity risks mitigated or aggravated by the inter-regional electricity transmission across China. Appl. Energy *238*, 413–422.

24. Rodrigues, J.F., Wang, J., Behrens, P., and de Boer, P. (2020). Drivers of CO2 emissions from electricity generation in the European Union 2000–2015. Renew. Sustain. Energy Rev. *133*, 110104.

25. Yang, L., and Lin, B. (2016). Carbon dioxide-emission in China's power industry: evidence and policy implications. Renew. Sustain. Energy Rev. *60*, 258–267.

26. Davis, S.J., and Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. Proc. Natl. Acad. Sci. USA *107*, 5687–5692.

27. Mi, Z., Zhang, Y., Guan, D., Shan, Y., Liu, Z., Cong, R., Yuan, X.-C., and Wei, Y.-M. (2016). Consumption-based emission accounting for Chinese cities. Appl. Energy *184*, 1073–1081.

28. Liao, X., Zhao, X., Hall, J.W., and Guan, D. (2018). Categorising virtual water transfers through China's electric power sector. Appl. Energy *226*, 252–260.

29. Zhai, M., Huang, G., Liu, L., Zheng, B., and Guan, Y. (2020). Inter-regional carbon flows embodied in electricity transmission: network simulation for energy-carbon nexus. Renew. Sustain. Energy Rev. *118*, 109511.

30. Li, X., Feng, K., Siu, Y.L., and Hubacek, K. (2012). Energy-water nexus of wind power in China: the balancing act between CO2 emissions and water consumption. Energy Pol. *45*, 440–448.

31. Liu, Z., Huang, Q., He, C., Wang, C., Wang, Y., and Li, K. (2021). Water-energy nexus within urban agglomeration: an assessment framework combining the multiregional input-output model, virtual water, and embodied energy. Resour. Conserv. Recycl. *164*, 105113.

32. Sun, L., Pan, B., Gu, A., Lu, H., and Wang, W. (2018). Energy–water nexus analysis in the Beijing–Tianjin–Hebei region: case of electricity sector. Renew. Sustain. Energy Rev. *93*, 27–34.

33. Zhao, D., Liu, J., Sun, L., Ye, B., Hubacek, K., Feng, K., and Varis, O. (2021). Quantifying economic-social-environmental trade-offs and synergies of water-supply constraints: an application to the capital region of China. Water Res. *195*, 116986.

34. China Electricity, Council. (2020). China Electricity Statistical Yearbook (China Statistics Press).

35. Lindner, S., Liu, Z., Guan, D., Geng, Y., and Li, X. (2013). CO2 emissions from China's power sector at the provincial level: consumption versus production perspectives. Renew. Sustain. Energy Rev. *19*, 164–172.

36. Zhu, Y., Ke, J., Wang, J., Liu, H., Jiang, S., Blum, H., Zhao, Y., He, G., Meng, Y., and Su, J. (2020). Water transfer and losses embodied in the West–East electricity transmission project in China. Appl. Energy *275*, 115152.

37. Wang, H., Wang, W., Liang, S., Zhang, C., Qu, S., Liang, Y., Li, Y., Xu, M., and Yang, Z. (2019). Determinants of greenhouse gas emissions from interconnected grids in China. Environ. Sci. Technol. *53*, 1432–1440.

38. Qu, S., Wang, H., Liang, S., Shapiro, A.M., Suh, S., Sheldon, S., Zik, O., Fang, H., and Xu, M. (2017). A Quasi-Input-Output model to improve the estimation of emission factors for purchased electricity from interconnected grids. Appl. Energy *200*, 249–259.

39. Qu, S., Liang, S., and Xu, M. (2017). CO2 emissions embodied in interprovincial electricity transmissions in China. Environ. Sci. Technol. *51*, 10893–10902.

40. Zhang, W., Wang, F., Hubacek, K., Liu, Y., Wang, J., Feng, K., Jiang, L., Jiang, H., Zhang,

B., and Bi, J. (2018). Unequal exchange of air pollution and economic benefits embodied in China's exports. Environ. Sci. Technol. *52*, 3888–3898.

41. Wei, W., Li, J., Chen, B., Wang, M., Zhang, P., Guan, D., Meng, J., Qian, H., Cheng, Y., Kang, C., et al. (2021). Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. Nat. Sustain. *4*, 739–747.

42. Chen, G., Yang, Q., and Zhao, Y. (2011). Renewability of wind power in China: a case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi. Renew. Sustain. Energy Rev. *15*, 2322–2329.

43. Chen, W., Lei, Y., Feng, K., Wu, S., and Li, L. (2019). Provincial emission accounting for CO2 mitigation in China: insights from production, consumption and income perspectives. Appl. Energy *255*, 113754.

44. Peters, G.P. (2008). From production-based to consumption-based national emission inventories. Ecol. Econ. *65*, 13–23.

45. Liu, L., Huang, G., Baetz, B., and Zhang, K. (2018). Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies. Appl. Energy *232*, 69–78.

46. Xu, Z., Li, Y., Chau, S.N., Dietz, T., Li, C., Wan, L., Zhang, J., Zhang, L., Li, Y., Chung, M.G., and Liu, J. (2020). Impacts of international trade on global sustainable development. Nat. Sustain. *3*, 964–971.

47. Chen, P., Wu, Y., Meng, J., He, P., Li, D., Coffman, D.M., Liang, X., and Guan, D. (2022). The heterogeneous role of energy policies in the energy transition of Asia–Pacific emerging economies. Nat. Energy *7*, 588–596.

48. Mallapragada, D.S., Papageorgiou, D.J., Venkatesh, A., Lara, C.L., and Grossmann, I.E. (2018). Impact of model resolution on scenario outcomes for electricity sector system expansion. Energy *163*, 1231–1244.

49. Bhattarai, P.R., and Thompson, S. (2016). Optimizing an off-grid electrical system in Brochet, Manitoba, Canada. Renew. Sustain. Energy Rev. *53*, 709–719.

50. Peng, X., and Tao, X. (2018). Decomposition of carbon intensity in electricity production: technological innovation and structural adjustment in China's power sector. J. Clean. Prod. *172*, 805–818.

51. Wang, S., Wang, J., Fang, C., and Feng, K. (2019). Inequalities in carbon intensity in China: a multi-scalar and multi-mechanism analysis. Appl. Energy *254*, 113720.

52. Zhang, W., Liu, Y., Feng, K., Hubacek, K., Wang, J., Liu, M., Jiang, L., Jiang, H., Liu, N., Zhang, P., et al. (2018). Revealing environmental inequality hidden in China's inter-regional trade. Environ. Sci. Technol. *52*, 7171–7181.

53. Yu, Y., Feng, K., and Hubacek, K. (2014). China's unequal ecological exchange. Ecol. Indic. *47*, 156–163.

54. Peng, X., Tao, X., Zhang, H., Chen, J., and Feng, K. (2021). CO2 emissions from the electricity sector during China's economic transition: from the production to the consumption perspective. Sustain. Prod. Consum. *27*, 1010–1020.

55. Zhang, C., Zhong, L., Fu, X., Wang, J., and Wu, Z. (2016). Revealing water stress by the thermal power industry in China based on a high spatial resolution water withdrawal and consumption inventory. Environ. Sci. Technol. *50*, 1642–1652.

56. The State Council (2014). National Energy Development Strategy Action Plan (2014–2020) (Beijing, China: State Council).

57. Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., et al. (2013). Ground water and climate change. Nat. Clim. Chang. *3*, 322–329.

58. The State Council (2007). Opinions about Accelerating Shutting Down Small Thermal Power Units (Beijing, China: State Council).

59. Ministry of Environmental Protection (2017). A Guide to Feasible Technologies for Pollution Prevention in Thermal Power Plants (Beijing, China: Ministry of Environmental Protection).

60. Byers, E.A., Coxon, G., Freer, J., and Hall, J.W. (2020). Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain. Nat. Commun. *11*, 2239.

61. Webster, M., Donohoo, P., and Palmintier, B. (2013). Water–CO2 trade-offs in electricity generation planning. Nat. Clim. Chang. *3*, 1029–1032.

62. Zhao, D., Cai, J., Shen, L., Elshkaki, A., Liu, J., and Varis, O. (2023). Delivery of energy sustainability: applications of the "STAR" protocol to the Sustainable Development Goal 7 index and its interaction analysis. J. Clean. Prod. *389*, 135884.

63. Zhao, D., and Liu, J. (2015). A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services. Phys. Chem. Earth, Parts A/B/C *79–82*, 40–46.

64. Liu, J., Zhao, D., Gerbens-Leenes, P.W., and Guan, D. (2015). China's rising hydropower demand challenges water sector. Sci. Rep. *5*, 11446.

65. Zhang, X., Liu, J., Tang, Y., Zhao, X., Yang, H., Gerbens-Leenes, P., van Vliet, M.T., and Yan, J. (2017). China's coal-fired power plants impose pressure on water resources. J. Clean. Prod. *161*, 1171–1179.

66. Shan, Y., Huang, Q., Guan, D., and Hubacek, K. (2020). China CO_2 emission accounts 2016–2017. Sci. Data *7*, 54.

67. Liang, S., Liu, Z., Crawford-Brown, D., Wang, Y., and Xu, M. (2014). Decoupling analysis and socioeconomic drivers of environmental pressure in China. Environ. Sci. Technol. *48*, 1103–1113.

68. Tapio, P. (2005). Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy *12*, 137–151.

69. Muratori, M., Smith, S.J., Kyle, P., Link, R., Mignone, B.K., and Kheshgi, H.S. (2017). Role of the freight sector in future climate change mitigation scenarios. Environ. Sci. Technol. *51*, 3526–3533.

70. Zhang, Y.-J., and Da, Y.-B. (2015). The decomposition of energy-related carbon emission and its decoupling with economic growth in China. Renew. Sustain. Energy Rev. *41*, 1255–1266.

71. Zhao, X., Zhang, X., and Shao, S. (2016). Decoupling CO2 emissions and industrial growth in China over 1993–2013: the role of investment. Energy Econ. *60*, 275–292.

72. Chen, J., Shi, Q., Shen, L., Huang, Y., and Wu, Y. (2019). What makes the difference in construction carbon emissions between China and USA? Sustain. Cities Soc. *44*, 604–613.

73. Miller, R.E., and Blair, P.D. (2009). Input-Output Analysis :Foundations and Extensions (Cambridge University Press).

74. Feng, K., Davis, S.J., Sun, L., and Hubacek, K. (2015). Drivers of the US CO 2 emissions 1997–2013. Nat. Commun. *6*, 7714.

75. Cai, B., Hubacek, K., Feng, K., Zhang, W., Wang, F., and Liu, Y. (2020). Tension of agricultural land and water use in China's trade: tele-connections, hidden drivers and potential solutions. Environ. Sci. Technol. *54*, 5365–5375.

76. Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., and Hubacek, K. (2015). Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. USA *112*, 1031–1035.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Fossil fuel data of thermal power generation	National Bureau of Statistics	http://www.stats.gov.cn/
Emission factor	Shan, Y. et al.[66] Liu, Z. et al.[31]	https://www.nature.com/articles/s41597-020-0393-y https://www.nature.com/articles/nature14677
Interregional electricity trade data	CHINA ELECTRICITY COUNCIL[34]	https://www.cec.org.cn/
Water consumption database	Zhang, C. et al.[55]	https://pubs.acs.org/doi/10.1021/acs.est.5b05374
Software and algorithms		
Excel	Microsoft	https://www.microsoft.com
R software	Bell Laboratories	https://www.r-project.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Prof. Chao Zhang (chao_zhang@tongji.edu.cn).

Materials availability

This study did not generate new materials.

Data and code availability

All data generated in this paper are available from the lead contact on reasonable request.

This paper does not report original code.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request, or Dandan Zhao (dandan.zhao@aalto.fi) and Xu Peng (jokexutj@163.com).

METHOD DETAILS

Decoupling method

To describe the decarbonizing relationship between the water consumption (CO_2 emission) and electricity trade, we adopted the OECD's decoupling method to measure the relative changes in water consumption (CO_2 emission) to the changes in electricity trade.[67–69] Relative decoupling means the growth rate of water consumption (CO_2 emission) is slower than the electricity trade, while absolute decoupling occurs when electricity trade grows but water consumption (CO_2 emission) decreases[68,70,71]

$$\text{Decoupling index} = \left(\frac{C_j^b - C_j^a}{C_j^a}\right) \Big/ \left(\frac{E_j^b - E_j^a}{E_j^a}\right) \qquad \text{(Equation 1)}$$

where C_i is the CO_2 emission (water consumption) of electricity in power grid i; E_i is the electricity trade level in power grid i.

Quasi-Input-Output model

Electricity transmission among regions is shown as electricity balance Equation 2.

$$f_i = p_i + \sum_j t_{ji} = c_i + \sum_j t_{ij} \qquad \text{(Equation 2)}$$

where f_i is the total electricity flow in power grid i; p_i is the electricity production; c_i is the electricity consumption; t_{ij} is the electricity transmission from power grid i to j.

To capture the share of interregional resource flow in power grids, we define direct outflow coefficient matrix $\boldsymbol{B}$ of electricity trade as followings:

$$B = \widehat{f}^{-1}T = \begin{pmatrix} 0 & \frac{t_{12}}{f_1} & \cdots & \frac{t_{1n}}{f_1} \\ \frac{t_{21}}{f_2} & 0 & \cdots & \frac{t_{2n}}{f_2} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{t_{n1}}{f_n} & \cdots & \frac{t_{n(n-1)}}{f_n} & 0 \end{pmatrix} \qquad \text{(Equation 3)}$$

The total CO_2 emission (water consumption) embodied in a connected power grid is shown as followings:

$$m^f = m^p + m^f B \qquad \text{(Equation 4)}$$

where $\boldsymbol{m^f}$ is the total resource consumption in electricity network, and $\boldsymbol{m^p}$ is resource consumption of electricity production. The total outflow coefficient matrix $\boldsymbol{G}$ of electricity network (quasi-Ghosh inverse matrix) is defined as followings:

$$G = (I - B)^{-1} \qquad \text{(Equation 5)}$$

where the element of matrix $\boldsymbol{G}$ is the total electricity flow in grid j induced by one unit of electricity production from grid i:

$$m^f = m^p(I - B)^{-1} = m^p G \qquad \text{(Equation 6)}$$

To capture the embodied virtual water (CO_2 emission) of purchased electricity, the share of power grid i's electricity consumption in its total electricity flow $\boldsymbol{B^c}$ is calculated by followings:

$$B^c = \widehat{c}\widehat{f}^{-1} \qquad \text{(Equation 7)}$$

$$m^c = m^p G B^c \qquad \text{(Equation 8)}$$

where $\boldsymbol{m^c}$ is the embodied virtual water (CO_2 emission) of purchased electricity.

It is worth noting that the QIO model is the limit of iterative method's result. The virtual water (CO_2 emission) per unit of purchased electricity $\mathbf{ef^f}$ is shown as followings:

$$ef^f = m^f \widehat{f}^{-1} \qquad \text{(Equation 9)}$$

Direct water consumption (CO_2 emission) per unit of electricity production $\mathbf{ef^p}$ is shown as followings:

$$ef^p = m^p \widehat{p}^{-1} \qquad \text{(Equation 10)}$$

We calculate the inflow ($\boldsymbol{m^{inflow}}$) and outflow ($\boldsymbol{m^{outflow}}$) of virtual water (CO_2 emission) embodied in electricity trade by disaggregating Equation 8.

Water-saving co-benefits of CO_2 reduction

Decomposition analysis could be used to quantify the driving factors of water consumption (CO_2 emission).[72–76] Here we used Quasi-Input-Output model combined with structural decomposition analysis (SDA) to quantify the impacts of energy substitution, efficiency improvement, and electricity trade on the water-saving co-benefits of CO_2 reduction in China's electricity sector. The water consumption (CO_2 emission) embodied in purchased electricity is shown in Equation 11.

$$m_i^c = m_i^p G_i B_i^c = \left(m_i^p / h_i\right) \cdot \left(\frac{h_i}{p_i}\right) \cdot p_i \cdot G_i \cdot B_i^c = e_1 \cdot e_2 \cdot e_3 \cdot e_4 \cdot e_5 \qquad \text{(Equation 11)}$$

where $\mathbf{m^c}$ is the water consumption (CO_2 emission) embodied in region i's electricity consumption; h_i is the thermal generation; e_1 is the water consumption (CO_2 emission) intensity of thermal power generation (efficiency level); e_2 is the share of thermal power generation (energy mix); e_3 is the total electricity production; e_4 is the interregional electricity exchange; and e_5 is the electricity consumption.

Equation 11 can be rewritten as Equation 12.

$$\mathrm{m}_i^c = \mathrm{m}_i^P \mathrm{G}_i \mathrm{B}_i^c = \left(\mathrm{m}_i^P / \mathrm{p}_i\right) \cdot \mathrm{p}_i \cdot \left(\mathrm{G}_i \cdot \mathrm{B}_i^c\right) = d_1 \cdot d_2 \cdot d_3 \quad \text{(Equation 12)}$$

where d_1 is the aggregated effect of energy substitution and efficiency improvement; d_2 is the electricity production; and d_3 is the electricity trade effect which includes electricity exchange and electricity consumption.

We use the differences in water consumption (CO_2 emission) between the baseline scenario and counterfactual scenario to represent the impacts of energy substitution, efficiency improvement, and electricity trade on the water-saving co-benefits of CO_2 reduction. Specifically, water saving or CO_2 reduction (∇m^c) is calculated by Equation 13:

$$\nabla m^c = \nabla D_1 + \nabla D_2 + \nabla D_3 = \Delta d_1 \cdot d_2 \cdot d_3 + d_1 \cdot \Delta d_2 \cdot d_3 + d_1 \cdot d_2 \cdot \Delta d_3 \quad \text{(Equation 13)}$$

$$\nabla D_1 = \Delta d_1 \cdot d_2 \cdot d_3 = \frac{1}{2} \cdot (d_{1T} - d_{1t}) \cdot (d_{2t} \cdot d_{3t} + d_{2T} \cdot d_{3T}) \quad \text{(Equation 14)}$$

$$\nabla D_3 = d_1 \cdot d_2 \cdot \Delta d_3 = \frac{1}{2} \cdot (d_{1t} \cdot d_{2t} + d_{1T} \cdot d_{2T}) \cdot (d_{3T} - d_{3t}) \quad \text{(Equation 15)}$$

$$\nabla D_2 = d_1 \cdot \Delta d_2 \cdot d_3 = 0 \quad \text{(Equation 16)}$$

where ∇D_1 is the annual average water saving (CO_2 reduction) due to energy substitution and efficiency improvement from time t to time T. The ∇D_3 is the annual average water saving (CO_2 reduction) due to electricity trade from time t to time T. Notably, ∇D_2 is zero because the increase in electricity production does not benefit water saving or CO_2 reduction.

Water-saving co-benefits of CO_2 reduction through energy substitution and efficiency improvement

Energy substitution and efficiency improvement could benefit the water saving and CO_2 reduction of electricity production.[2] The changes in water consumption (CO_2 emission) per unit of electricity production from time t to T are calculated as followings:

$$\Delta ef^p = ef_T^p - ef_t^p = d_{1T} - d_{1t} \quad \text{(Equation 17)}$$

In the counterfactual scenario, we assume that region i produces electricity without the changes in energy mix and efficiency level in study period. The annual average water-saving co-benefits of CO_2 reduction through energy substitution and efficiency improvement are shown as Equation 18:

$$\nabla D_1 = \frac{1}{2} \cdot \Delta ef^p \cdot (d_{2t} \cdot d_{3t} + d_{2T} \cdot d_{3T}) \quad \text{(Equation 18)}$$

$$r = \left(ef_T^p - ef_t^p\right) / \left[ef_t^p \cdot (T - t)\right] \quad \text{(Equation 19)}$$

where r is the annual water-saving (CO_2 reduction) rate through energy substitution and efficiency improvement.

Water-saving co-benefits of CO_2 reduction through electricity trade

The interregional electricity trade contributes to the water-saving co-benefits of CO_2 reduction in China's electricity sector. In the counterfactual scenario, we assume that region i produces electricity without the changes in interregional electricity trade. The impacts of electricity trade on water-saving co-benefits of CO_2 reduction are shown as Equation 20.

$$\nabla D_3 = \frac{1}{2} \cdot (d_{1t} \cdot d_{2t} + d_{1T} \cdot d_{2T}) \cdot \left(\mathrm{G}_{iT} \cdot \mathrm{B}_{iT}^c - \mathrm{G}_{it} \cdot \mathrm{B}_{it}^c\right) = \frac{1}{2} \cdot \left(\mathrm{m}_T^p + \mathrm{m}_t^p\right) \cdot \left(\mathrm{G}_{iT} \cdot \mathrm{B}_{iT}^c - \mathrm{G}_{it} \cdot \mathrm{B}_{it}^c\right) \quad \text{(Equation 20)}$$

$$r^{*} = \mathrm{I} \cdot \left(\mathrm{G}_{\mathrm{iT}} \cdot \mathrm{B}_{\mathrm{iT}}^{\mathrm{c}} - \mathrm{G}_{\mathrm{it}} \cdot \mathrm{B}_{\mathrm{it}}^{\mathrm{c}}\right) \cdot \mathrm{I}^{\mathrm{T}} \Big/ \left[\mathrm{I} \cdot \left(\mathrm{G}_{\mathrm{it}} \cdot \mathrm{B}_{\mathrm{it}}^{\mathrm{c}}\right) \cdot \mathrm{I}^{\mathrm{T}} \cdot (T - t)\right] \qquad \text{(Equation 21)}$$

where $\mathbf{m}^{\mathrm{P}}$ is the water consumption (CO_2 emission) of electricity production. I matrix is $1 \times n$ matrix and all elements are one. r^{*} is the annual water-saving (CO_2 reduction) rate through electricity trade. The positive value of ∇D indicates the water consumption and CO_2 emission are more than they might otherwise be thought and has a lower intensity level than that of its connected power grids, vice versa. The ∇D is determined by the resource intensity gap between the local production and the weighted level of power grid-connected regions and the amounts of electricity exchange.