Environmental Science & Technology

pubs.acs.org/est

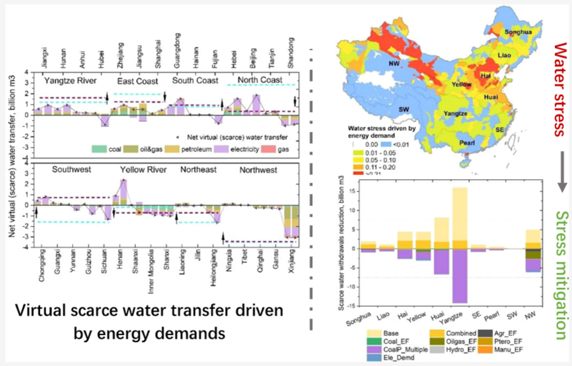
Article

Assessing Transboundary Impacts of Energy-Driven Water Footprint on Scarce Water Resources in China: Catchments under Stress and Mitigation Options

Xi Liu, Huibin Du,* Xin Zhang,* Kuishuang Feng,* Xu Zhao, Honglin Zhong, Ning Zhang, and Zhenni Chen

Cite This: *Environ. Sci. Technol.* 2023, 57, 9639−9652

ABSTRACT: The energy supply chains operating beyond a region's jurisdiction can exert pressure on the availability of water resources in the local area. In China, however, there is a lack of transboundary assessments that investigate the effects of energy consumption on water stress within and across river basins. In this study, we therefore investigate transboundary impacts on scarce water resources that are induced by energy demands (i.e., electricity, petroleum, coal mining, oil and gas extraction, and gas production). We develop a bottom-up high spatial resolution water inventory and link it to a 2017 multiregional input−output (MRIO) table of China to analyze supply chain scarce water use at provincial and river basin levels. We find that the energy-driven water footprint accounts for 21.6% of national water usage, of which 35.7% is scarce water. Nonelectric power energy sectors contribute to around half of the nation's scarce water transfer. We identify three sets of catchments whose water resources are stressed by energy demand, i.e., (a) from the northern Hai River Basin to the eastern part of the Yellow River Basin and the Huai River Basin, (b) the northern area of the Northwest Rivers, and (c) the developed coastal city clusters in the Yangtze River Basin and the Pearl River Basin. We then evaluate the impacts of eight mitigation options, which may potentially shift around half of the moderate- or high-stress areas in the Hai River Basin and the Northwest Rivers to low to moderate (or even low) stress. We highlight the need for transboundary collaboration to sustain water-constrained energy demand and to develop targeted measures to mitigate stress on water resources within a river basin.



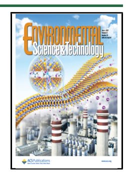
KEYWORDS: *scarce water for energy, transboundary impacts, high spatial resolution inventory, river basin, water stress, multiregional input−output analysis*

1. INTRODUCTION

Water is critical for energy production and is needed along the whole energy supply chain, ranging from fossil fuel extraction to transport and processing, power production, and the irrigation of feedstock for biofuels.[1] As the world's second-largest water user, the energy sectors consisting of power generation and primary energy production, accounted for about 10 and 3% of the world total in water withdrawals and consumption in 2014, respectively, according to the International Energy Agency.[2] Evidence suggests that water availability and fluctuation will have an impact on energy access and security. The intimate links between energy and water systems call for concrete investigation on the energy−water nexus. Increasing efforts are being made to assess water demand and show water stress in the energy industry with high technological specificity and high spatial resolution.[3−8]

Water use is influenced by local energy demand,[9−13] but it is further affected by transboundary energy impacts. These transboundary impacts are driven by energy trade activities, resulting in distributed sources of inputs for energy production and final demand, which separates the water use for energy production and consumption apart. It adds complexity to the policies and options for the effective management of energy and water security since energy and water are traditionally under separate government regulations. There is an increasing understanding on the transboundary water impacts driven by energy demand in various regions around the globe.[14−16] For China, the imbalance between the energy supply and demand has promoted inter-regional energy trade among provinces,[17]

Received: October 31, 2022
Revised: April 25, 2023
Accepted: April 26, 2023
Published: June 21, 2023



such as the West-to-East Electricity Transmission Project and the natural gas transmission project, which is characterized by virtual water flows from areas with higher water scarcity to lower places.[18] Therefore, understanding and locating the geographic mismatch between water use and energy demand is crucial for energy−water sustainability in China, as it will assist policymakers in understanding and mitigating water stress caused by energy demand from both local and transboundary perspectives.

Much effort has been devoted to studying the water−energy nexus at a subnational scale in China; most research evaluates transboundary water use induced by energy trade with a focus on direct process water use, mainly for electricity generation and coal production.[19−30] They conclude that the transboundary impacts on water consumption due to electricity transmission have increased the water stress in provinces, e.g., Inner Mongolia, Shanxi, and Ningxia.[25] Furthermore, some researchers have attempted to trace water use across the supply chain but only focused on particular regions, such as the two megalopolises (Jing-Jin-Ji and the Yangtze Delta) and Liaoning province, or electricity grids.[31−34] Moreover, the unequal water impacts of energy, given provincial water scarcity or water quality, have been addressed in a few limited studies,[35,36] such as megacity case studies[37,38] and again in work on the electricity sector.[25] Such analyses enable a better understanding of the causes of water scarcity related to energy demand and the vulnerability of the region suffering from such scarcity.[39] Existing studies have generally relied on the top-down modeling method, notably the input−output analysis model, to estimate transboundary impacts; however, there is a lack of understanding of the spatial layout of various enterprises and their associated water usage. Failing to integrate a spatially explicit water inventory to top-down modeling further impedes reliable assessment of the magnitude and spatial distribution of transboundary impacts, particularly the scarce water impacts, since they typically average out the water scarcity at the subnational level.

Additionally, the transboundary water impacts of energy demand are highly localized and attaches with high spatial heterogeneity. Previous studies have mostly measured the water impacts of energy demand solely by jurisdiction, mostly provinces, which may ignore the identification of water impacts at a high spatial resolution. A more appropriate measure may be the hydrological catchment, which the World Resources Institute's Aqueduct Water Risks Atlas (Aqueduct) defines as an area of land that drains to a single outlet point.[40] Using catchment scale analysis provides a good spatial match between the water supply and demand, reflecting differentiated water scarcity in high spatial resolution units, thereby more precisely connecting water impacts and energy demand from a consumption perspective and allowing the development of more practical and targeted energy−water management strategies. In addition, the water impacts mitigation capacity of various transboundary collaboration measures is unclear, even though this is essential for informing more effective practices in the energy−water nexus for sustainable development.

To fill this research gap, we investigate the potential transboundary unequal water impacts related to five energy sectors (i.e., coal mining and washing; oil and gas extraction; petroleum processing, coking, and nuclear processing; electricity generation; and gas production) in China. We develop an integrated modeling framework consisting of a bottom-up sectoral scarce water use estimation approach with high spatial resolution and an environmentally extended multiregional input−output (MRIO) model (Figure S1). We reliably quantify the freshwater and scarce water usage driven by energy demands in China's 31 provinces and describe the virtual scarce water trade pattern for each province to identify importers and exporters for each energy demand. Moreover, we quantify water stress to assess potential water impacts at the catchment scale and the water stress mitigation potential of a set of technology options and demand-side measures. This study advances the present knowledge in transboundary unequal water usage and impacts driven by energy demands from a holistic supply chain angle to inform effective and refined energy−water management.

2. MATERIALS AND METHODS

2.1. Provincial Freshwater Usage Driven by Energy Demand. The multiregional input−output (MRIO) approach has been widely applied to water footprint studies, tracing the supply chain environmental impacts embodied in trade activities from a consumption-based perspective.[17] The MRIO method has advantages such as reattributing direct sectoral water usage after economic transactions to the final consumers. This method helps determine the quantity of freshwater usage as well as impacts driven by energy demand locally or in other places. In the MRIO modeling framework, different regions are linked through inter-regional trade. The intermediate use coefficient between sectors among regions can be calculated directly as $\mathbf{A^*} = [A^{rs}]$, composed of $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ elements, where z_{ij}^{rs} is the intermediate input from the ith sector in region r to the jth sector in region s, and x_j^s is the total output of the jth sector in region s. The final consumption matrix is $\mathbf{Y^*} = [y^{rs}]$, where y_j^{rs} is the trade from the jth sector in region r to region s as final consumption. The export vector is $\mathbf{e^*} = [e^r]$, with e_i^r indicating the export of the ith sector in region r.

The virtual water flow from region s to region r to satisfy the energy demand of region r can be calculated as follows, excluding those sectors not related to the five energy sectors from the calculation

$$\mathrm{VF}^{sr} = [d^{s1} \quad d^{s2} \quad \cdots \quad d^{sn}]\left(\begin{bmatrix} z^{1r} \\ z^{2r} \\ \vdots \\ z^{nr} \end{bmatrix} + \begin{bmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{nr} \end{bmatrix}\right) \quad (1)$$

where d^{rs} is the row vector whose elements d_j^{rs} denote the supply chain water used to generate per unit of final demand (in monetary unit) in the jth sector of region s (Section S1.1).

The water footprint of region r (WF^r) is the total water use associated with the production of goods and services along the whole supply chain to satisfy the energy demand of region r. The water footprint includes the water use related to energy from all regions VF^{sr} and imported water footprint from abroad $\mathrm{VF}^{\mathrm{im}r}$, which can be decomposed into virtual water associated with intermediate goods imported $\mathrm{VF}^{\mathrm{iim}r}$ and final goods imported $\mathrm{VF}^{\mathrm{fim}r}$[41]

$$\mathrm{VF}^{\mathrm{im}r} = \mathrm{VF}^{\mathrm{fim}r} + \mathrm{VF}^{\mathrm{iim}r} \quad (2)$$

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

Based on the virtual water inflows and outflows related to energy, we obtain the virtual water trade balance (VTB, Figure S2) as follows

$$\mathrm{VTB}^r = \sum_{s}^{n} (\mathrm{VF}^{sr} - \mathrm{VF}^{rs}) \tag{3}$$

where a positive VTB for region r shows that it is an importer of virtual water (mitigating water stress), while a negative VTB shows a net virtual water exporter (aggregating water stress).

Since water resource depletion may severely impact human health and ecosystem health in a more water-scarce province, we consider water scarcity, as detailed in Feng et al.[35] and our previous study by Liu et al.[39] Specifically, we refer to the Aqueduct global water risk maps developed by the World Resources Institute to illustrate the spatial distribution of water scarcity in China.[40] Baseline water stress (BWS), defined by the Aqueduct maps, is measured as the ratio of total annual water withdrawals to average annual available blue water in a catchment. The annual available blue water is estimated by subtracting consumptive upstream water use from the total amount of surface water available to a catchment, which is the mean value of blue water supply in 1950−2010. The long time series is used to reduce the effect of multiyear climate cycles and to ignore short-term water storage-related influences (e.g., dams). Specifically, the water supply was computed from runoff (including subsurface and surface runoff components), accounting for precipitation, evapotranspiration, and changes in soil moisture storage.

By applying the adjusted BWS (Section S1.2 and Figure S3) as the weight, we can obtain the sectoral scarce water uses. Similar to normal water calculations, the provincial scarce water footprints, indicating the whole supply chain scarce water use driven by energy demand, are quantified. This scarce water analysis illuminates the environmental impacts of water use related to energy consumption for more informed policy making on energy−water nexus management.

2.2. High Spatial Resolution Sectoral Water Withdrawal Inventory. The provincial−sectoral water withdrawal inventory is an important input for the MRIO modeling. Water used by primary industry is mostly agricultural—crops, grassland, forestry, orchards, and fishing. Secondary industry's water use is concentrated in mining, manufacturing, electricity, and construction for production, cooling, etc. Tertiary industries use water to produce services, e.g., commerce, restaurants, posts, cargo transportation, and telecommunications.

To obtain more reliable accounting for provincial−sectoral water withdrawals, we compile a complete list of coal mining sites, refineries, and coking plants. We also develop two databases: the coal-fired electricity generation units (EGUs) database, which distinguishes units by capacity, combustion technology, and cooling system types and the hydropower plants database for China (as listed in 2017). We use a bottom-up approach to estimate the water withdrawals of each plant, namely, activity level (e.g., coal production, refining products, coking products, coal electricity, and hydropower) multiplied by the water withdrawal factors. For the remaining sectors, we estimate the water withdrawals at the provincial level for the MRIO modeling.

To estimate the scarce water inventory more accurately, we use the differentiated BWS in each catchment derived from Aqueduct, where in each catchment, the BWS of different grids has the same value, i.e., the BWS value of that catchment. The provincial−sectoral water uses are mapped at the grid level using the approach described in Zhang et al.[6] Specifically, agricultural water use is assigned at the grid level based on irrigated areas (at 5-arc-minute resolution). The water withdrawals of each coal mining site, oil refinery, coking plant, EGU, hydropower plant, and remaining industrial factories (more than 57,000 enterprises) are spatially matched with the catchments. The population density (at 30-arc-second resolution) is used to disaggregate the provincial water use into grids for tertiary sectors. Finally, the scarce water use at the plant or grid level is obtained and aggregated to the provincial or catchment level for energy demand-driven scarce water modeling.

2.3. Water Stress Induced by Energy Demand. To quantitatively understand the implications of freshwater use related to the energy sector, we calculate the water stress induced by energy demand. Two types of water stress have been proposed by scholars, namely, physical and holistic water scarcity. Physical water scarcity indicates water resource endowments, and one popular and basic indicator is the ratio of water usage to availability (withdrawal-to-availability (WTA) ratio). Scholars have further developed complicated measurements for the basic indices by incorporating variations in monthly or annual flows[42] or considering the impacts of socioeconomic drivers, such as population, on water demand.[43] Besides physical water shortage, water scarcity can be characterized by the capacity of societies to deal with different water scarcity levels, recognized as the holistic water scarcity matrix.[44] Indices such as the Water Poverty Index,[45] the Social Resource Water Stress/Scarcity Index,[46] and the Human Development Index (HDI)[47] have been proposed to describe holistic water scarcity levels.

Limited by data availability for these complicated indices, we follow the definition of BWS to calculate the water stress, that is, withdrawal-to-availability ratio ($\mathrm{WTA}_{\mathrm{En}}$) driven by energy demand, substituting total water withdrawals with total water withdrawals for energy demand ($\mathrm{WW}_{\mathrm{En}}$). The indicator, $\mathrm{WTA}_{\mathrm{En}}$, which reflects the magnitude of water withdrawals driven by energy demand compared to average available blue water in a catchment, can be obtained as follows

$$\mathrm{WTA}_{\mathrm{En}} = \mathrm{WW}_{\mathrm{En}}/\mathrm{mean(Ba)} \tag{4}$$

where mean(Ba) is the annual blue water supply mentioned above. $\mathrm{WW}_{\mathrm{En}}$ can be obtained by quantifying the production-side provincial−sectoral water withdrawals (defined in Section 2.1 above) and processing them at the catchment scale.[16,48] Referring to the Global Drainage Basin Database and information processed by Aqueduct, a total of 1117 catchments are identified within China, all of which belong to the 10 major river basins defined by the Chinese government.

2.4. Stress Mitigation Scenarios. To assess effective strategies for mitigating the stress on supply chains induced by energy demand, we follow the what-if framework to test a set of eight different mitigation options related to both energy and nonenergy sectors using the following scenario analysis (Table S1).

(1) Increase the water use efficiency of coal mining and washing activities to comply with the water intensity level of advanced technologies established by the National or Provincial Industrial Water Withdrawal Quota (Coal_EF). (2) Similar to Coal_EF, increase the water use efficiency of the oil refining and coking industry (Petro_EF). (3) Increase the

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

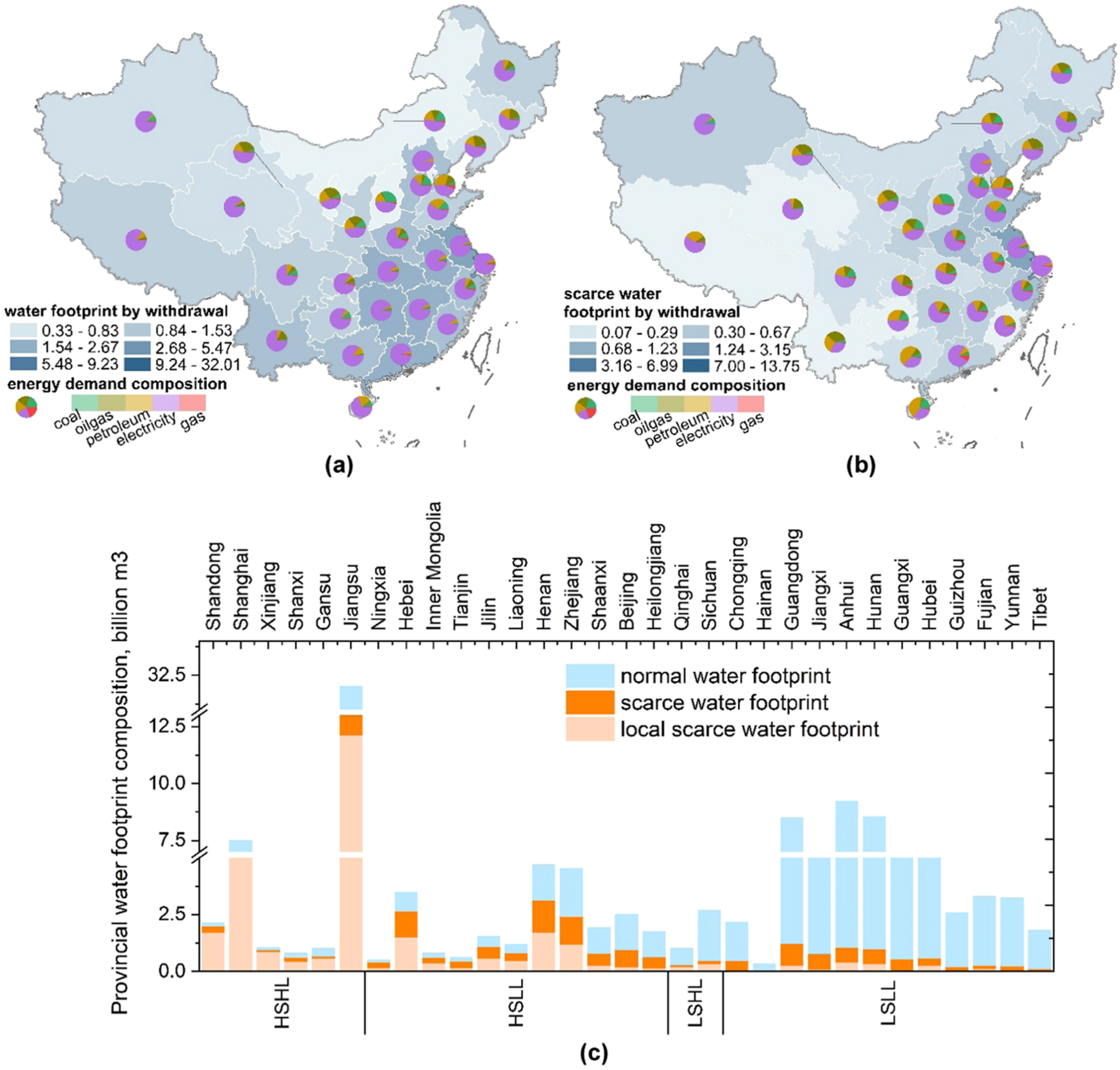


Figure 1. (a, b) Provincial water and scarce water footprints driven by different energy demands; (c) provincial water footprint sources driven by energy demand. Note: In panels (a) and (b), the color of each province indicates the magnitude of the provincial water or scarce water footprint driven by energy demand; the pie chart indicates the percentage of water or scarce water footprint of each energy demand. Coal: coal mining and washing sector; oilgas: oil and gas extraction sector; petroleum: petroleum processing, coking, and nuclear processing sector; electricity: electricity sector; gas: gas production sector. The provinces are listed in Figure S4. In panel (c), four categories of provinces are shown, i.e., a higher scarcity level than national average and high local contribution (HSHL), a higher scarcity level than national average and low local contribution (HSLL), a lower scarcity level than national average and high local contribution (LSHL), and a lower scarcity level than national average and low local contribution (LSLL). The province order is determined by the percentage of scarce water in the total water footprint in each category.

water use efficiency of two sectors, the oil and gas extraction industry and the gas production industry, to stay within national average levels (Oilgas_EF). (4) Increase the total efficiency of hydropower plants (up to 10%) (Hydro_EF). (5) For coal power plants, we consider four promising measures (CoalP_Multiple). One measure is to shut down the old, small, and less water-efficient coal power plants of less than 300 MW that have been operating for longer than 10 years.[49] Another measure is to increase the percentage of renewable electricity (wind and solar power) used in total provincial electricity to 30%, which is the threshold renewable power penetration rate needed to maintain power stability under the current grid network capability without additional balancing measures.[50] The final two measures are switching to seawater cooling for coal power plants within a zone of less than 100 km from the coastline, or replacing once-through or wet cooling systems with dry (air) cooling for coal plants located in dry regions (catchments under moderate stress, i.e., adjusted BWS > 0.2).[4] (6) Increase the agricultural water use efficiency to the national average level for those less efficient provinces (Agr_EF). (7) Increase the manufacturing sector water use efficiency to the national average level for those less efficient provinces (Manu_EF). (8) Reduce local electricity demand by improving the provincial power consumption efficiency (kWh/GDP) to the national average level through diversified demand-side measures for those less efficient provinces (Ele_Demd). (9) All options in a combined scenario. These eight options are assumed to occur in the year 2017 to directly assess the impacts on water stress induced by energy demand against the baseline data from that year. We create nine scenarios in which we model these eight options one by one. After comparing the results with the current situation of no options (i.e., base scenario), we can quantify the scarce water

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

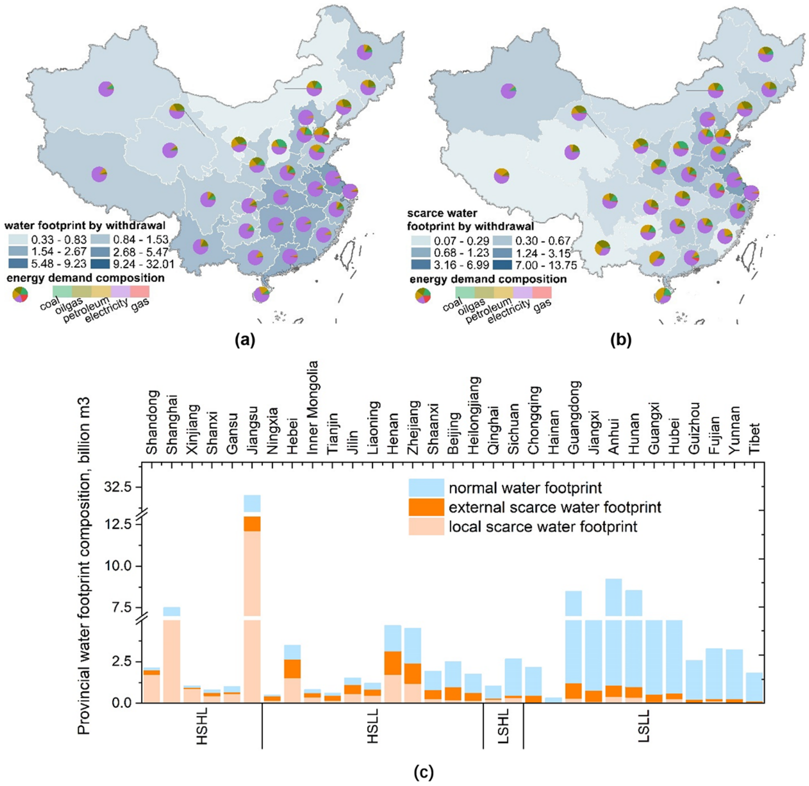


Figure 2. Net virtual (scarce) water transfer driven by energy demand among provinces. Note: There are two columns for each province, the left indicating scarce water and the right indicating normal water. Positive values indicate virtual water import, and negative values indicate virtual water export. The red dashed line indicates the region's scarce water transfer, while the green dashed line indicates the region's normal water transfer.

usage reduction and stress mitigation level of each option as well as of the combined options.

2.5. Data Sources. The 2017 MRIO table is taken from the Carbon Emission Accounts & Datasets (CEADs), including monetary transactions among 42 sectors across 27 provinces and 4 province-level municipalities.[51] As the table does not include data from Taiwan, Hong Kong, or Macau, we do not consider them in the following analysis. The MRIO table directly shows the following sectors: coal mining and washing; oil and gas extraction; petroleum processing, coking, and nuclear processing; and electricity generation and gas production sectors (Table S2).

This analysis focuses mainly on blue water withdrawals to estimate the interprovincial trade implications on provincial and national water usage to capture the impact of energy demand on local water resources and ecosystems, similar to existing studies.[52,53] Water withdrawal is mainly incorporated to reflect the reliance on and disturbance to the water, e.g., harm on thermal quality standards and potential reduction of short-term water availability,[3,54,55] enabling us to trace the contribution of energy demand to the water stress in a more integrated way. The sector aggregation water withdrawal values for the primary (agricultural), secondary (production), and tertiary (service) industries are mainly extracted from the Chinese Statistical Yearbook 2018[56] and the China Urban–Rural Construction Statistical Yearbook 2017.[57] Except for the energy sectors (coal, oil refining and coking, and electricity), we refer to sectoral water use percentage in the Chinese Economic Census Yearbook 2008[58] and the growth rate of sectoral total production output from 2008 to 2017 to breakdown the water use data in secondary industry in 2017.[59,60]

For the coal mining and washing sector and the oil refining and coking sector, the water withdrawal factors refer to the National or Provincial Industrial Water Withdrawals Quota Guidelines. The water withdrawal factors for coal-fired EGUs are derived from Zhang et al.[7] For hydropower, the water withdrawal factor indicates the evaporation and seepage from reservoirs, making this factor a function of the reservoir surface area, reference evaporation, reservoir electricity generation, and an allocation coefficient defined as the ratio of the annual revenue generated from hydroelectric power to the total annual revenue generated by the hydroelectric power plant.[61] Detailed data sources for the plant-level energy sector database compilation, the high spatial resolution water inventory, and water stress mitigation scenarios are presented in Sections S1.3 and S1.4.

3. RESULTS

3.1. Spatial Distribution of Energy Demand-Driven Scarce Freshwater Footprints. The national water footprint driven by all types of energy demands was 130.4 billion m^3 in 2017, 35.7% of which was scarce water. Overall, the energy-driven water footprint was close to the national total industrial water usage, accounting for 21.6% of the national water use. At the provincial scale, most provinces with large energy-driven water footprints were in South China. However, for the scarce water footprint, the rankings of those northern water-scarce provinces shifted upward. Hebei and Shandong Provinces ranked among the top 6 for scarce water footprints, at odds with their being 11th and 18th for freshwater footprints (Figure 1a,b). Meanwhile, the water-scarce coastal and northern provinces (e.g., Shandong, Shanghai, Xinjiang,

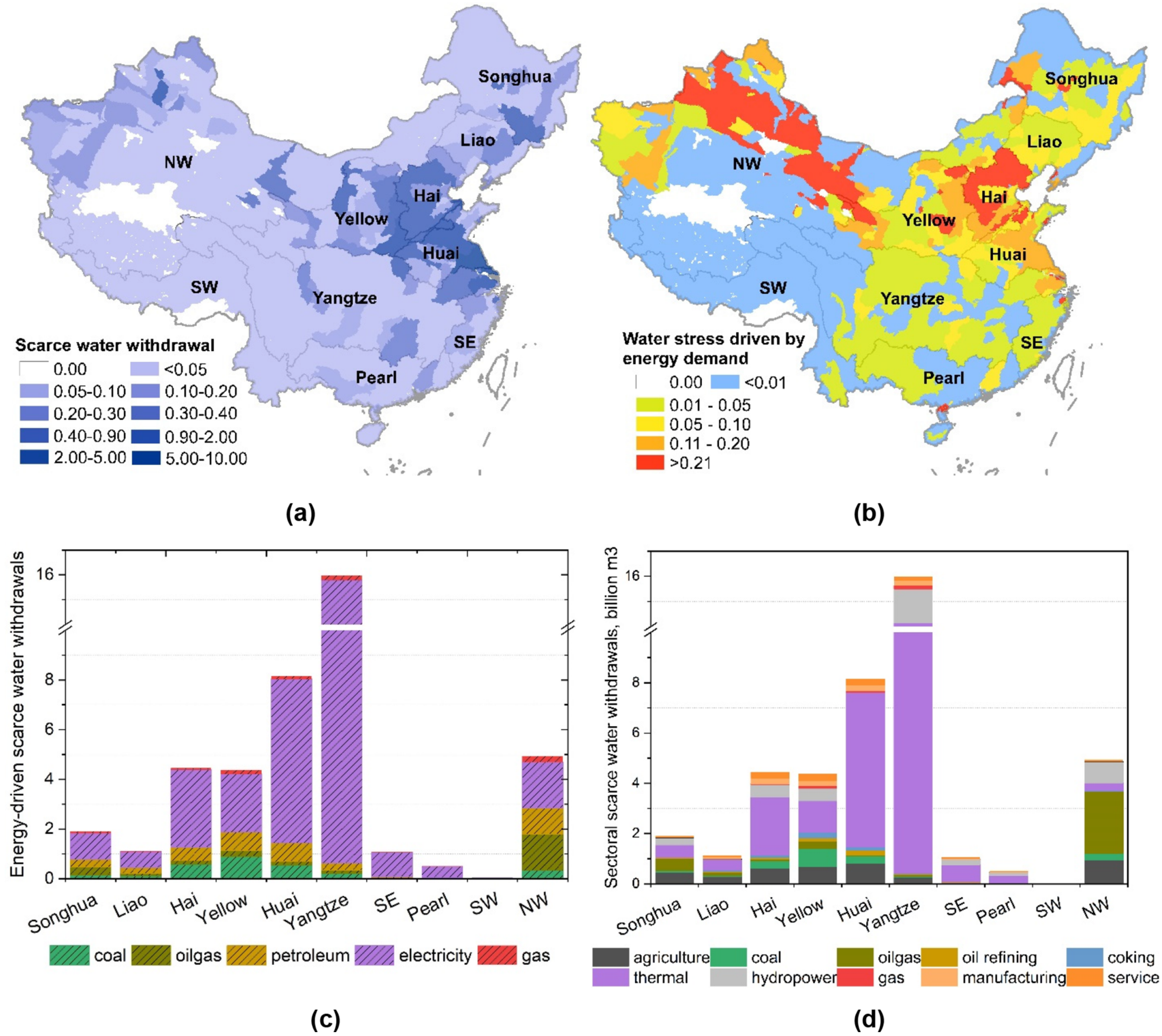


Figure 3. (a) Scarce water withdrawals induced by energy demand at the catchment level (billion m^3); (b) water stress (water withdrawal-to-availability ratio) induced by energy demand at the catchment level; (c) energy demand structure that induces scarce water withdrawals at the river basin level (billion m^3); (d) supply chain sectoral scarce water withdrawals driven by energy demand at the river basin level (billion m^3). Note: The 10 major Chinese river basins defined by the government include the Songhua River Basin (Songhua), Liao River Basin (Liao), Hai River Basin (Hai), Yellow River Basin (Yellow), Huai River Basin (Huai), Yangtze River Basin (Yangtze), Southeast Rivers (SE), Pearl River Basin (Pearl), Southwest Rivers (SW), and Northwest Rivers (NW). For water withdrawal-to-availability (WTA) ratio, the indicator categories are low (<0.1), low to medium (0.1−0.2), medium to high (0.2−0.4), high (0.4−0.8), and extremely high (>0.8). High-resolution spatial resolution of each energy and manufacturing plant's scarce water withdrawals are shown in Figure S6.

Ningxia, and Shanxi) ranked at the top with high percentages of scarce water in their total water footprints, 77−94.2% (Figure 1c). Our results indicate that energy demand in these provinces leads to this extensive scarce water usage, specifically the energy demand of production activities rather than household or government consumption.

Among the five types of energy demand, electricity demand dominated the total energy demand-driven scarce water and water footprint for the whole nation, accounting for 75.0% (84.5%) of the total national scarce water (total water) footprint associated with energy demand, followed by petroleum processing, coking, and nuclear processing (petroleum for short hereinafter) (10.0% (6.2%)), coal mining and washing (6.5% (4.0%)), oil and gas extraction (6.5% (3.9%)), and gas (2.0% (1.3%)). The electricity sector dominated water usage among all energy types because its cooling processes are much more water-intensive than the other energy sectors, about more than 5 times that of the other energy sectors at the national average level.[62] While electricity relied less on scarce water than other types of energy demand do (Figure 1a,b), its scarce water usage still accounted for 31.7% of the total water footprint for electricity, only slightly lower than the percentage for all energy types, 35.7%. All 31 provinces followed the electricity and petroleum-dominated pattern in their scarce water footprint composition, which together shared 60.1−98.5% of the provincial water footprint. A different composition was observed for large coal mining areas (e.g., Hebei, Shanxi, and Xinjiang) or oil and gas extraction areas (e.g., Liaoning, Jilin, Heilongjiang, Gansu, Qinghai, and Ningxia), in which coal or oil and gas extraction was the second main contributor driving the water footprint.

When the source of scarce water is distinguished between local and other provinces, some northern provinces, e.g., Hebei and Ningxia, were found to import from other provinces to meet energy demands in the HSLL category (higher scarcity level than national average and low local contribution), indicating the vulnerability of these northern provinces. When the energy demand in one province heavily relied on several other provinces' water resources, that province was particularly vulnerable to water scarcity in its supplier provinces. To evaluate the level of virtual scarce water imports, we calculated the Herfindahl Index (HHI) of each province (Section S1.5 and Figure S5). A high HHI indicated a high percentage of water imports in the form of scarce water from limited places and thus high vulnerability. For example, Ningxia received more than 42% of scarce water from Xinjiang, which can be explained by the high water intensity of electricity generation in Xinjiang (∼3 times the national average), as well as by the high water scarcity and large commodities outsourcing (electricity and oil refining products) from Xinjiang.

3.2. Scarce Water Transfer Networks. The virtual (scarce) water transfer networks in China were shaped by the interprovincial trade of electricity (42.6% of total virtual scarce water trade), petroleum (20.8%), oil and gas extraction (17.1%), and coal mining and washing (15.2%) with varied exporters and importers (Figure 2 and Section S2) and were mostly consistent with the energy transfer scheme, i.e., from the west or inland regions to the coastal regions. One exception was that the Southwest Region was found to be a scarce water importer rather than a water exporter, indicating the importance of taking provincial water scarcity into consideration to reveal the impacts on scarce water resources.

3.2.1. Water for Electricity Generation. The virtual water transfer in the electricity sector was consistent with China's West (Southwest and Northwest Region) to East (Central Region, North and South Coast Region) Electricity Project, while a slight difference was observed in virtual scarce transfer network. Interestingly, we found Jiangsu in the East Coast Region among the top five scarce water exporters, and Shanghai shifted from an importer to a scarce water exporter, which can be explained by the high levels of water scarcity in both provinces. In contrast, the less water-scarce Southwest Region imported scarce water to meet the domestic demand for energy. Virtual scarce water flows were embodied in different types of electricity based on the regional power structure, e.g., Northwest Region to North Coast (30.3% in thermal power; 69.7% in hydropower) and Southwest Region to North Coast (17.2% in thermal power; 82.8% in hydropower).

3.2.2. Water for Petroleum Processing, Coking, and Nuclear Processing. For the petroleum processing, coking, and nuclear processing sector, under the "North Oil to South" scheme, the Northwest Region, Yellow River Region, and Northeast Region were the major sources of virtual (scarce) water outflows. The Northwest Region exported virtual (scarce) water as high as 3 (4) times the regional (scarce) water footprint. Among these regions, Xinjiang, Shanxi, and Heilongjiang were the largest (scarce) water exporters, producing large quantities of oil products (8% of the total national production in monetary units) and sustaining the water-intensive oil refining industry or oil and gas extraction industry.

3.2.3. Water for Coal Mining and Washing. For the coal mining and washing sector, under the "North Coal to South" network in China, the large coal producers, the Yellow River Region and Northwest Region were highlighted for virtual scarce water outflows, 0.96 and 1.31 times the scarce water footprint. Shanxi, Inner Mongolia, Xinjiang, and Ningxia, producing 57% of national coal, were the top virtual (scarce) water exporters. It was interesting to see that the less water-scarce Southwest Region, as the coal supplier in the south and accounting for 6% of the national coal production in 2017, was a virtual water exporter but a scarce water importer; this shift was also observed for Yunnan and Guizhou.

3.2.4. Water for Oil and Gas Extraction. For the oil and gas extraction sector, the Northwest was the top region for exporting virtual (scarce) water, 2.5 (3.1) times the normal water (scarce water) footprint, followed by the Northeast Region. The East Coast Region was a large importer of virtual (scarce) water. We also found that the Yellow River Region shifted from a virtual water exporter to a scarce water importer as it imported goods and services from the highly water-scarce Northwest Region.

3.3. Spatial Distribution of Scarce Water Withdrawals Driven by Energy Demand. Catchments with large scarce water withdrawals for energy demand mainly located in northern China or the Yangtze River Basin (Figure 3a). The top five catchments with the largest scarce water withdrawals (>1.9 billion m^3) were in the lower reaches of the Yangtze River Basin, the northwestern part of the Northwest Rivers, and the northern part of the Huai River Basin, in total accounting for around half of the national scarce water withdrawals for energy demand. Additionally, catchments in the Yellow River Basin, Hai River Basin, and Songhua River Basin underwent considerable scarce water withdrawals (>0.5 billion m^3) for local or external energy demand. In comparison, the spatial distribution of water withdrawals for energy demand was significantly different from that of scarce water withdrawals. For example, catchments in the Yangtze River Basin and Pearl River Basin had the highest water withdrawals for energy demand (>2 billion m^3).

Catchments varied in sectoral scarce water usage patterns (Figure 3c,d) by attributing the whole water usage supply chain to five types of final energy demand, including that for intermediate use (e.g., processing materials, labor, energy, and others). Mainly driven by electricity demand, the scarce water usage in the Yangtze River Basin primarily occured in the sector itself (i.e., thermal power cooling water and hydropower water evaporation), sharing as high as 94% in the total energy demand-driven scarce water usage. A similar pattern was observed for the Southeast Rivers and Pearl River Basin. In contrast, for the Northwest Rivers, driven by demand for oil and gas extraction and oil refining and coking products, around half of the total scarce water usage took place in the oil and gas extraction sector. As one of the most important coal suppliers, the Yellow River Basin used 17% of the scarce water withdrawals for coal mining and washing activities. Notably, the water usage of the agricultural sector, as an indirect input for energy production in the whole supply chain, played a crucial role particularly in the Songhua River Basin (Songhua),

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

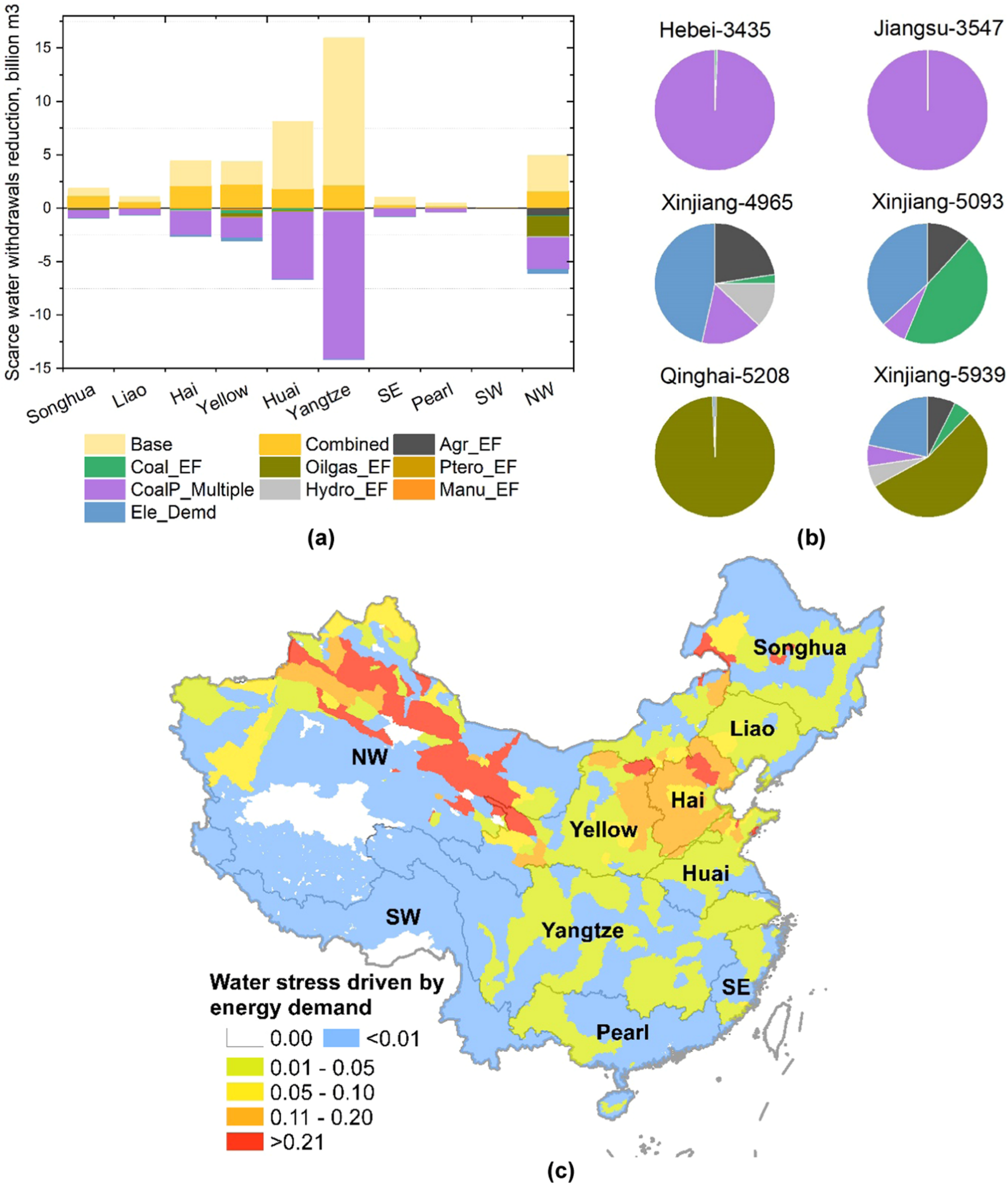


Figure 4. (a) Scarce water withdrawals in the base and combined scenarios and the reduction in each of the other eight scenarios; (b) the contribution of each option to the total scarce water withdrawal reduction in selected catchments; (c) water stress (WTA ratio) induced by the energy demand at the catchment level in the combined scenario. Note: Positive values in panel (a) indicate the absolute scarce water withdrawals in the base and combined scenarios. Negative values indicate the cumulative scarce water withdrawal reduction of each scenario compared with the base scenario. Scarce water reduction potential of electricity demand savings equals to the total reduction minus that of the production-side measures. Details for the selected catchments in panel (b) are in Figure S3. Panel (b) follows the same legend as panel (a).

Liao River Basin (Liao), and Northwest Rivers due to these regions' higher agricultural water intensity than other sectors.

3.4. Water Stress Induced by Energy Demand. We observed extremely uneven distribution for the contribution of energy demand to water stress (Figure 3b), which was notable in 62 catchments (totaling 1117 catchments), mainly located in three regions: (a) from the northern Hai River Basin to the eastern part of the Yellow River Basin and the Huai River Basin (coastal area of Shandong Province), (b) the northern area of the Northwest Rivers, and (c) the Yangtze River Delta and Pearl River Basin, particularly the developed coastal city clusters in eastern and southern China.

Both the Hai River Basin and Yellow River Basin were the most water-scarce areas in China, with water resources per person of less than 500 m^3/capita in Hebei and Shanxi Provinces (absolute water scarcity[63]). Despite this water scarcity, large coal reserves, coal mining sites, coking or oil refining plants, and coal power plants concentrated in this region, driven by the high energy demands due to high population density and economy development in North China. With different types of plants located in these catchments, they suffered from moderate to extremely high water stress induced by energy demand (>0.2). Similarly, the water stress induced by energy demand in the coastal city of Shandong Province reached up to 0.6, where oil refining products contributed to one-third of the stress.

For the Northwest Rivers, around 7% of the catchments (43 catchments), mainly in Xinjiang Province, were found to experience moderate or higher water stress (>0.2) induced by energy demand. The reason can be explained by the spatial mismatch between energy generation (or upstream sector production, e.g., agricultural production) and water availability. For instance, the two largest coal-based energy centers in Xinjiang Province were located in the water-scarce Hami District and Changji Hui Autonomous Prefecture, where one catchment occupied 10% of the provincial coal power capacity. Hydropower was also a crucial water user due to water evaporation, which contributed to 74% of the water stress in one catchment in the Tarim River.

The Yangtze River Delta and the coastal area of Guangdong Province in the Pear River Basin, mainly those developed coastal city clusters, were also hotspots with high water stress driven by large electricity or oil and coking products demands (>0.2). Large coal power and oil refining plants were located alongside the rivers, e.g., the Yangtze River and Pearl River, which used water-intensive once-through cooling technology for production. In general, water resources were abundant in South China, but the high water stress induced by energy demand still required further attention to avoid potential negative impacts, such as water pollution or unexpected water shortage consequences (e.g., energy supply risks).

In addition, the water stress in each catchment was driven by both local and external (i.e., in other provinces) energy demand, yielding distinct performance metrics in each catchment, even within the same basin or province (Figure S7). For the catchments with moderate to extremely high water stress in the Yellow River Basin, the contribution of external energy demand to water stress was above 60% (50% in the river basin). For most of the catchments in the Northwest Rivers, 40−95% of the water stress was attributed to the energy demand in other provinces. In contrast, for the Yangtze River Basin and Pearl River Basin, the contribution of external energy demand to water stress was much lower, <16% at the river basin level.

3.5. Stress Mitigation. We evaluated the impacts of eight possible water stress mitigation options (Figure 4), including water use efficiency improvement in the agricultural (Agr_EF), manufacturing (Manu_EF), coal mining and washing (Coal_EF), oil and gas extraction (Oilgas_EF), and oil refining and coking (Petro_EF) sectors; hydropower generation efficiency improvement (Hydro_EF); four measures to mitigate water usage in coal power plants (CoalP_Multiple); and electricity demand reduction (Ele_Demd) (see Section 2.2). Results showed when multiple-sectoral water-saving measures are adopted (combined scenario), through which the national scarce water withdrawals can be significantly cut down by 71.4%, from 42.4 to 12.2 billion m^3. The measures for coal power plants contributed to the greatest reduction by 56.9% compared with the national scarce water use in the base case, followed by oil and gas extraction (5.4%), coal mining and washing (1.9%), and agricultural (2.6%) water use efficiency improvement. Besides, the electricity demand reduction solely generated 4.4% of the national scarce water savings compared with the national total in the base scenario.

We applied these mitigation options to understand how energy demand-driven scarce water usage can be largely reduced in the Yangtze River Basin and North China. For the Yangtze River Basin, where water-intensive once-through cooling technology was popular in coal power plants, the greatest scarce water reduction by 13.8 billion m^3 would be possible mainly due to the shift from once-through freshwater cooling to seawater cooling for coastal coal-fired EGUs by 33 GW or to dry cooling in dry areas by 35 GW located in Jiangsu and Shanghai Provinces. In addition, the Yellow River Basin, Huai River Basin, Northwest Rivers, and Hai River Basin in North China can reduce total scarce water use for energy demand by 14.2 billion m^3. Notably, for the Yellow River Basin and Northwest Rivers, besides reforming the coal power sector, mitigating options in the coal mining and washing and oil and gas extraction activities would contribute to considerable scarce water reductions. Furthermore, the upstream sectors for energy generation presented mitigation potential for scarce water use along the whole supply chain, such as the agricultural sector in the less water-efficient Northwest Rivers (by 0.70 billion m^3) and the manufacturing sector in the Yangtze River Basin (by 0.10 billion m^3). It should be noted that reducing local electricity demand would help to reduce scarce water in other provinces, particularly in Northwest Rivers (by 0.64 billion m^3). For example, Xinjiang province in the Northwest Rivers saved 5% of its scarce water withdrawals due to reduced electricity demand in eastern parts, e.g., Hebei province.

Water stress induced by energy demand can be significantly mitigated by lessening water withdrawals from catchments. Water stress reduction ranged from less than 0.01 to as high as or larger than 1 according to Figure 4c, if all eight options were adopted. While nearly half (28 catchments) of the 62 catchments with moderate or high water stress induced by energy demand, mainly located in the Hai River Basin and Northwest Rivers, would shift to low or low to moderate stress. A similar performance was found for the catchments in the eastern and southern coastal city clusters, which could attain very low water stress after adopting these water-saving measures. In addition, Figure 4b shows that, for these hotspots, the contribution of each measure to the stress mitigation varied greatly due to different water use structures driven by energy demand.

4. DISCUSSION AND POLICY IMPLICATIONS

In this study, we investigate water use driven by energy demands in different energy sectors and the implications on water stress at the catchment level by combining a bottom-up water use estimation approach and a top-down MRIO approach. The methodology framework we develop facilitates our capturing of the whole energy demand-driven water usage supply chain, identifying hotspots of water stress, and quantifying the contribution of inter-regional trade (i.e., transboundary impacts) at high spatial resolution in a more comprehensive and reliable way, all of which can be applied to the study of the energy−water nexus in other countries. In addition, we examine the water stress mitigation potential of a set of options from the supply chain perspective, which enables derivation of practical and effective policies to alleviate water stress induced by energy demand for targeted areas.

4.1. Policy Implications. The study demonstrates that the water-scarce coastal and northern provinces, e.g., Jiangsu, Shanghai, Ningxia, and Shandong, were more vulnerable to water shortage due to the high percentages of scarce water in

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

their total water footprint. Notably, higher vulnerability was also observed for the nonelectricity energy sectors in some parts of provinces (e.g., Heilongjiang and Liaoning in northeastern China), with higher scarce water percentages than that of the electricity sector. The undesirable impacts of water availability on energy generation and demand have already been observed in China; for instance, hydropower plants were forced to reduce production because of restricted water resources in the dry summer of 2022 in Sichuan Province. Similarly, coal mining activities have been constrained by limited water availability in the Yellow River Region in North China.[64] Thus, we highlight that different adaptive measures are essential to ensure the energy demand security for different types of provinces. When a province relies on scarce water imports from other provinces, shifting the import to provinces with abundant water resources or to less water-intensive products (e.g., renewable electricity rather than thermal electricity) may be effective. Conversely, for provinces which rely on local scarce water (e.g., Jiangsu and Shanghai), water-efficient technology adoption and changing water sources to alternatives such as seawater or gray water would be potential ways to adapt to the water scarcity. Overall, the quantification of the local and external water scarcity by this study is important to strengthen energy security for China and its individual provinces, as addressed in Djehdian et al.[65] We suggest that addressing water resource usage and water scarcity is an essential aspect in the energy security evaluation framework to improve the resilience of a nation's capacity to meet its energy demand.

Nonelectricity energy sectors and cross-regional trade play important roles in aggravating the water stress induced by energy demand, while energy−water management at the catchment scale provides a suitable spatial unit. We identify hotspots in three areas (located in the Hai River Basin and Yellow River Basin, Northwest Rivers, and coastal city clusters) with moderate or high water stress induced by energy demand. For instance, besides coal power plants, large coal mining sites and oil refineries concentrated in Hebei and Shanxi Provinces (lower reaches of the Yellow River Basin) induce high water stress, of which more than 15 and 70% were by energy demand in other provinces. Similarly, in the Northwest Rivers, the coal mining and oil and gas extraction activities were major contributors to the region's high water stress, where as high as 90% of water stress arose from exporting to meet the energy demand in other provinces. Nevertheless, the Chinese government aims to build five new coal bases and coal chemical industry bases in the Yellow River Basin (e.g., Shanxi, Inner Mongolia, and Shaanxi) and Northwest Rivers (e.g., Xinjiang) to guarantee national coal, oil, and gas production supply in the 14th Five-Year Plan of Energy Development, indicating potentially high water stress in these catchments in the future. To mitigate this water stress, using water resources as constraints for energy planning in these hotspot catchments, known as the "red line" for water withdrawals, is one of the most urgent strategies,[66] as proposed by the Ecological Protection and High-quality Development of the Yellow River Basin. Besides local actions, cross-regional cooperation, e.g., ecological compensation between provinces within basins, is another crucial option for water resource conservation.[67] Based on our findings, we advocate incorporating into the energy−water policy framework with means of ecological compensation for water resources across provinces and even basins from the energy demand to the supply area, especially in these hotspot catchments.

Diversified and targeted options in both energy and nonenergy sectors are required to mitigate the water stress induced by energy demand. The water-saving options within coal power plants are the most efficient to reduce national scarce water usage. Switching to seawater cooling for coastal areas or dry cooling for dry inland areas would contribute to most of this scarce water use reduction, which is particularly crucial for the Yangtze River Basin and Hai River Basin. It is also interesting to see that those different options for water use efficiency improvement in the agricultural or oil and gas extraction sectors, as well as the external power demand reduction, are promising options for water stress mitigation in hotspots in Xinjiang Province. Specific measures for water saving in different energy sectors and the manufacturing sectors have been established by the government, e.g., Water Efficiency Guidelines for Key Industries,[68] and various tools to encourage industrial water use efficiency improvement should continue to be proposed. For instance, implementing a stricter water quota policy and differentiated water prices[69] in the Yellow River Basin, particularly in Shanxi and Inner Mongolia Provinces where water withdrawal standards for the coal mining industry are relatively loose, to encourage the water-saving measure adoption could be useful. Furthermore, many provinces, such as Hebei[70] and Jiangsu,[71] have established policies for electricity savings through a variety of means, such as increasing the penetration rate of energy-efficient appliances, energy-saving campaigns for industrial enterprises, electricity conservation behavior guidance for households, and real-time monitoring, among others. These efforts will have significant impacts on water savings in other provinces, such as Xinjiang.

Our findings further reveal that the promotion of local renewable energy with a penetration rate of 30% would generate moderate water stress mitigation potential under the existing provincial trade network. Renewable energy has been considered as a win−win option to alleviate water shortage as well as other environmental impacts,[72] but its wide deployment faces technological, political, and financial barriers. In particular, the spatial distribution of renewable energy resources and electricity consumption in China are not well aligned, so renewable electricity would have to rely on a long-distance transmission grid.[73] The technological bottlenecks include lags in the construction of transmission grids, limited storage capacity, and intermittent electricity production leading to cost increases to manage the instability of renewable electricity. Acknowledging the effort already being expended to deal with these disadvantages, we suggest including the critical role of alleviating local water scarcity in the renewable power deployment framework now under rapid expansion.

4.2. Comparisons between Results Based on Water Withdrawals and Consumption. In assessing the energy−water nexus, it is critical to distinguish water withdrawal and water consumption. Both indicators have been frequently evaluated for the energy sector previously.[7,74−77] Water withdrawal is a metric that is orders of magnitude greater than water consumption, particularly in the power industry, and it allows for the capturing of the impact to thermal quality requirements as well as the possible loss in short-term water availability.[3] Thermal pollution from the plants, in particular, may raise the temperature of the water, potentially causing power plant shutdowns or influencing other usage when the river temperature approaches environmental regulation thresh-

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

olds,[78,79] reducing water supply. Water withdrawal is considered as more appropriate as water restrictions in energy sector planning,[80] as well as reflecting water reliance in vulnerability assessment.[4,81] Water consumption, on the other hand, more directly reflects the influences on renewable water flows and availability. The use of the two metrics is contentious due to their disparate performance, notably in the coal power sector, and potential trade-offs have been highlighted, such as the fact that high water withdrawal does not always mean high water consumption.[26] Furthermore, the water withdrawal-to-availability (WTA) ratio has been frequently employed in analyzing water stress (or scarcity) caused by an individual sector,[82] including the energy industry.[6,7,83] The WTA ratio assesses competition and depletion of available water resources and is thus a suitable proxy for water risks, such as those imposed by water pollution.[84] The WTA ratio provides us with a broad picture of the water stress caused by energy production operations. However, researchers found that the WTA ratio overestimated physical water scarcity due to the inclusion of returned water.[85] As a result, the water consumption-to-availability (CTA) ratio was proposed and evaluated for the energy sector,[26] although it was critiqued for its unnecessarily low level of scarcity.[86]

We conducted comprehensive comparisons to analyze the differences between water withdrawals and consumption in the energy−water nexus quantification in our work for more integrated and comprehensive understandings (see details in Section S3). Despite the magnitude differences, the major findings are comparable. Southern provinces have the largest water footprint in terms of both withdrawals and consumption. The virtual water transfer network across provinces follows a similar pattern, and most provinces' trade balance directions have not changed, with the exception of Jiangsu, which has shifted from an exporter of water withdrawal to an importer of water consumption in the electricity sector. In terms of river basin water use, the Yangtze River Basin is the largest water user in terms of both water withdrawals and consumption for energy demand. Meanwhile, we have identified common hotspots of significant water stress in the Northwest Rivers, Yellow River Basin, and Hai River Basin. Those southern provinces, on the other hand, contributed less to the national consumptive water footprint as well as the national virtual water outflows. This is mostly due to the fact that coal power plants in the southern provinces were typically outfitted with once-through cooling systems, which have an extraordinarily high withdrawal factor but a low consumption factor.[7] Another distinction is that some Yellow River Basin, Pearl River Basin, and Yangtze River Basin catchments shift from medium to high water stress categories based on the WTA ratio to low or low to medium water stress categories based on the CTA ratio. However, the findings remind us that, if we solely consider the CTA ratio, we may overlook possible water stress and energy supply risks in these areas. As a result, we recommend that, where data is available, both water withdrawals and consumption be evaluated to fully understand the water use impacts of the energy system.

Limitations of the study lie in the high spatial resolution water use inventory development, such as sectorwise water use by a secondary sector, for which more reliable and timely reporting of water use data by enterprises is required. Another uncertainty lies in the stress mitigation option modeling, particularly for renewable power penetration. The impacts of water consumption of wind or solar power and their provincial cost curves to determine the recommended expansion rate on stress mitigation will need to be explored in a future study for more comprehensive and reliable understandings.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c08006.

Detailed methodology on multiregional input−output model, baseline water stress calculation, high spatial resolution sectoral water and scarce water use inventory compilation, Herfindahl Index calculation and data sources; further details on results, including breakdown of water footprints by flows for major scarce water exporters and comparisons between results based on water withdrawals and consumption; additional figures on modeling framework and results, including provincial Herfindahl Index, high-resolution spatial distribution of energy, and manufacturing sectors' scarce water withdrawals driven by energy demand, top scarce water flows, provincial consumptive (scarce) water footprints, scarce water consumption, and water stress at the catchment level; and additional tables on scenarios description, sectoral details in the multiregional input−output table, and provincial power mix (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Huibin Du − *College of Management and Economics, Tianjin University, Tianjin 300072, China; National Industry-Education Platform of Energy Storage, Tianjin University, Tianjin 300072, China;* orcid.org/0000-0001-9616-2407; Email: duhuibin@tju.edu.cn

Xin Zhang − *Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, Maryland 21532, United States*; Email: Xin.Zhang@umces.edu

Kuishuang Feng − *Department of Geographical Sciences, University of Maryland, College Park, Maryland 20742, United States;* orcid.org/0000-0001-5139-444X; Email: kfeng@umd.edu

Authors

Xi Liu − *Institute of Blue and Green Development, Shandong University, Weihai 264209, China; College of Management and Economics, Tianjin University, Tianjin 300072, China; Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, Maryland 21532, United States*

Xu Zhao − *Institute of Blue and Green Development, Shandong University, Weihai 264209, China;* orcid.org/0000-0002-7461-852X

Honglin Zhong − *Institute of Blue and Green Development, Shandong University, Weihai 264209, China; Academy of Plateau Science and Sustainability, Qinghai Normal University, Xining 810016, China*

Ning Zhang − *Institute of Blue and Green Development, Shandong University, Weihai 264209, China*

Zhenni Chen − *School of Economics and Finance, Xi'an Jiaotong University, Xi'an 710061, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.2c08006

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (Grant Nos. 71834004, 71673198, 72074138, 72204148, 72225013, 72074136, and 72174111), the Key Research & Development Project of Qinghai Province (2022-SF-173), the National Social Science Fund of China (No. 21ZDA065), and MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 21YJC630014). Views and ideas expressed herein are solely ours and not those of funding agencies.

■ REFERENCES

(1) World Energy Council. *Water for Energy*; World Energy Council, 2010; pp 1−51.

(2) International Energy Agency. *Water Energy Nexus, Excerpt from World Energy Outlook 2016*; International Energy Agency, 2016; pp 1−59.

(3) Behrens, P.; van Vliet, M. T. H.; Nanninga, T.; Walsh, B.; Rodrigues, J. F. D. Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nat. Energy* **2017**, *2*, No. 17114.

(4) van Vliet, M. T. H.; Wiberg, D.; Leduc, S.; Riahi, K. Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Change* **2016**, *6*, 375−380.

(5) van Vliet, M. T. H.; Yearsley, J. R.; Ludwig, F.; Vögele, S.; Lettenmaier, D. P.; Kabat, P. Vulnerability of US and European electricity supply to climate change. *Nat. Clim. Change* **2012**, *2*, 676−681.

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

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

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

(9) Gerbens-Leenes, W.; Hoekstra, A. Y.; van der Meer, T. H. The water footprint of bioenergy. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 10219−10223.

(10) Dubreuil, A.; Assoumou, E.; Bouckaert, S.; Selosse, S.; Maïzi, N. Water modeling in an energy optimization framework − The water-scarce middle east context. *Appl. Energy* **2013**, *101*, 268−279.

(11) Spang, E. S.; Moomaw, W.; Gallagher, K.; Kirshen, P.; Marks, D. The water consumption of energy production: an international comparison. *Environ. Res. Lett.* **2014**, *9*, No. 105002.

(12) Hejazi, M. I.; Voisin, N.; Liu, L.; Bramer, L. M.; Fortin, D. C.; Hathaway, J. E.; Huang, M.; Kyle, P.; Leung, L. R.; Li, H.-Y.; et al. 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. *Proc. Natl. Acad. Sci. U.S.A.* **2015**, *112*, 10635−10640.

(13) Cai, B.; Zhang, B.; Bi, J.; Zhang, W. Energy's thirst for water in China. *Environ. Sci. Technol.* **2014**, *48*, 11760−11768.

(14) Okadera, T.; Chontanawat, J.; Gheewala, S. H. Water footprint for energy production and supply in Thailand. *Energy* **2014**, *77*, 49−56.

(15) Fulton, J.; Cooley, H. The Water Footprint of California's Energy System, 1990-2012. *Environ. Sci. Technol.* **2015**, *49*, 3314−3321.

(16) Holland, R. A.; Scott, K. A.; Florke, M.; Brown, G.; Ewers, R. M.; Farmer, E.; Kapos, V.; Muggeridge, A.; Scharlemann, J. P. W.; Taylor, G.; Barrett, J.; Eigenbrod, F. Global impacts of energy demand on the freshwater resources of nations. *Proc. Natl. Acad. Sci. U.S.A.* **2015**, *112*, E6707−E6716.

(17) Wei, W.; Li, J.; Chen, B.; Wang, M.; Zhang, P.; Guan, D.; Meng, J.; Qian, H.; Cheng, Y.; Kang, C.; Feng, K.; Yang, Q.; Zhang, N.; Liang, X.; Xue, J. Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. *Nat. Sustainability* **2021**, *4*, 739−747.

(18) China Electricity Council Annual Country's Electricity Supply and Demand Situation Analysis of the Forecast Report, March 2015. http://www.cec.org.cn/guihuayutongji/gongxufenxi/dianligongxufenxi/2015-03-30/135847.html.

(19) Xin, L.; Feng, K. S.; Siu, Y. L.; Hubacek, K. Challenges faced when energy meets water: CO2 and water implications of power generation in inner Mongolia of China. *Renewable Sustainable Energy Rev.* **2015**, *45*, 419−430.

(20) Feng, K.; Hubacek, K.; Siu, Y. L.; Li, X. The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. *Renewable Sustainable Energy Rev.* **2014**, *39*, 342−355.

(21) Liao, X.; Hall, J. W.; Eyre, N. Water use in China's thermoelectric power sector. *Global Environ. Change* **2016**, *41*, 142−152.

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

(23) Zhu, X. J.; Guo, R. P.; Chen, B.; Zhang, J.; Hayat, T.; Alsaedi, A. Embodiment of virtual water of power generation in the electric power system in China. *Appl. Energy* **2015**, *151*, 345−354.

(24) Guo, R. P.; Zhu, X. J.; Chen, B.; Yue, Y. L. Ecological network analysis of the virtual water network within China's electric power system during 2007-2012. *Appl. Energy* **2016**, *168*, 110−121.

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

(26) Jin, Y.; Behrens, P.; Tukker, A.; Scherer, L. The energy-water nexus of China's interprovincial and seasonal electric power transmission. *Appl. Energy* **2021**, *286*, No. 116493.

(27) Zhang, C.; He, G.; Zhang, Q.; Liang, S.; Zipper, S. C.; Guo, R.; Zhao, X.; Zhong, L.; Wang, J. The evolution of virtual water flows in China's electricity transmission network and its driving forces. *J. Cleaner Prod.* **2020**, *242*, No. 118336.

(28) Fang, D. L.; Chen, B. Linkage analysis for water-carbon nexus in China. *Appl. Energy* **2018**, *225*, 682−695.

(29) Wang, S.; Cao, T.; Chen, B. Urban energy−water nexus based on modified input−output analysis. *Appl. Energy* **2017**, *196*, 208−217.

(30) Wang, S.; Liu, Y.; Chen, B. Multiregional input−output and ecological network analyses for regional energy−water nexus within China. *Appl. Energy* **2018**, *227*, 353−364.

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

(32) Liao, X.; Zhao, X.; Jiang, Y.; Liu, Y.; Yi, Y.; Tillotson, M. R. Water footprint of the energy sector in China's two megalopolises. *Ecol. Modell.* **2019**, *391*, 9−15.

(33) Zhang, C.; Anadon, L. D. Life cycle water use of energy production and its environmental impacts in China. *Environ. Sci. Technol.* **2013**, *47*, 14459−14467.

(34) Okadera, T.; Geng, Y.; Fujita, T.; Dong, H. J.; Liu, Z.; Yoshida, N.; Kanazawa, T. Evaluating the water footprint of the energy supply of Liaoning Province, China: A regional input-output analysis approach. *Energy Policy* **2015**, *78*, 148−157.

(35) Feng, K.; Hubacek, K.; Pfister, S.; Yu, Y.; Sun, L. Virtual scarce water in China. *Environ. Sci. Technol.* **2014**, *48*, 7704−7713.

(36) Li, H.; Liang, Y.; Chen, Q.; Liang, S.; Jetashree; Yang, Z. Pollution exacerbates interregional flows of virtual scarce water driven by energy demand in China. *Water Res.* **2022**, *223*, No. 118980.

(37) Liao, X.; Zhao, X.; Liu, W.; Li, R.; Wang, X.; Wang, W.; Tillotson, M. R. Comparing water footprint and water scarcity

footprint of energy demand in China's six megacities. *Appl. Energy* **2020**, *269*, No. 115137.
(38) Zhao, X.; Liao, X.; Zhang, C.; Zhang, X.; Mao, G.; Zhang, S.; Tillotson, M. R. Unveiling the dynamic of water-electricity conflict within and beyond megacity boundary. *J. Environ. Manage.* **2021**, *286*, No. 112259.
(39) Liu, X.; Du, H.; Zhang, Z.; Crittenden, J. C.; Lahr, M. L.; Moreno-Cruz, J.; Guan, D.; Mi, Z.; Zuo, J. Can virtual water trade save water resources? *Water Res.* **2019**, *163*, No. 114848.
(40) Gassert, F.; Luck, M.; Landis, M.; Reig, P.; Shiao, T. *Aqueduct Globa Maps 2.1-Constructing Decicion Relevant Global Water Risk Indicators*; World Resources Institute: Washington, DC, 2015.
(41) Su, B.; Ang, B. W. Input−output analysis of CO2 emissions embodied in trade: competitive versus non-competitive imports. *Energy Policy* **2013**, *56*, 83−87.
(42) Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater consumption in LCA. *Environ. Sci. Technol.* **2009**, *43*, 4098−4104.
(43) Asheesh, M. Allocating Gaps of Shared Water Resources (Scarcity Index) Case Study on Palestine-Israel. *Water Resources in the Middle East*; Springer: Heidelberg, 2007; pp 241−248.
(44) Damkjaer, S.; Taylor, R. The measurement of water scarcity: Defining a meaningful indicator. *Ambio* **2017**, *46*, 513−531.
(45) Lawrence, P. R.; Meigh, J.; Sullivan, C. *The Water Poverty Index: An International Comparison*, Economics Research Papers; Keele University, 2002.
(46) OhIsson, L. Water conflicts and social resource scarcity. *Phys. Chem. Earth, Part B: Hydrol, Oceans Atmos.* **2000**, *25*, 213−220.
(47) Zhang, Y. *China National Human Development Report 2013: Sustainable and Liveable Cities: Toward Ecological Civilization* UNDP: Beijing, China, 2013.
(48) Wang, R.; Zimmerman, J. Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world. *Environ. Sci. Technol.* **2016**, *50*, 5143−5153.
(49) Cui, R. Y.; Hultman, N.; Cui, D.; McJeon, H.; Yu, S.; Edwards, M. R.; Sen, A.; Song, K.; Bowman, C.; Clarke, L.; Kang, J.; Lou, J.; Yang, F.; Yuan, J.; Zhang, W.; Zhu, M. A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nat. Commun.* **2021**, *12*, No. 1468.
(50) Cao, Y.; Chen, J.; Liu, B.; Adair, T. *Decarbonizing the Electricity Sector: The Pathway to Carbon Neutrality*; Rocky Mountain Institute, 2021.
(51) Zheng, H.; Zhang, Z.; Wei, W.; Song, M.; Dietzenbacher, E.; Wang, X.; Meng, J.; Shan, Y.; Ou, J.; Guan, D. Regional determinants of China's consumption-based emissions in the economic transition. *Environ. Res. Lett.* **2020**, *15*, No. 074001.
(52) Dong, H.; Geng, Y.; Fujita, T.; Fujii, M.; Hao, D.; Yu, X. Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. *Sci. Total Environ.* **2014**, *500−501*, 120−130.
(53) Zhao, X.; Yang, H.; Yang, Z.; Chen, B.; Qin, Y. Applying the input-output method to account for water footprint and virtual water trade in the Haihe River basin in China. *Environ. Sci. Technol.* **2010**, *44*, 9150−9156.
(54) Raptis, C. E.; Boucher, J. M.; Pfister, S. Assessing the environmental impacts of freshwater thermal pollution from global power generation in LCA. *Sci. Total Environ.* **2017**, *580*, 1014−1026.
(55) Raptis, C. E.; van Vliet, M. T. H.; Pfister, S. Global thermal pollution of rivers from thermoelectric power plants. *Environ. Res. Lett.* **2016**, *11*, No. 104011.
(56) China National Bureau of Statistics. *China Statistical Yearbook*; China Statistics Press: Beijing, 2018.
(57) Ministry of Housing and Urban−Rural Development. *China Urban−Rural Construction Statistical Yearbook 2017*; China Planning Press: Beijing, 2017; pp 1−215.
(58) The State Council's Second National Economic Census Leading Group Office. *China Economic Census Yearbook 2008*; China Statistics Press: Beijing, 2010.
(59) Zhao, X.; Li, Y. P.; Yang, H.; Liu, W. F.; Tillotson, M. R.; Guan, D.; Yi, Y.; Wang, H. Measuring scarce water saving from interregional virtual water flows in China. *Environ. Res. Lett.* **2018**, *13*, No. 054012.
(60) Xin, M.; Wang, J.; Xing, Z. Decline of virtual water inequality in China's inter-provincial trade: An environmental economic trade-off analysis. *Sci. Total Environ.* **2022**, *806*, No. 150524.
(61) Liu, J.; Zhao, D.; Gerbens-Leenes, P. W.; Guan, D. China's rising hydropower demand challenges water sector. *Sci. Rep.* **2015**, *5*, No. 11446.
(62) Zhang, C.; Anadon, L. D. Life Cycle Water Use of Energy Production and Its Environmental Impacts in China. *Environ. Sci. Technol.* **2013**, *47*, 14459−14467.
(63) Rijsberman, F. R. Water scarcity: Fact or fiction? *Agric. Water Manage.* **2006**, *80*, 5−22.
(64) Shang, Y.; Lu, S.; Li, X.; Hei, P.; Lei, X.; Gong, J.; Liu, J.; Zhai, J.; Wang, H. Balancing development of major coal bases with available water resources in China through 2020. *Appl. Energy* **2017**, *194*, 735−750.
(65) Djehdian, L. A.; Chini, C. M.; Marston, L.; Konar, M.; Stillwell, A. S. Exposure of urban food−energy−water (FEW) systems to water scarcity. *Sustainable Cities Soc.* **2019**, *50*, No. 101621.
(66) Zhang, C.; He, G.; Johnston, J.; Zhong, L. Long-term transition of China's power sector under carbon neutrality target and water withdrawal constraint. *J. Cleaner Prod.* **2021**, *329*, No. 129765.
(67) Guan, D.; Wu, L.; Cheng, L.; Zhang, Y.; Zhou, L. How to measure the ecological compensation threshold in the upper Yangtze River basin, China? An approach for coupling InVEST and grey water footprint. *Front. Earth Sci.* **2022**, *10*, No. 988291.
(68) Ministry of Industry and Information Technology of P.R.C., Ministry of Water Resources of P.R.C. *The Catalogue of Encouraged Industrial Water-Saving Processes, Technologies and Equipment 2019*; Ministry of Industry and Information Technology of P.R.C., Ministry of Water Resources of P.R.C., 2019; pp 1−51.
(69) Wang, W.; Xie, H.; Zhang, N.; Xiang, D. Sustainable water use and water shadow price in China's urban industry. *Resour., Conserv. Recycl.* **2018**, *128*, 489−498.
(70) Hebei Development and Reform Commission. *Electricity Saving Proposal*; Hebei Development and Reform Commission, 2022.
(71) Industry and Information Technology Department of Jiangsu. *Notice on Special Action Plan for Electricity Saving and Ensuring Power Supply in Jiangsu Province*; Industry and Information Technology Department of Jiangsu, 2022.
(72) Peng, W.; Wagner, F.; Ramana, M. V.; Zhai, H.; Small, M. J.; Dalin, C.; Zhang, X.; Mauzerall, D. L. Managing China's coal power plants to address multiple environmental objectives. *Nat. Sustainability* **2018**, *1*, 693−701.
(73) Yang, J.; Li, X.; Peng, W.; Wagner, F.; Mauzerall, D. L. Climate, air quality and human health benefits of various solar photovoltaic deployment scenarios in China in 2030. *Environ. Res. Lett.* **2018**, *13*, No. 064002.
(74) Zhang, C.; Anadon, L. D. A multi-regional input−output analysis of domestic virtual water trade and provincial water footprint in China. *Ecol. Econ.* **2014**, *100*, 159−172.
(75) Qin, Y. Global competing water uses for food and energy. *Environ. Res. Lett.* **2021**, *16*, No. 064091.
(76) Chini, C. M.; Stillwell, A. S. The changing virtual water trade network of the European electric grid. *Appl. Energy* **2020**, *260*, No. 114151.
(77) Wang, Y.-D.; Lee, J. S.; Agbemabiese, L.; Zame, K.; Kang, S.-G. Virtual water management and the water−energy nexus: A case study of three Mid-Atlantic states. *Resour., Conserv. Recycl.* **2015**, *98*, 76−84.
(78) Miara, A.; Vörösmarty, C. J.; Stewart, R. J.; Wollheim, W. M.; Rosenzweig, B. Riverine ecosystem services and the thermoelectric sector: strategic issues facing the Northeastern United States. *Environ. Res. Lett.* **2013**, *8*, No. 025017.
(79) Förster, H.; Lilliestam, J. Modeling thermoelectric power generation in view of climate change. *Reg. Environ. Change* **2010**, *10*, 327−338.

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652

(80) Liu, L.; Hejazi, M.; Iyer, G.; Forman, B. A. Implications of water constraints on electricity capacity expansion in the United States. *Nat. Sustainability* **2019**, *2*, 206−213.
(81) Zheng, X.; Wang, C.; Cai, W.; Kummu, M.; Varis, O. The vulnerability of thermoelectric power generation to water scarcity in China: Current status and future scenarios for power planning and climate change. *Appl. Energy* **2016**, *171*, 444−455.
(82) Averyt, K.; Meldrum, J.; Caldwell, P.; Sun, G.; McNulty, S.; Huber-Lee, A.; Madden, N. Sectoral contributions to surface water stress in the coterminous United States. *Environ. Res. Lett.* **2013**, *8*, No. 035046.
(83) Li, H.; Cui, X.; Hui, J.; He, G.; Weng, Y.; Nie, Y.; Wang, C.; Cai, W. Catchment-level water stress risk of coal power transition in China under 2°C/1.5°C targets. *Appl. Energy* **2021**, *294*, No. 116986.
(84) Berger, M.; Finkbeiner, M. Methodological Challenges in Volumetric and Impact-Oriented Water Footprints. *J. Ind. Ecol.* **2013**, *17*, 79−89.
(85) Hoekstra, A. Y.; Mekonnen, M. M. *Global Water Scarcity: The Monthly Blue Water Footprint Compared to Blue Water Availability for the World's Major River Basins*; UNESCO-IHE Institute for Water Education: The Netherlands, 2011; pp 1−65.
(86) Liu, J.; Yang, H.; Gosling, S. N.; Kummu, M.; Florke, M.; Pfister, S.; Hanasaki, N.; Wada, Y.; Zhang, X.; Zheng, C.; Alcamo, J.; Oki, T. Water scarcity assessments in the past, present and future. *Earths Future* **2017**, *5*, 545−559.

https://doi.org/10.1021/acs.est.2c08006
Environ. Sci. Technol. 2023, 57, 9639−9652