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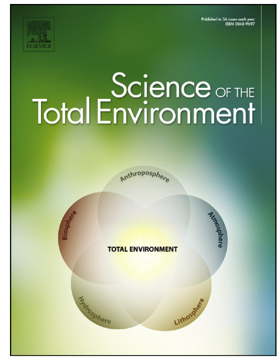

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Globalized energy-water nexus through international trade: the dominant role of non-energy commodities for worldwide energy-related water use

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Abstract

The increasing energy demand in future will inevitably escalate pressures on water resources, as energy production needs huge amounts of water inputs. Globalization has resulted in the geographic separation between the source of water inputs for energy production and the sink of its final consumption, making it crucial to factor global supply chain effect into water-energy nexus management. Therefore, this paper investigates water use for energy from source of exploitation to sink of final consumption along global supply chains based on embodiment accounting method. In total, the energy-related water use embodied in international trade is in magnitude about 80% of global total energy-related water use in 2011. It should be noted that non-energy commodities contribute more than four fifths of energy-related water use embodied in international trade and global final consumption. China serves the largest exporter of energy-related water use while EU28 is the biggest receiver. From a perspective of global supply chains, two thirds of USA' direct energy-related water use sinks into final consumption from rest of the world, and over a quarter of that embodied in Mainland China's final consumption is from USA, showing the tight relation between them on global supply chains. Findings highlight the urgent need to consider international trade (i.e., energy and non-energy commodity trade) and global supply chain effects for water-energy nexus policy-making to ensure the sustainable water supply for energy development.

Keywords: Globalization; Energy-water nexus; International trade; Global supply chains; Virtual water; Embodiment accounting

Introduction

A worldwide combination of formidable population growth, economic development and lifestyle change causes massive inputs of energy resources to human society. In 2017 alone, global primary energy consumption ascends to 13.5 billion tons oil equivalent, growing by 17% compared to that in 2007, while global electricity generation amounts to 25.5 PWh, increasing by 27% compared to that a decade before [1]. It is predicted that global energy demand will grow by a third until 2040 [2]. The rising demand not only amplifies pressures on energy resource but causes externality for other elements required for energy production, such as water resources [3]. Water is required for various stages of energy production, consisting of extraction [4, 5], processing and conversion [6, 7], as well as power generation [8, 9]. In 2010, global water withdrawal for energy production accounts for about 15% of total water withdrawal [10]. In the meantime, severe water crisis is threatening over 2 billion people, leading to a rising potential for water conflicts among energy sectors and other sectors (i.e., agriculture sector) [11]. Given that energy sector requires enormous water inputs [12], water constrains should be considered in energy management.

Some policies have already taken water-energy nexus issue into consideration. For instance, *the 13th Five-Year Plan for Water-Saving Society Construction* in China notes that new power plants in the Northwest and North China should give priority to the use of unconventional water sources and promote air-cooling technology [13]. Besides, In the United States, *Cooling Water Intakes — Final 2014 Rule for Existing Electric Generating Plants and Factories* under the Clean Water Act limits water use of existing power generating facilities that are designed to withdraw more than 2 million gallons per day of water and use at least 25% of the water they withdraw exclusively for cooling purposes [14]. European Parliament also established laws on water conservation for power plants and biofuels [15, 16]. However, in existing policy frameworks, energy-water nexus policies are largely trapped in sovereign territory.

It is noteworthy that globalization causes the separation of production and consumption, thus leading to the global redistribution of natural resources or emissions [17]. In the meantime, given that energy is used to produce goods and services, water exploited from environment for energy production therefore becomes the embodiment in goods and services within socio-economy. As energy-related water resources become a property inherent in goods and services, global economic system to some extent can be regarded as a network that redistributes energy-related water resources via international trade. Many previous works about water use embodied in international trade are mainly focused on water use for agricultural sector (i.e., accounting for roughly 70% of global water withdrawals [18]) or for all sectors [19-21], without a specific attention towards energy sector (i.e. representing some 15% of the world's total withdrawals [22]). In this context, some researchers discussed energy-related water use embodied in international trade, merely focusing on energy commodity trade [23-26]. For example, Zhang et al. investigates energy-related water flows embodied in international energy trade [26]. However, international energy commodity trade is insufficient to capture the impact of total international trade on redistributing energy-related water use, in that it neglects water embodied in energy inputs for non-energy commodities, which cover large amounts of products and services provided by non-energy sectors, such as agriculture, manufacturing, construction, public service, etc. Take iron and steel industry for example. As an energy-intensive industry, iron and steel industry consumes above 20% of total industrial energy use [27]. Around one fifth of iron and steel products is traded internationally, along with water resources embodied in the energy inputs to produce those products, and finally sinks into the world. Though water itself is not moved, enormous amounts of energy-related water as commodity embodiment can be transferred through global supply chains via inherent inter-sector connections. In this way, energy-related water use is not only embodied in energy commodities but non-energy commodities which take advantage of energy-related water in their supply chains. As highlighted by Franz et al., the interrelation of nexus and globalization should be understood thoroughly under global value chain and global production network [28]. Since previous studies failed to uncover the dominant role of non-energy commodities on sectoral and regional distribution of energy-related water use, a more comprehensive analysis on energy-related water use embodied in global supply chains as well as relevant policy suggestions is still needed for better management of water use for energy production.

Given all of the above, based on embodiment accounting method, this work aims to trace the energy-related water flows embodied in both energy commodities and non-energy commodities via global supply chain – from source of production to sink of final consumption in 2011. The dominant role of non-energy commodities for worldwide energy-related water use is firstly estimated. In fact, the non-energy commodities induce the majority of energy-related water, accounting for more than four fifths in international trade and almost all in global final consumption. To underpin this analysis, a high-resolution inventory of water use for energy (i.e. coal, oil, gas, petroleum and electricity) is compiled under a global unified framework. Besides, intermediate trade and final trade are estimated separately in this study, considering that trade in intermediate inputs takes approximately two thirds of international trade [29]. The remainder of this study is structured as follows: Section 2 reviews literatures for energy-related water embodied in trade, Section 3 introduces the method and data sources, Section 4 outlines the results, and Section 5 discusses the policy implications.

2 Literature review for energy-water nexus in trade

The growing tension between global water availability and increasing energy demand has inspired researches on interactions of water and energy resources. In this context, some studies on global energy-water nexus aimed to estimate current operational water use [30-32] or project future trend of water demand [33-35] for energy production. Besides on-site operational energy-related water use, many researches used life cycle assessment (LCA) to take account of water use in different stages of energy production [36]. Water requirement of various types of energy can thus be analyzed from cradle to grave or even cradle to cradle. Some LCA studies focused on water use for primary energy such as shale gas and conventional natural gas [37]. Others chose to estimate life cycle water use of biofuel [38, 39] and electricity [40-43], the latter covering thermal electricity (coal [44-46], gas [44, 47, 48], etc) and electricity generation by renewables [49, 50] (wind [51-53], solar [54], hydropower [55], biomass [56], etc). Although operational and life cycle energy-related water use estimations have been conducted in above-mentioned cases, the increasing geographic disconnection among exploitation, processing and consumption of commodities as well as relevant environmental impacts makes it necessary to understand the impact of trade on energy-water nexus.

There are a growing number of studies exploring the water-energy nexus by trade on various scales (e.g., provincial, national and international level), with emphasis on electricity trade. The majority of existing studies quantified interregional water flows embodied in energy trade within territory, mostly in China [57-60] and the USA [61-63]. For China, He et al. evaluated China's water transfer embodied in electricity trade among sub-grids based on various data sources [57]. What's more, a number of such studies have applied water stress indicators to energy-related water trade in order to quantify provincial water stress transfer [64-68]. Zhang et al. investigated the interprovincial electricity trade by evaluate the "positivity" and "negativity" of electricity trade based on the water scarcity indicator [64]. For the USA. Chini et al. analyzed the US's water flows in electric grid from 2010 to 2016 using plant-level water usage data [61].

Moreover, international trade has dramatically expanded in the past few decades, intensifying resource transfers between countries [21, 69, 70]. The implications of final consumption of products for water resources and human society can only be fully understood by incorporating the transfer of energy-related water through international trade. Some studies focused on one specific region's energy-related water imports and exports induced by international energy trade, such as China [23, 71], Spain [72], and Thailand [24]. For instance, Liu and Chen et al. evaluated global water use embodied in energy supply chains of China in a unified framework, including international energy trade [71]. Okadera et al. explored the impact on global water stress by Thailand's international energy trade [24]. In addition, very few studies have analyzed pressures on global water resources raised by international energy trade on a global perspective. Zhang et al. calculated global embodied water imports and exports embodied in international energy trade and gave different policy recommendations to different countries [26]. Holland et al. revealed water driven by global demand of three energy sectors (gas, petroleum and electricity) and associated water induced by international energy trade [25].

In general, current studies discussed water embodied in energy trade from various scales and presented a number of useful quantitative results. However, considering a great amount of energy used territorially to produce commodities for international trade, enormous energy-related water has been consequently embodied in non-energy commodities traded globally. Hence, this paper expands these existing studies by incorporating energy-related water driven by global non-energy commodity trade, providing the first comparison of energy-related water induced by international energy and non-energy commodities. A more complete picture is provided with energy-related water driven by different sectors and the global geographical flows of such water use. It should be noted that analyzing energy-related water driven by both energy and non-energy trade would provide critical policy implications on an integrated global governance of water and energy.

3 Method and Materials

3.1 Energy-related water use inventory

Following our previous study [71], the energy-related water use inventory is built by top-down method. In this paper, direct freshwater withdrawal of five energy sectors (i.e., coal, oil, gas, petroleum and electricity, with details in Table S4 in Supplementary 1) in 140 regions in 2011 is calculated by top-down method, which multiplies global activity data of five energy sectors by water intensity data. It covers the whole supply chain at a macro-perspective, yet lacking details in high-resolution energy products. In contrary, the bottom-up method can help to gain a detailed and accurate understanding of energy-related water use, though incomplete energy-related water data (i.e., failure to take the power plants all over the world into account) as well as huge amount of data sources and analysis work will lead to discrepancy. In this study, energy commodities are defined as commodities produced by five energy sectors (i.e., coal, oil, gas, petroleum and electricity), while non-energy commodities are defined as commodities produced by rest of the sectors. Details about the description of commodities can be found in Supplementary Table 3.

In summary, water use for renewable energy is not included in this study. Renewable energy mainly covers bioenergy (aka. biofuel and electricity generation by biomass) and electricity generation by hydro, wind, solar PV, and others. The reasons are as follows. As for bioenergy, specific sector for bioenergy cannot be distinguished from agricultural sectors in GTAP (Global Trade Analysis Project) database [73], and consequently the calculation of water for bioenergy cannot be conducted. As for hydropower, it is controversial to recognize how dams change surface water evaporation patterns thus consume water [74], and the lack of information at national level makes it hard to provide reliable estimates at global level. As for wind and solar PV, water used by wind and solar power for cleaning or panel washing is negligible [74, 75]. As for other uncommon renewables, the slight penetration and lacking data make them hard to be estimated [18]. Besides, this study focuses on water withdrawal, which means water resources removed from natural sources and used in human activity before returning to environment [76].

3.2 Embodiment accounting

Herendeen [77] et al. firstly established the framework of embodiment accounting by calculating the direct and indirect energy inputs to produce goods or services of the United States. Chen and his colleagues integrated the biophysical balance model by Herendeen [77] with the embodiment concept by Odum’s work [78-80], developing the embodied energy accounting to embodiment accounting on the basis of multi-regional input-output table. The embodiment accounting makes it possible to track environmental elements through global supply chain – from source of production to sink of final consumption, such as land [81, 82], energy [83-87] , water [19, 21, 71], mercury [88-92], carbon emissions [93, 94], etc. Then Wu et al. further developed it by taking account of resource use or emissions embodied in primary inputs, which is regarded as feedback from the society [20, 95]. It is noted that there exist various accounting methods based on input-output tables [96], such as final-demand-based accounting [97-99], production-based accounting [100], income-based accounting [101, 102], sales-based accounting [103], etc., of which demand-pull perspective that assign direct resource use or emissions to final demand is mostly used. Different from those normative accounting methods to assign environmental elements to different agents [98, 100, 102-105], embodiment accounting traces environmental elements rather than merely monetary flows within the global economic network, as if the environmental elements (i.e., energy-related water use) become a property inherent in them [20]. Besides, intermediate trade plays the dominant role (over two-thirds of trade volume) in global trade [29], whereas many works fail to distinguish environmental elements embodied in intermediate and final trade. Unlike previous works, the embodiment accounting based on input-output tables is able to pay equal attention to environmental elements embodied in trade of intermediate goods and services as well as final goods and services.

In embodiment accounting, the energy-related water flows into a sector can be divided in three parts: exogenous direct energy-related water inputs exploited from the environment; energy-related water use embodied in intermediate inputs; energy-related water use embodied in primary inputs. The sum of these three parts is equal to energy-related water use embodied in the sector’s total output. Regard the world economy as a m-region network, each region consisting of n sectors and k kinds of final demand. Thus, the biophysical balance equation of embodiment accounting can be illustrated as:

$$w_e^r + \varepsilon_p p_i^r + \sum_{s=1}^{m} \sum_{j=1}^{n} (\varepsilon_j^s z_{ji}^{sr}) = \varepsilon_i^r x_i^r \quad (1)$$

in which w_e^r is the direct water exploitation by five energy sectors (i.e., coal, oil, gas, petroleum and electricity) in Region r; p_i^r is the primary inputs from the society into Sector i in Region r; ε_p is the embodied intensity of primary inputs into economic sectors; ε_i^r is the embodied energy-related water intensity of goods or services generated by Sector i in Region r, ε_j^s is the embodied energy-related water intensity of goods or services generated by Sector j in Region s; x_i^r is the monetary value of total outputs by Sector i in Region r, comprising $\sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^{rs}$ (the monetary value of intermediate output from Sector i in Region r into Sector j in Region s), $\sum_{s=1}^{m} f_{iC}^{rs}$ (the monetary value of final output from Sector i in Region r into Sector s as final consumption) and $\sum_{s=1}^{m} f_{iO}^{rs}$ (the monetary value of final output from Sector i in Region r into Sector s as the remainder of final demand). Meanwhile, energy-related water embodied in primary inputs is equal to that embodied in rest of final demand to support economic activities [20, 95]. However, social accounting matrixes corresponding to global multi-regional input-output account is not available currently, leaving ε_p of each sector in each region unknown. So ε_p is simplified to be a scalar, for all the primary inputs are assumed to have the same embodied intensity. Then another biophysical balance equation can be formulated as:

$$\varepsilon_p \sum_{r=1}^{m} \sum_{i=1}^{n} p_i^r = \sum_{s=1}^{m} \sum_{r=1}^{m} \sum_{i=1}^{n} \varepsilon_i^r f_{iO}^{rs} \quad (2)$$

Therefore, the matrix form of Eq. (1) and (2) can be written as:

$$W + \varepsilon_p P + EZ = E\hat{X} \quad (3)$$

$$\varepsilon_p P_{sum} = \varepsilon F_O \quad (4)$$

Combining Equation (3) and (4) yields:

$$E = W(\hat{X} - Z - \frac{1}{P_{sum}} F_O P)^{-1} \quad (5)$$

The amount of energy-related water resources embodied in commodities or services hence can be calculated via multiplying the embodied water intensities by the monetary value flows of corresponding sectors. The energy-related water embodied in final consumption of Region r (*WEC*) can be formulated as:

$$WEC^r = \sum_{s=1}^{m} \sum_{j=1}^{n} \varepsilon_j^s f_{jC}^{sr} \quad (6)$$

In contrast to *WEC*, the total energy-related water exploited directly from the environment (*DW*) in Region r can be expressed as:

$$DW^r = \sum_{i=1}^{n} w_e^r \quad (7)$$

The energy-related water use embodied in international trade can be classified into energy-related water use embodied in intermediate trade and final trade. For Region r, the energy-related water embodied in intermediate imports (*WEII*) and energy-related water embodied in final imports (*WEFI*) can be calculated as:

$$WEII^r = \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \sum_{i=1}^{n} \varepsilon_j^s z_{ji}^{sr} \quad (8)$$

$$WEFI^r = \sum_{s=1(s\neq r)}^{m} \sum_{j=1}^{n} \varepsilon_j^s f_j^{sr} \quad (9)$$

In the meantime, for Region r, the energy-related water embodied in intermediate exports (*WEIE*) and energy-related water embodied in final exports

(*WEFE*) can be formulated as:

$$WEIE^r = \sum_{s=1(s\neq r)}^{m} \sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_i^r z_{ij}^{rs} \tag{10}$$

$$WEFE^r = \sum_{s=1(s\neq r)}^{m} \sum_{i=1}^{n} \varepsilon_i^r f_i^{rs} \tag{11}$$

Then the energy-related water embodied in intermediate trade balance (*WEIB*) and that embodied in final trade balance (*WEFB*) can be determined as:

$$WEIB^r = WEII^r - WEIE^r \tag{12}$$

$$WEFB^r = WEFI^r - WEFE^r \tag{13}$$

A region owning positive *WEIB* or *WEFB* possesses energy-related water surplus embodied in intermediate or final trade, whereas it possesses energy-related water deficit embodied in intermediate or final trade.

3.3 Data sources

The GTAP is selected as the data source of global multi-regional input-output table in this paper, which presents globally consistent data on consumption, production, and international trade of goods and services divided in 57 sectors of 140 regions [73]. Categories of sectors and regions are illustrated in Supplementary 1. Then, to compile the water inventory of energy-related water, the water intensity and activity energy production data are needed. Water intensity is defined as the ratio of the volume of water withdrawn from the environment to the unit of energy that is produced [74]. The electricity freshwater withdrawal data of few regions can be found in previous literatures [106, 107], while other regions' data should be calculated by the water intensity.

Following our previous study [71], global average water intensity data are used in Sector *Coal*, *Oil*, *Gas*, *Petroleum* and *Electricity*, because national water use data of energy sectors is mostly not available as many countries failed to collect these data, and current methods of data collection and reporting are imprecise and often fraught with omissions, errors and uncertainty [108]. Nevertheless, as the world's leading energy producers and consumers, the water intensities of Sector *Coal*, *Oil*, *Petroleum* and *Electricity* in the U.S. and China are calculated separately [10]. Details of water intensities for five energy sectors are in Supplementary 1. The activity data includes production data of 5 energy sectors in 140 regions. Energy production (coal, gas, oil) and oil refinery data is derived from IEA Sankey Diagram [109]. The electricity production data of each region is derived from the Food and Agriculture Organization of the United Nations [110].

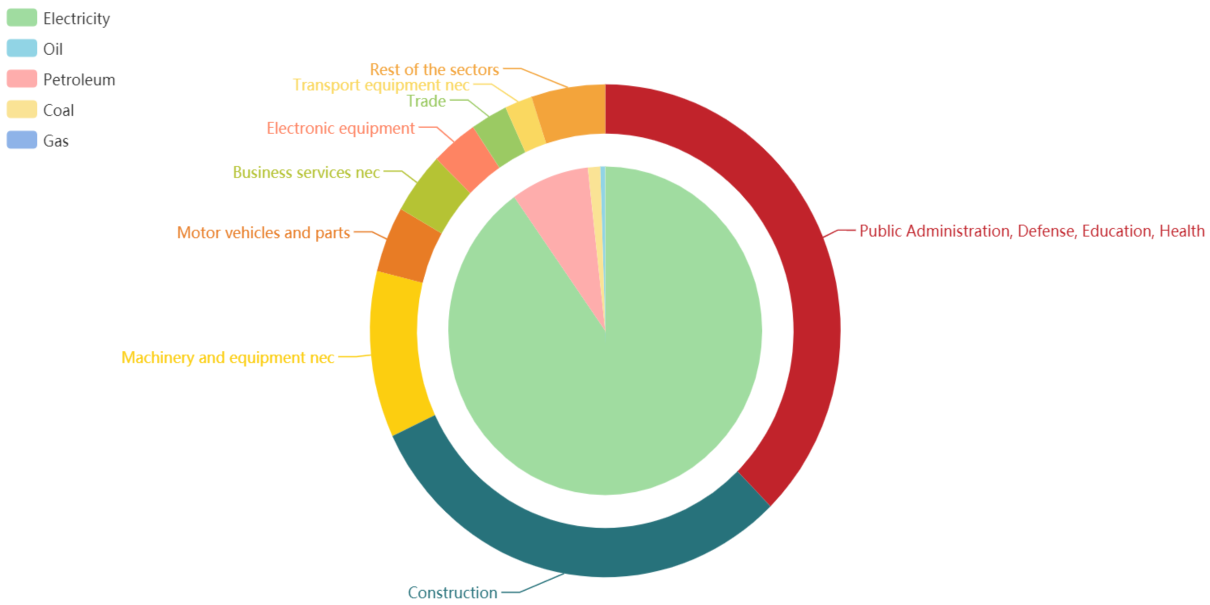


Figure 1. Global direct water withdrawal of energy sectors and its final consuming

sectors in 2011

4 Results

4.1 Energy-related water use at both ends of the global supply chains

Global freshwater withdrawal of energy sectors exploited directly from the environment amounts to 512 bcm in 2011. As shown in central circle from Figure 1, the *Electricity* sector ranks first in terms of direct energy-related water withdrawal with the volume of 461 bcm. The *Petroleum* sector is the second largest energy sector to extract water (41 bcm). The *Coal*, *Oil* and *Gas* sector take the last three positions, summing up to around 6, 3 and less than 1 bcm, respectively. As seen in the outer annulus, global water withdrawal of energy sectors is driven by final consumption of all kinds of sectors. Sector *Public Administration, Defense, Education, Health* accounts for 37.6% of total water use embodied in final consumption, followed by Sector *Construction* sharing 30.4%, Sector *Machinery and equipment nec* sharing 10.9%, Sector *Motor vehicles and parts* sharing 4.3%, and Sector *Business services nec* sharing 4.1%, etc. It shall arouse our attention that public service, construction and manufacturing industry, which are highly energy intensive thus energy-related water intensive, serve the dominant final consuming sectors of direct energy-related water withdrawal.

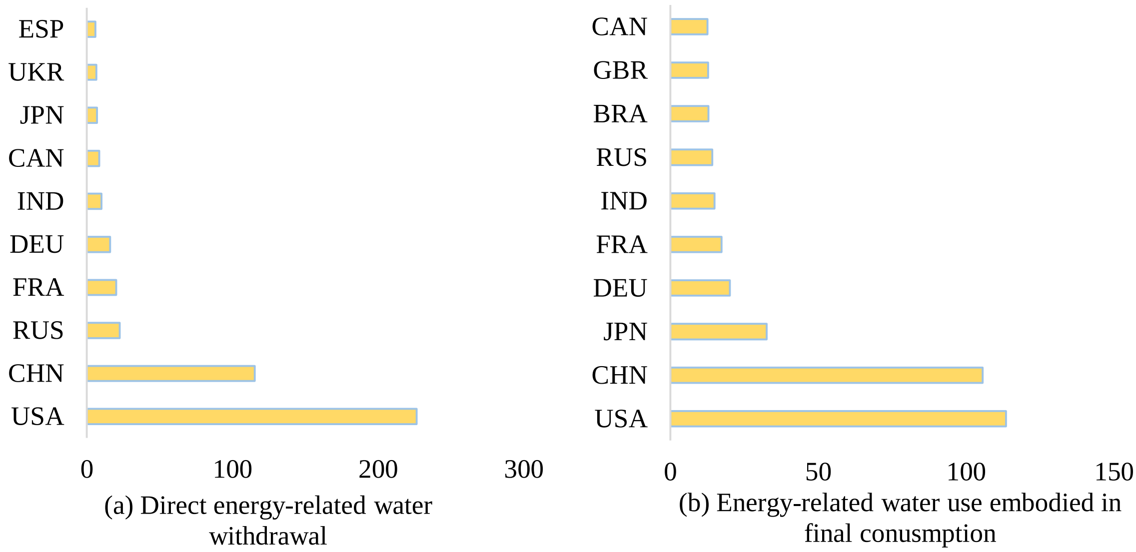
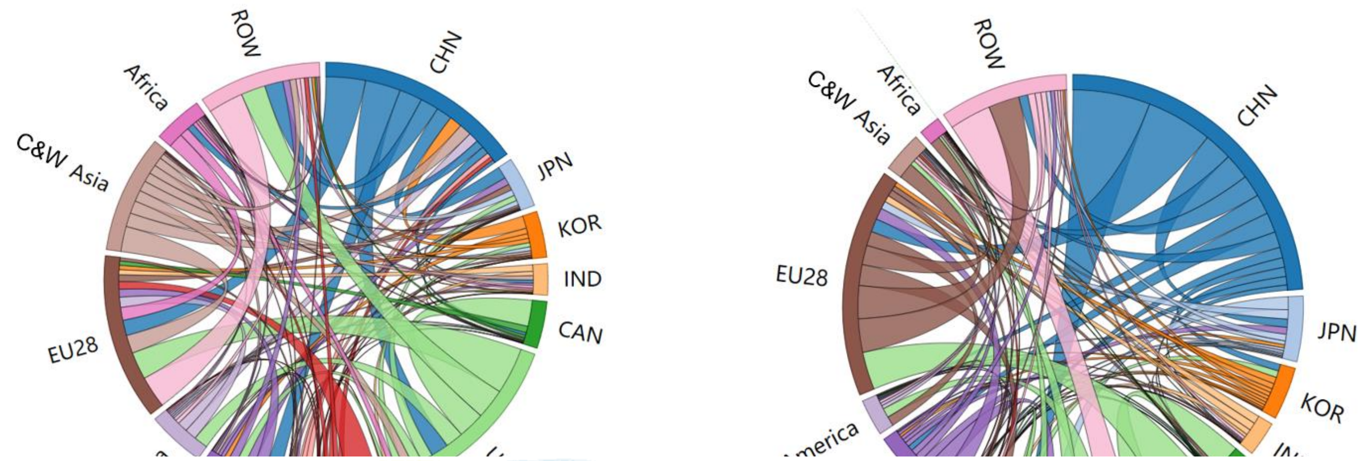


Figure 2. Direct water withdrawal of energy sectors and energy-related water embodied in final consumption of top 10 region. (unit: bcm)

Energy-related water withdrawal exploited directly from the environment and embodied in final consumption of top 10 regions is presented in Figure 2. In terms of energy-related water embodied in final consumption, the United States is the largest final consumer with an amount of 113.5 bcm. It represents that 113.5 bcm water withdrawal is exploited from the environmental system to sustain the consumption activities of households and governments in the United States. China (mainland) is the second largest final user with 105.6 bcm of water withdrawal extracted from the environment, followed by Japan with an amount of 32.6 bcm, Germany with 20.1

bcm, and France with 17.3 bcm. The top 5 final users drive respectively 22.2%, 20.7%, 6.4%, 3.9% and 3.4% of the global direct energy-related water withdrawal. In terms of water exploited directly from the environment, the United States and China still takes top two places, accounting for 226.4 bcm and 115.3 bcm. It is worth noting that the United States has a much lower water embodied in final consumption than that exploited directly from the environment. Russia ranks third in direct energy-related water withdrawal amounting to 22.6 bcm. France takes the fourth place while Germany drops to the fifth.



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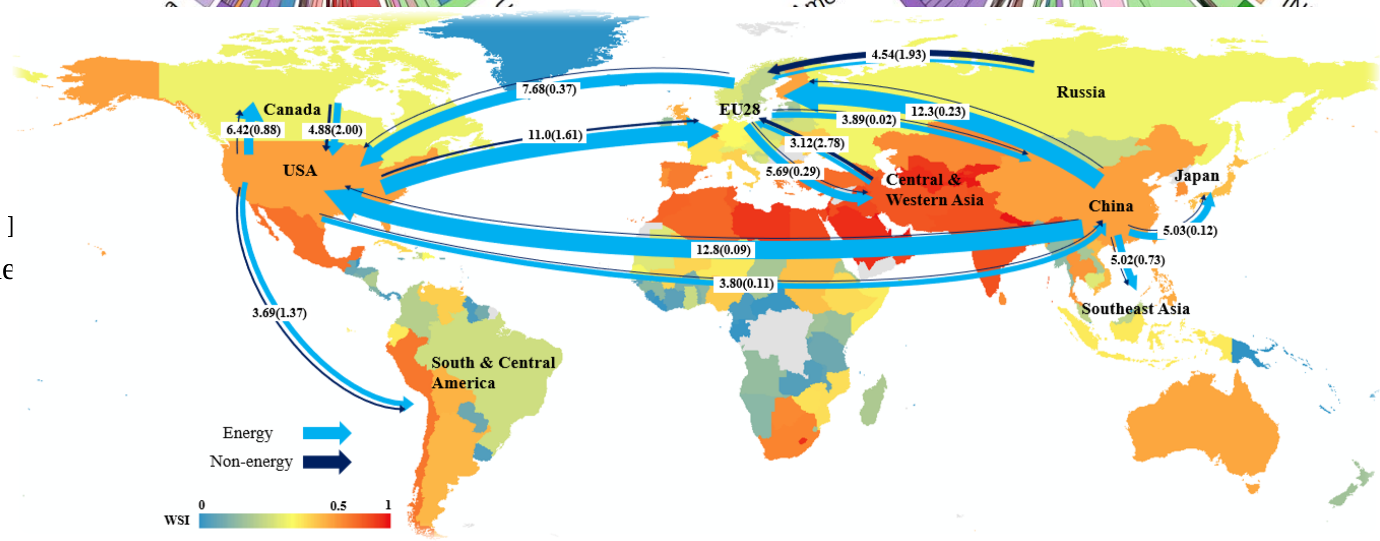


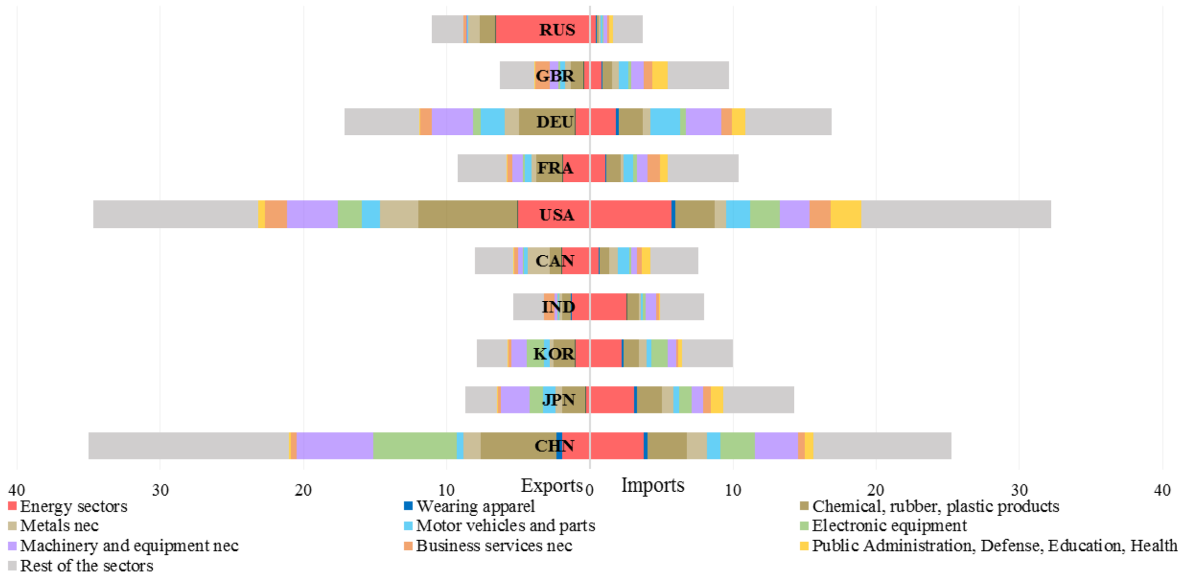
(c) Energy-related water use embodied in total international energy and non-energy trade

Figure 3. Intertwined relations of energy-related water use embodied in intermediate trade (a) and final trade (b) between the fourteen economies, and (c) major flows of energy-related water embodied in total international energy and non-energy trade (unit: bcm). (C&W Asia is Central & Western Asia, S&C America is South & Central America, WSI is water stress index derived from Pfister et al.'s study [111].)

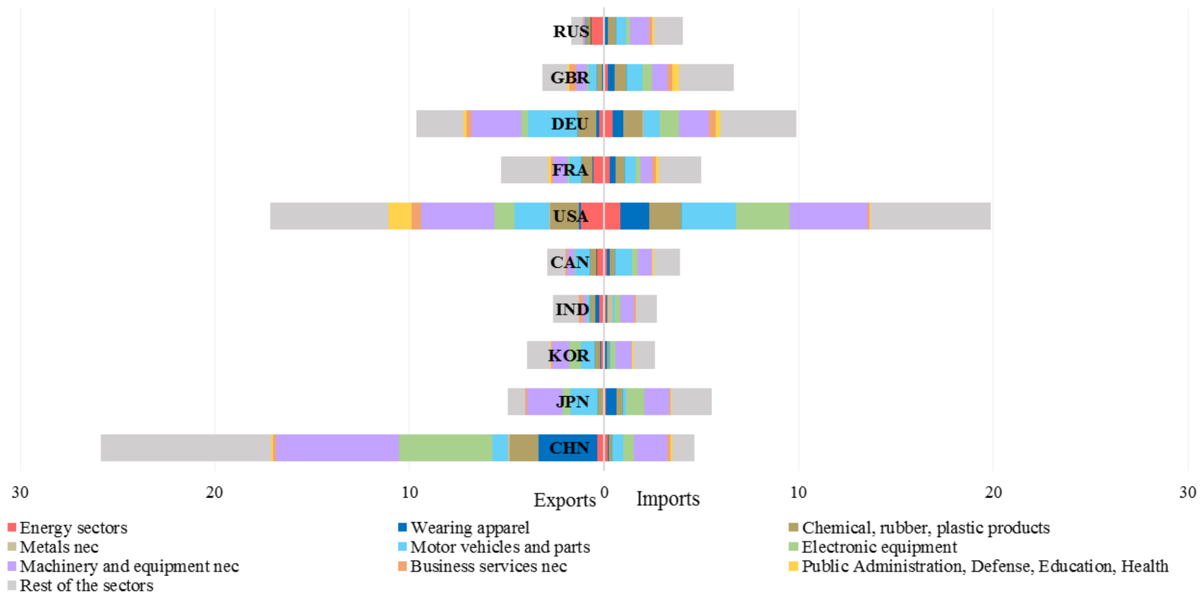
4.2 Energy-related water use embodied in international energy and non-energy trade

Figure 3 (a) presents the trade relationships of energy-related water embodied in intermediate trade between 14 regions. Supplementary 1 gives the details of region aggregation. As illustrated, China and the United States serve the largest exporters of energy-related water embodied in intermediate trade, EU28 is the biggest receiver. The largest flow of energy-related water is from the United States to EU28, amounting to 8.5 bcm. Within energy-related water embodied in the United States' intermediate exports (34.7 bcm), around a quarter is received by EU28, one-seventh to Canada, one-tenth to South & Central America, one-tenth to China, 6% to Japan, one-twentieth to Southeast Asia, etc. Meanwhile, within the China's intermediate exports (35.0 bcm), about one-fifth to EU28, 18% to the United States, 12% to Southeast Asia, 8% to Japan, 6% to Korea, etc. And among these 14 regions, Central & Western Asia comes as the third exporter for energy-related water embodied in intermediate trade. The three major destinations of Central & Western Asia's intermediate exports are the United States, EU28 and China, respectively sharing 26%, 22% and 19%. For the 44.0 bcm of energy-related water embodied in EU28's intermediate imports, about one-fifth of them are from the United States, 16% from China, 13% from Russia, one-tenth from Central & Western Asia, 6% from Africa, etc.

Figure 3 (b) demonstrates the relations of energy-related water use embodied in final trade of 14 regions, which differ from the intermediate trade relationships presented in Figure 3 (a). China still maintains the first place for energy-related water use embodied in final exports (25.8 bcm), with the United States, EU28 and Japan respectively receiving 24%, 21% and 9% of China's energy-related water outflows. For EU28, its energy-related water use embodied in final imports (19.5 bcm) is mainly from China, the United States, Southeast Asia and ROW, and its final exports (17.3 bcm) are mainly to the United States, the Central & Western Asia, Russia and ROW. With regards to the United States, its final imports (19.9 bcm) are majorly from China, EU28, Canada and ROW, while EU28, Canada and ROW are also major destinations of its final exports (17.1 bcm) of energy-related water. For Southeast Asia, its final imports (5.2 bcm) are mainly from China, EU28 and the United States, while EU28, the United States and Japan are main destinations of its energy-related water use embodied in final exports (6.7 bcm). Figure 3 (c) shows the major flows of energy-related water embodied in international energy and non-energy trade, including both intermediate and final trade. In total, the non-energy commodities induce the majority of energy-related water, accounting for more than four fifths in international trade. It is worth noting that as to specific trade flows, the energy-related water driven by energy trade is about one tenth or even lesser the volume of water driven by non-energy trade.



(a)



(b)

Figure 4. The sectoral contributions of energy-related water embodied in intermediate trade (a) and final trade (b) of the top traders (unit: bcm).

Sectoral contributions of major energy-related water flows embodied in intermediate and final trade are illustrated respectively in Figure 4. It should be noted that the non-energy trade induces the majority of energy-related water, accounting for more than four fifths of direct global water use for energy. As shown in Figure 4 (a), the United States ranks in the first place in intermediate imports of energy-related water. Within the 32.2 bcm of energy-related water embodied in the United States' intermediate imports, *Energy* products account for 5.7 bcm, followed by the *Chemical, rubber, plastic* products (2.7 bcm), etc. In common, for Mainland China, Japan, Korea, India and Germany, foreign *Energy* and *rubber, plastic* sectors also take big shares in their intermediate imports. Additionally, for Germany, the United States and Mainland China, foreign *Motor vehicles and parts* products, *Electronic equipment* and *Machinery and equipment nec* products also take major shares in intermediate imports. With regards to the intermediate exports, Mainland China takes the first place in energy-related water use embodied in exports. Within the 35.0 bcm energy-related water use of Mainland China's intermediate exports, Sector *Electronic equipment* account for 5.8 bcm, followed by Sector *Machinery and equipment nec* (5.4 bcm) and Sector *Chemical, rubber, plastic* (5.3 bcm). Sector *Chemical, rubber, plastic* and Sector *Machinery and equipment nec* also hold a big portion of energy-related water use embodied in intermediate exports for Japan, Korea, the United States, France, Germany and the United Kingdom. Besides, Sector *Energy* especially *Oil* holds a major portion in Russia's intermediate exports.

As presented in Figure 4 (b), energy-related water induced by energy commodity trade takes a much smaller proportion in final trade. While the United States, Germany and the United Kingdom are leading importers of energy-related water use embodied in final trade, China is illustrated as a leading exporter. For the United States, foreign Sector *Motor vehicles and parts* (2.8 bcm), Sector *Machinery and equipment nec* (4.0 bcm), Sector *Electronic equipment* (2.8 bcm), and Sector *Chemical, rubber, plastic* (1.7 bcm) dominate the energy-related water use embodied in its final imports (19.9 bcm). A similar situation is witnessed for Germany, the United Kingdom and France, while other countries' final imports are also dominated by some of the four sectors. Meanwhile, energy-related water use embodied in China's final exports (25.8 bcm) are mainly induced by the massive non-energy exporting of *Machinery and equipment nec* products (6.3 bcm), *Electronic equipment* products (4.8 bcm) and *Wearing apparel* products (4.0 bcm) to meet foreign final consumption. Exports of the United States and Germany are mainly due to the outflow of *Machinery and equipment nec* products, *Motor vehicles and parts* products and *Chemical, rubber, plastic* products.

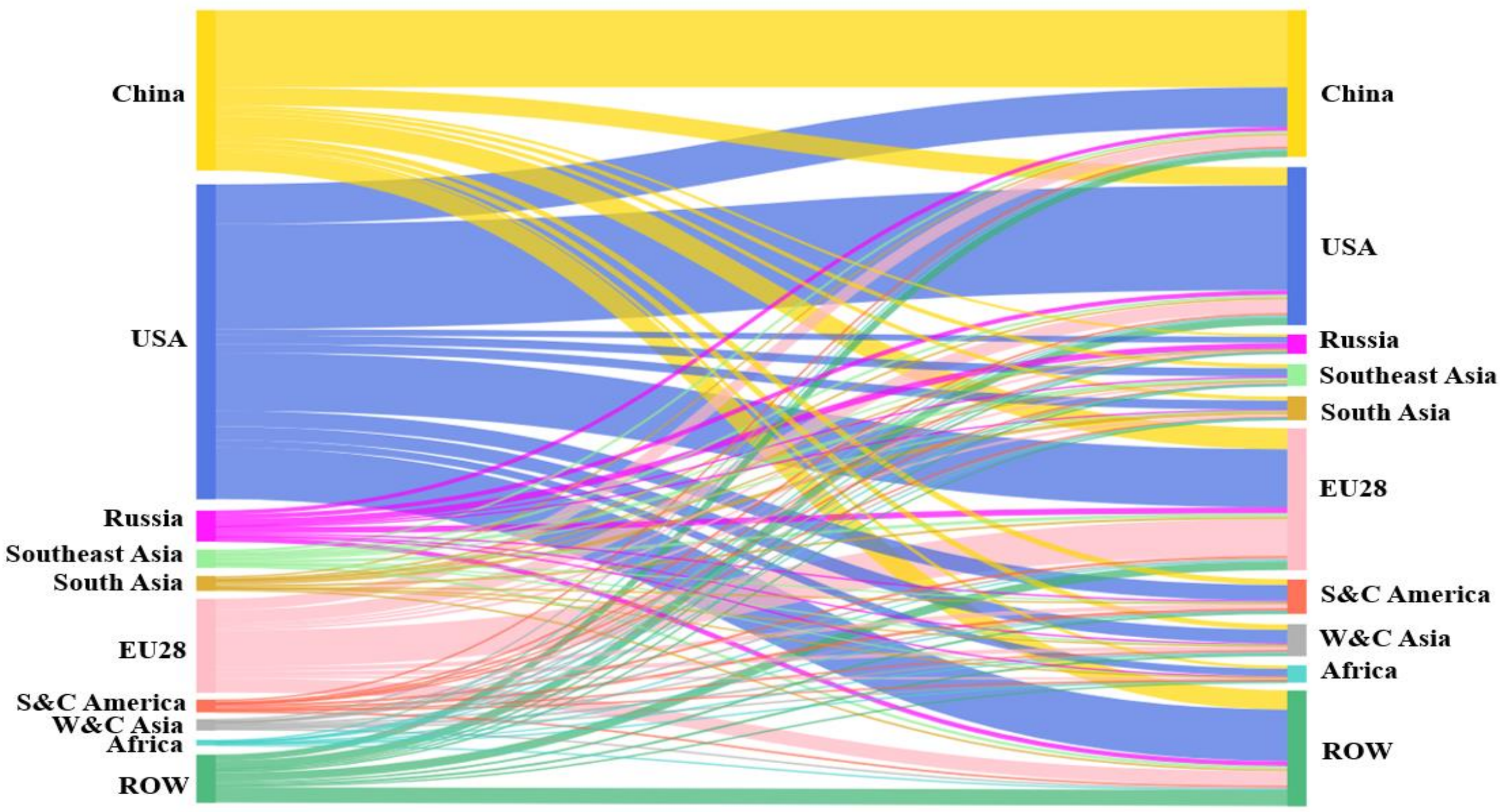
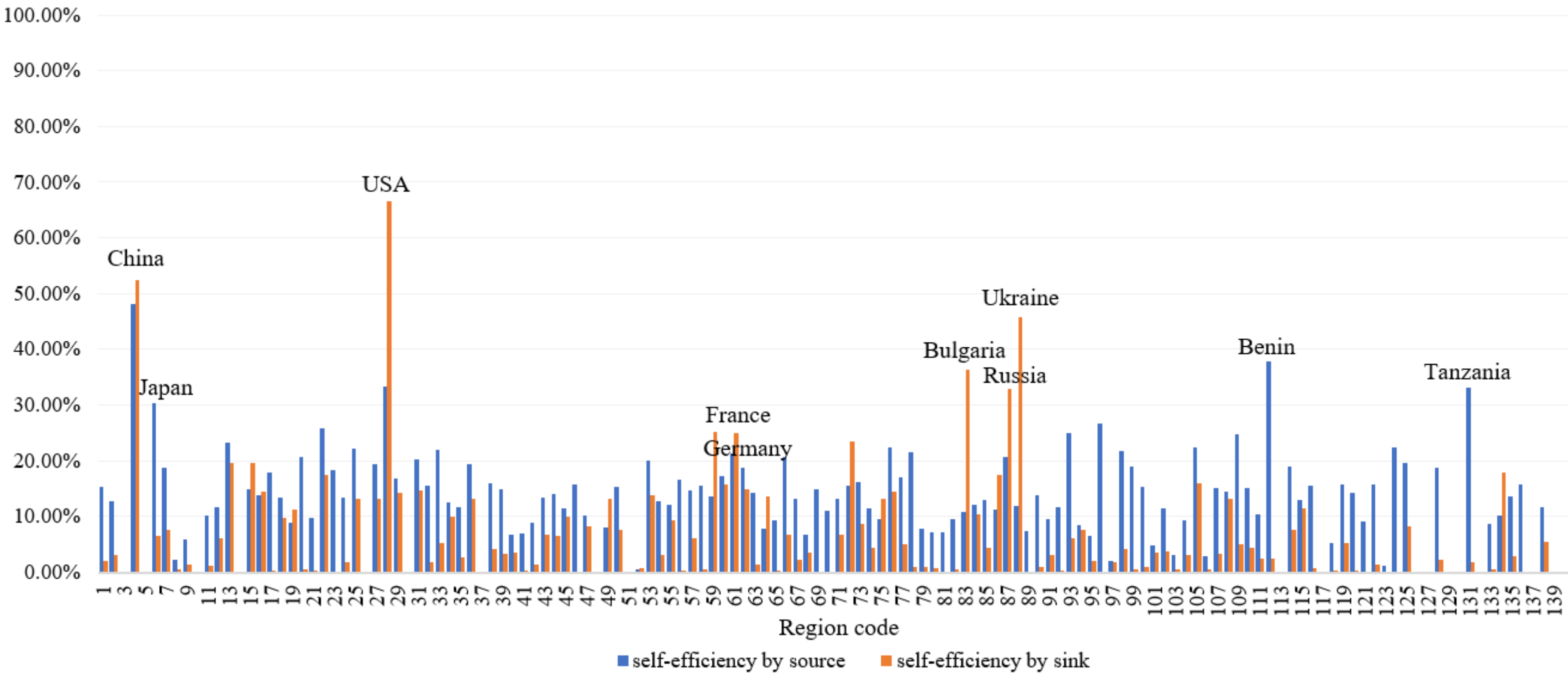


Figure 5. Source-sink relations of energy-related water use between major economies.



(C&W Asia is Central & Western Asia; S&C America is South & Central America)

Figure 6. Energy-related water use self-sufficiency rate by source and sink for each

region.

4.3 Source-to-sink budget for global energy-related water use

The source to sink budget of energy-related water use is depicted in Figure 5, in which the world is reorganized into 10 regions, with details in Supplementary 1. The energy-related water use self-sufficiency rate by source and that by sink for each region are illustrated in Figure 6. Two indicators in terms of energy-related water use self-sufficiency rate by source and that by sink are defined, following similar indices defined for arable land use study [95] and energy use study [83]. For a region in the world economy, energy-related water use self-efficiency by source is defined as the ratio of the energy-related water use extracted locally for its own final consumption to the total energy-related water extracted locally. Energy-related water use self-efficiency rate by sink of a region is defined as the energy-related water use extracted locally for its own final consumption to the region's energy-related water use embodied in total products and services used as its final consumption.

In total, 328 bcm energy-related water use in source regions are used to satisfy the final consumption of products/services of all sectors in foreign economies, accounting for 64% of global total energy-related water withdrawal in 2011. Specifically, the United States is the largest source of energy-related water use, 151 bcm of which is used to meet final consumption in regions outside the United States and 75 bcm of which is used for local final consumption. Its energy-related water use self-sufficiency rate by source and that by sink are 33.32% and 66.48%, respectively. This shows that from the supply side, about one third of the welfare provided by local energy-related water resources finally sinks into the products and services in domestic final consumption. Additionally, the energy-related water use self-sufficiency rate by sink indicates that around one third of the United States energy-related water use stems from the energy-related water resources extracted from other regions' environment. China and Russia are another two regions have more energy-related water as the source (115 bcm and 23 bcm) than that as the sink (106 bcm and 14 bcm). It merits to note that China's energy-related water use self-sufficiency rate by source and that by sink are respectively 48.06% and 52.46%. As seen, China keeps at home nearly half of the energy-related water resources, keeping the largest proportion of domestic energy-related water resources at home. Besides, about half of the energy-related water use embodied in China's final consumption originates from foreign regions. For sink regions of energy-related water use in the global supply chains, EU28 is the third largest sink region after the United States (113 bcm) and China (106 bcm). 102 bcm of energy-related water use is embodied in EU28’s final consumption, of which 26% is exploited in local environment, 41% is from the United States, 15% is from China, 4% is from Russia. What’s more, 18% of the United States’ energy-related water is used by EU28, making EU28 the dominate receiver of the United States’ energy-related water. Consequently, EU28 would suffer the biggest energy-water nexus loss if the United States cut down the relevant goods supply. For some African regions such as Benin and Tanzania, their energy-related water use self-sufficiency rates by source are respectively 37.94% and 33.17%, while those by sink are respectively 2.50% and 1.78%. As seen, African regions have high dependency on energy-related water derived from the world, which means if their trade is cut off, they would face big losses to meet domestic consumption. Most of the regions have a higher self-efficiency rate by source than that by sink, which leads to a conclusion that specific regions (i.e. China and the United States) offer most of the energy-related water use embodied in exported products to satisfy global consumption.

5 Discussions

5.1 Managing energy-related water use from production and consumption side

Sustainable water use for energy has become a significant issue for sustainable development [18], of which water and energy are two basic elements of the 17 interconnected Sustainable Development Goals (SDG) raised by United Nations. SDGs try to balance sustainable development's three vital dimensions: environmental, social and economic [112]. However, if addressing singly, one of the global problems that SDGs aim to deal with may be reduced somewhat at risk of exacerbating others [113]. In fact, there exist complex interlinkages (synergies and trade-offs) between SDGs. For example, the actions to achieve affordable and clean energy (SDG 7) would affect clean water and sanitation (SDG 6) within and between sectors [114], which is also known as energy-water nexus. To promote energy-water nexus planning and governance, some countries/regions start to take water-for-energy consideration into policy-making, mainly through adopting and promoting water-saving technologies in energy industry. In this study, embodiment accounting method takes account of the energy-related water transfer from source of exploitation to sink of consumption through global supply chains, making it possible to identify the critical producers and consumers. From the production side, power production is the largest water user, accounting for 90% of direct energy-related water withdrawal (see in Section 3.1). Thus, reducing the water intensity of power production it an effective way to reduce water use in energy production, which is also the focus of current water-energy policies. For example, China sets water-for-energy policies separately on norm of water intake, cooling technology choices and site selection of coal-fired power plants in view of local water endowment. Specifically, in China's 13th Five-Year Plan for Water-Saving Society Construction in 2017, water intensity of thermoelectric power generation is limited to about 1 kg/kWh. More water-for-energy policies around the world can be found in Supplementary 1. Given that traditional fossil fuels still hold a dominant position in power generation, renewable power is growing rapidly. To keep a balance, nations can resort to natural gas as a transition from fossil fuel to renewable power generation. Natural gas combined cycle (NGCC) becomes the alternative that can offer water benefits over other water-cooling facilities [115]. For instance, the United States, the largest natural gas producer and energy-related water user in the world, conducts the replacement of coal-fired by natural gas-fired generation in power sector [108, 115], which should be carried on to help with water resource conservation. Besides, it is predicted that 60% of electricity in 2030 will be generated by renewable sources, showing that renewable is the future trend of energy production [116]. Water intensities of some renewable power such as wind power and solar photovoltaics (PV) are negligible, for they are not based on rotating generators with heat engines which require water for cooling [117]. Regions with coastlines can further develop offshore wind power without land occupation. Except for power generation by PV, Solar desalination driven by PV is also a great alternative for regions suffering from water stress such as Middle East and North Africa [118]. In fact, nations should pay attention to energy adjustments to the existing power grid, storage capacity and other factors [64]. Overall, energy transition to water-saving renewables becomes a key solution from the production side.

Additionally, there are arguments that consumers should share responsibility with producers for international traded environmental impacts, in that every member along the supply chain is influenced by their source suppliers and affects their receivers [119]. Take EU28 as an instance, its direct energy-related water use accounts for 67.5 bcm whereas its energy-related water embodied in final consumption is 101.9 bcm. To address water for energy issues from the consumption side, environmental label raised by World Trade Organization may be a helpful choice. Those consumption-oriented nations can adopt environmental labels to provide environmental information (i.e., water intensity for consumed energy) of products from energy-intensive sectors, such as illustrated in Figure 1 (i.e., Sector *Public Administration, Defense, Education, Health,* Sector *Construction* and Sector *Machinery and equipment nec*). Besides, when considering water scarcity, India becomes the third largest direct energy-related water user and the fifth largest energy-related water consumer. Details about energy-related water use considering water stress index (WSI) can be found in Supplementary 1. Results with WSI pinpoint regions such as India should attach importance to local energy-related water use condition and set limit to water use for energy production and energy-related water embodied in trade outflows.

5.2 The significant role of non-energy commodities in managing energy-related water use

In fact, the non-energy commodities induce the majority of energy-related water, accounting for more than four fifths in international trade and almost all in global final consumption. Major flows of energy-related water embodied in international energy and non-energy trade are illustrated in Figure 3 (c), while the leading role of non-energy commodities in terms of global final consumption is shown in Figure 1. It is clear that with regard to specific trade flows, the energy-related water driven by energy trade is about one tenth or even lesser the volume of water driven by non-energy trade. Besides, energy-related water mainly sinks in final consumption of Sector *Public Administration, Defense, Education, Health,* Sector *Construction*, and Sector *Machinery and equipment nec*, whereas energy-related water use sinking in final consumption of energy sectors is nearly negligible. Previous studies on merely energy-related water embodied in energy commodities underestimated the scale of energy-related water induced by non-energy commodities. With trade and demand of non-energy commodities increasing over time, being highly responsive to relevant energy-related water use, it is significant to consider these water concerns in policy-making.

For instance, EU28, who receives enormous energy-related water by international non-energy commodity trade, should integrate the impacts of energy-related water stress transferred along global supply chains into its trade policies, such as the Sustainability Impact Assessment (SIA). SIA is obliged to provide analysis of potential environmental impacts of ongoing trade negotiations, as a trade-specific tool for supporting EU's major trade negotiations [120]. SIA should take energy-related water driven by both energy and non-energy commodity trade into analysis, especially when holding negotiations with major energy-related water exporters such as China and the United States. In a global perspective, energy-related water driven by both energy and non-energy commodity trade should be introduced into environmental assessments of WTO, at least be raised and discussed at Regular Trade and Environment Committee [121]. Meanwhile, policies from demand side should include attention to specific non-energy sectors that induce large amounts of energy-related water, as shown in Figure 1. Improving energy efficiency in identified non-energy sectors is an effective way to save corresponding energy-related water use.

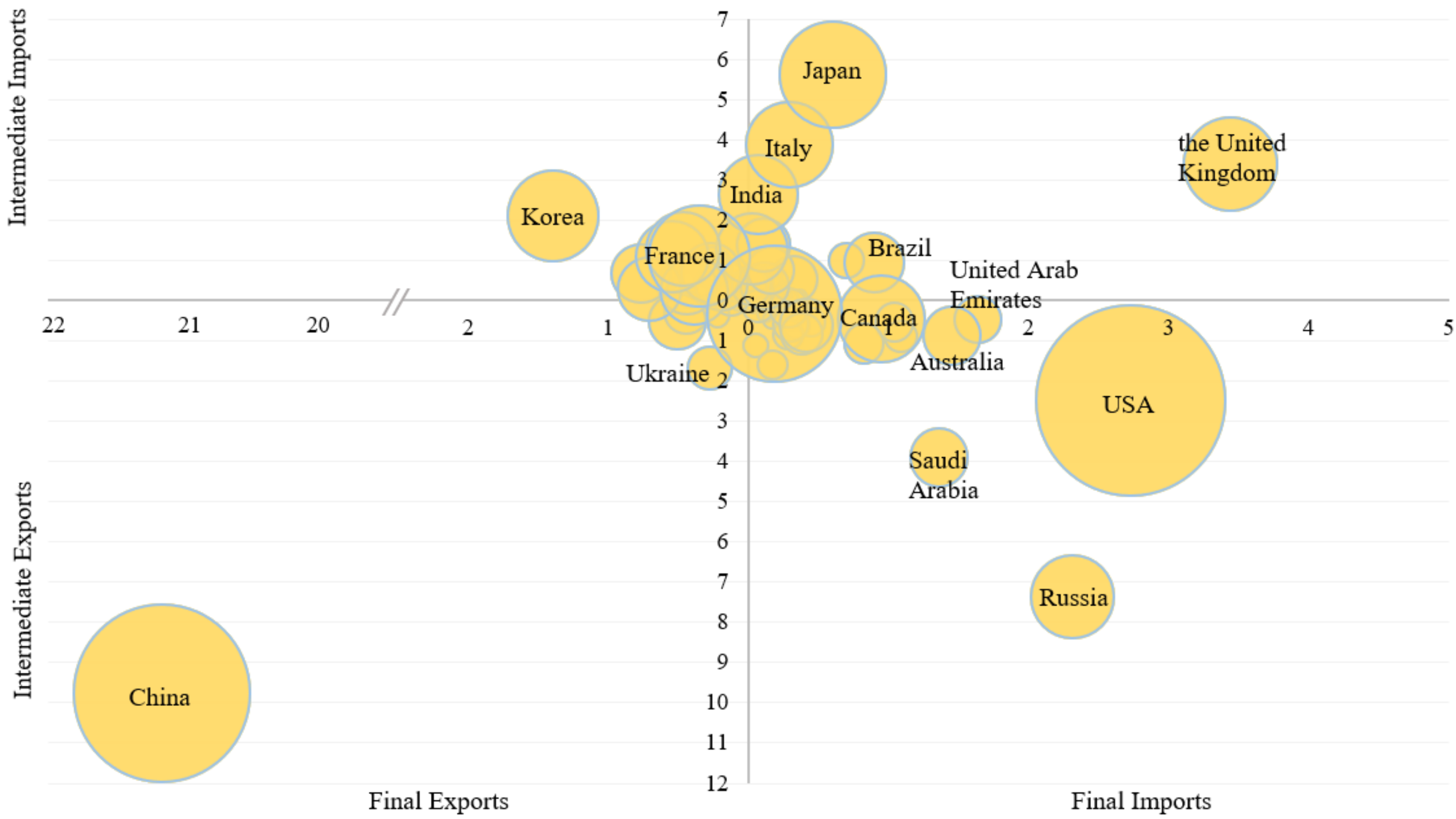


Figure 7. Trade imbalances of energy-related water use for regions (unit: bcm).

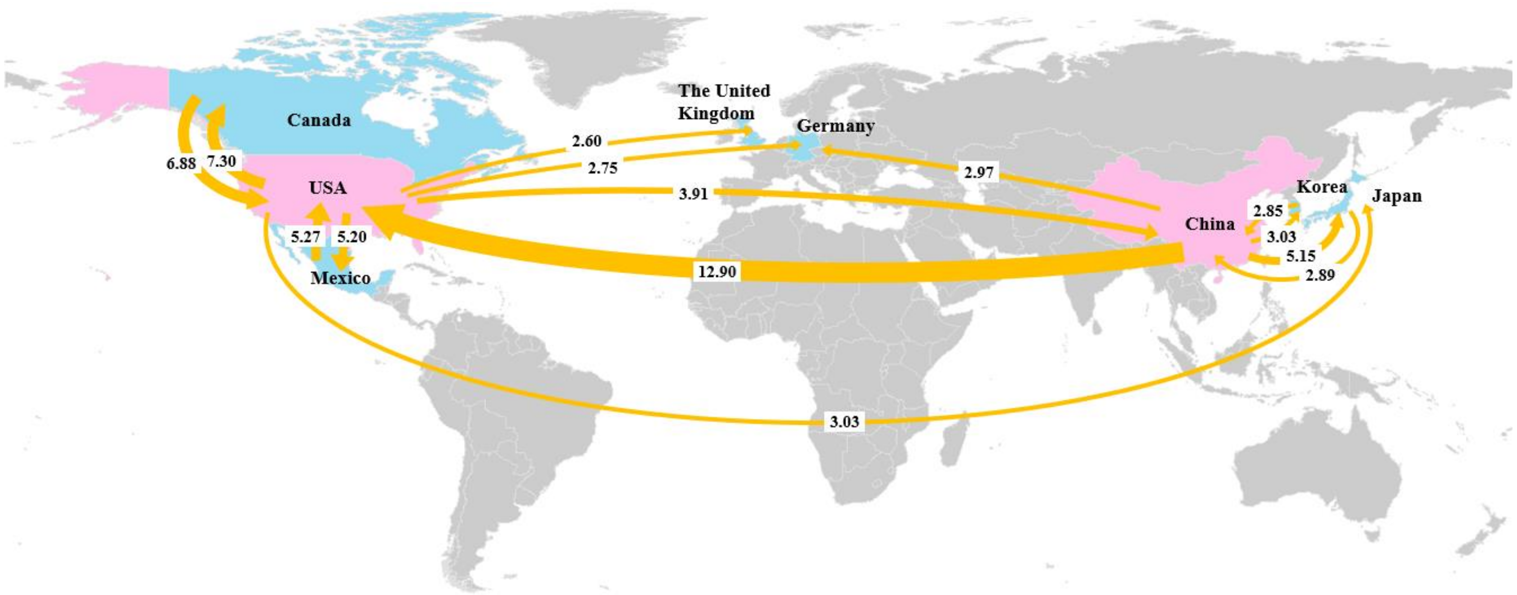


Figure 8. Major flows of energy-related water use for the United States and Mainland China (unit: bcm).

5.3 Trade imbalance of major regions and implications

Trade imbalance in terms of monetary has been explored and identified to cause risks and inequity between regions [122], whereas trade balance of ecological elements such as water [123-126] often shows a different picture and need further estimation. The trade imbalances of energy-related water use for regions are showed in Figure 7. Trade patterns of different regions can be observed. Thus, policies can be set for certain trade pattern and certain trade sector. The United Kingdom, Japan, Italy, India and Brazil, which lie in the first quadrant of the coordinate, are net importers of energy-related water in both intermediate and final trade, causing water pressures on regions with energy-related water outflows. Take the United Kingdom for example, an abstraction license is needed if one (e.g., a power plant) is likely to take more than 20 cubic meters water a day from environment, which is a territorial water policy [127]. In international trade scale, a license to limit the volume of energy-related water embodied in trade may be effective to reduce exporters' excessive pursuit for monetary surplus and overlook of water loss. Korea, France, and so on situate in the second quadrant of the coordinate, which gain a surplus in intermediate trade, but a deficit in final trade. Sector *Petroleum, coal products* and Sector *Chemical, rubber, plastic products* are major sectors importing energy-related water use embodied in intermediate trade, while much of energy-related water is exported by Sector *Machinery and equipment nec* in final trade. Given the context of energy demand expansion, population growth, climate change, and other unpredictable factors, these regions should attach importance to water for energy issue in global supply chains in an early stage to avoid future water crises [26].

China and the United States, which lie in the third and fourth quadrant respectively, are top traders in trade volume as well as top direct energy-related water extraction countries. Major trade flows of energy-related water use for the United States and China are depicted in Figure 8. There are water policies especially for energy production in China and the United States, such as policies on water-saving energy technology promotion, norm of water intake for power plants, or site selection of power plants in view of local water endowment (details in Supplementary 1), yet all limited within borders. Besides, many bills for water-energy nexus are raised in the United States. Recently, one called Energy and Water Research Integration Act of 2019 is received in the Senate and read twice and referred to the Committee on Energy and Natural Resources, aiming to ensure consideration of water intensity in the Department of Energy’s energy research, development, and demonstration programs, while former similar bills were died in a previous congress [128]. However, even energy-related water embodied in energy commodity trade is not mentioned in the bill, let alone for non-energy trade. Reasonable bills of water-energy nexus should be passed in the United States, with supplementary content of energy-related water embodied in international trade. It is also important to China, which experiences huge energy-related water loss by exports, to make policies about limiting energy-related water outflow. Moreover, cooperation between China and the United States can expand into water for energy domain through not only trade negotiation but science and technology research.

6 Conclusions

The growth of energy demand is accompanied by the increasing of water use for energy production. Energy is used to produce goods and services, and water exploited from environment for energy production is therefore embodied in goods and services, including non-energy commodities. Global economic system can be regarded as a network to redistribute energy-related water resources via international trade. By the embodiment accounting model, this paper investigates energy-related water use from source of exploitation to sink of final consumption along global supply chains. Overall, the volume of energy-related water embodied in global trade activities is about 80% of the total. Non-energy commodities induce more than four fifths of energy-related water embodied in international trade. China serves the largest exporter while EU28 is the top receiver of energy-related water use. The United States takes the secondary position of gross volumes of both imports and exports. As for policy implications, production-oriented countries should reduce water intensities by promoting relevant technologies, while consumption-oriented nations can adopt environmental labels attached to commodities to save energy-related water. Besides, the invisible transfers of energy-related water use embodied in goods and services call for considering global supply chain effects (aka, energy and non-energy supply chain). It is suggested to introduce environmental assessments of energy-related water driven by both energy and non-energy trade into trade negotiations. Therefore, energy-related water conservation strategies can be made for both local energy production and global supply chain management.

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SUPPORTING INFORMATION

The supporting information provides supplemental Tables and Figures supporting the main text.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT author statement

Yitong Liu: Formal analysis; Investigation; Resources; Writing - Original Draft; Writing - Review & Editing

Bin Chen: Conceptualization; Writing - Original Draft; Visualization; Supervision

Guoqian Chen: Methodology; Project administration; Funding acquisition

Zhi Li: Software

Jing Meng: Validation

Hayat Tasawar: Data Curation

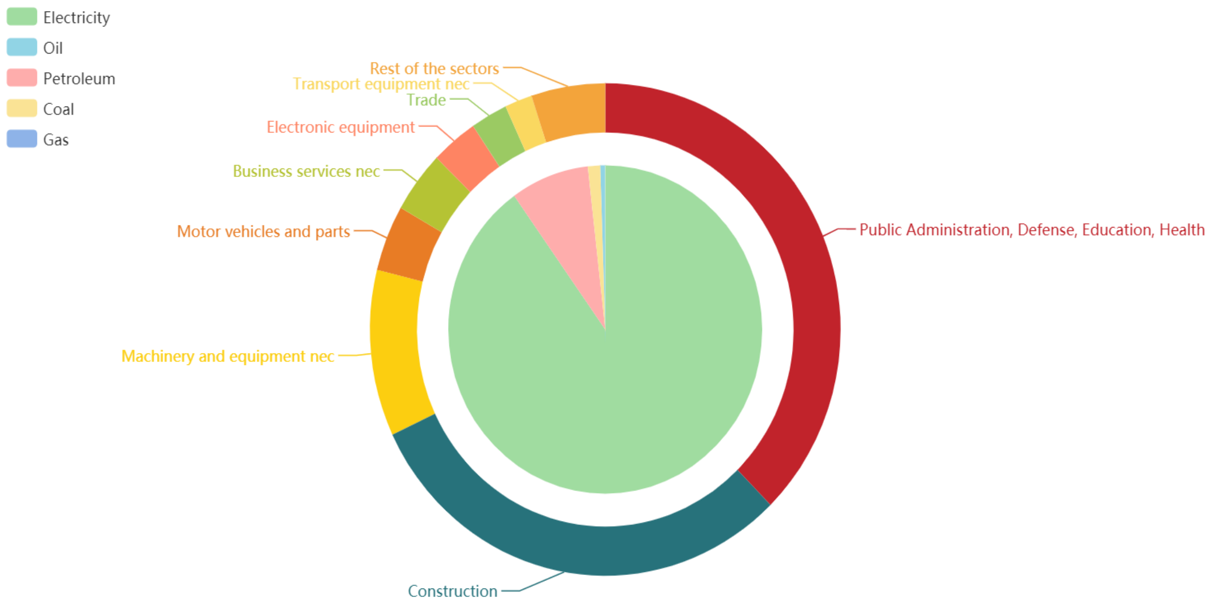


Figure 1. Global direct water withdrawal of energy sectors and its final consuming sectors in 2011

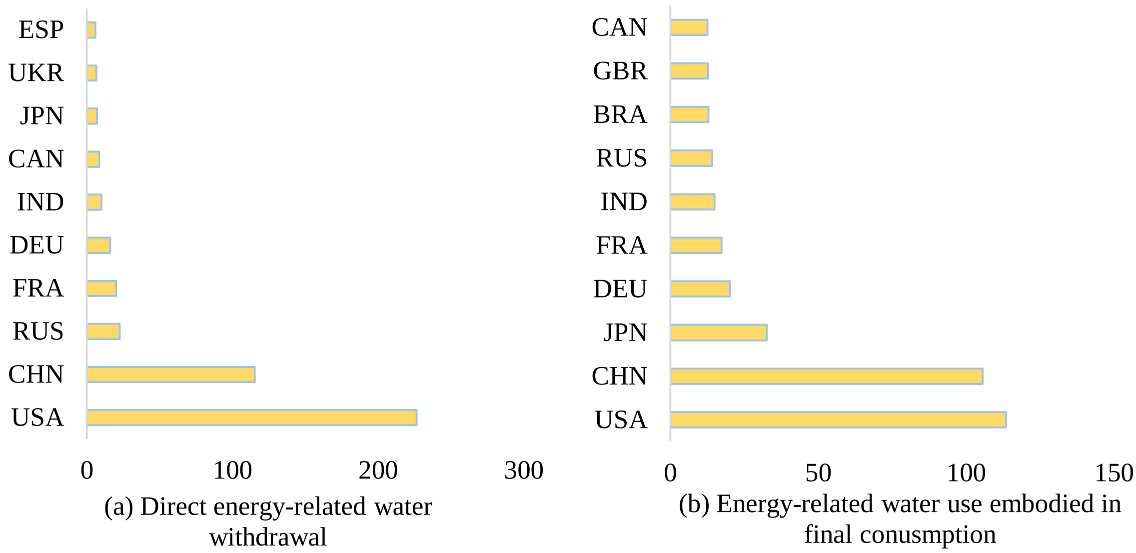
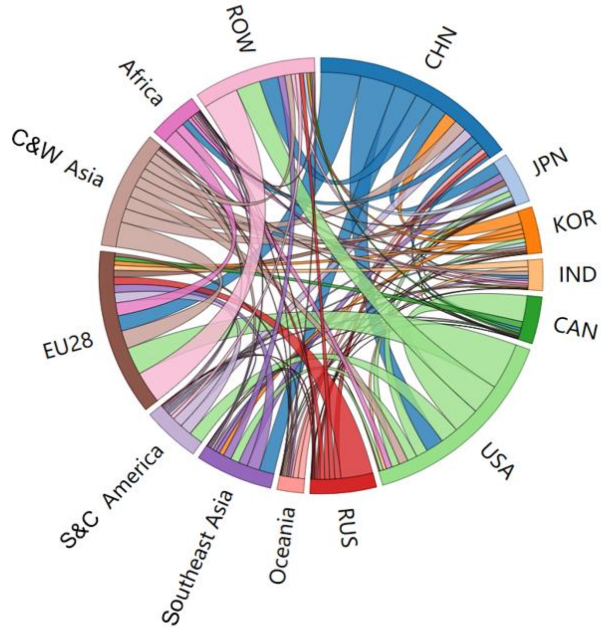
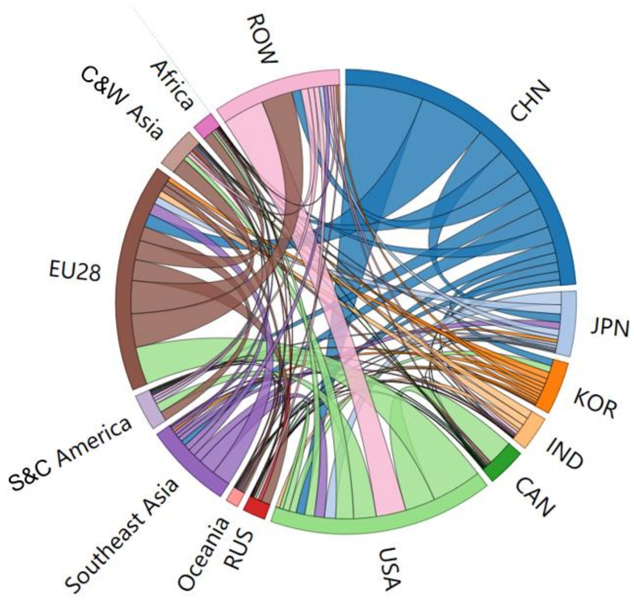


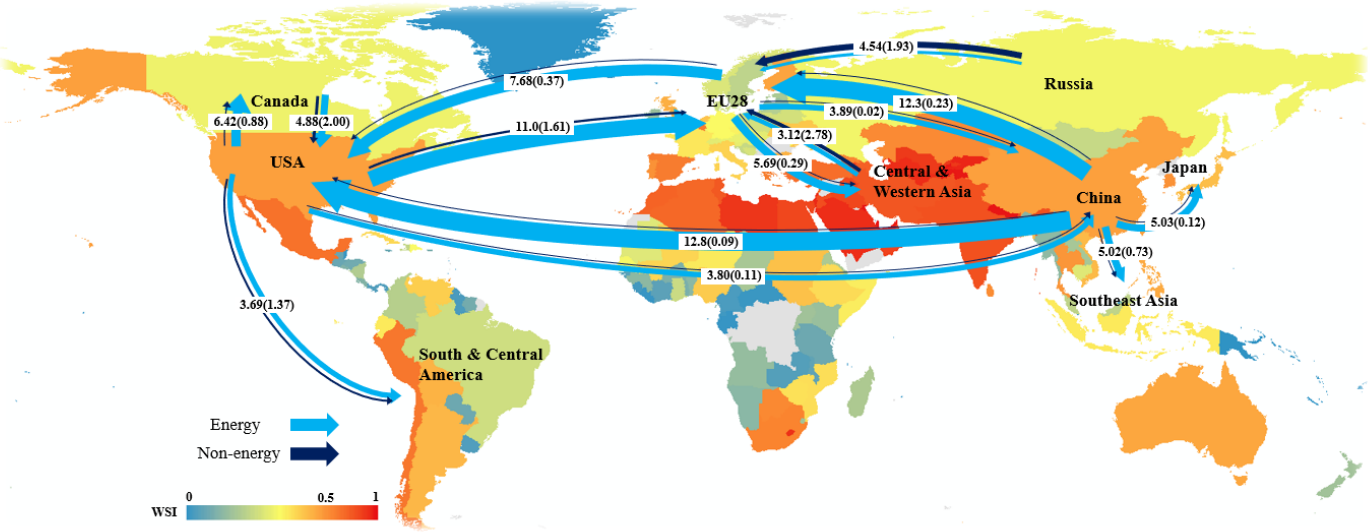
Figure 2. Direct water withdrawal of energy sectors and energy-related water embodied in final consumption of top 10 region. (unit: bcm)



(a) Energy-related water use embodied in intermediate trade



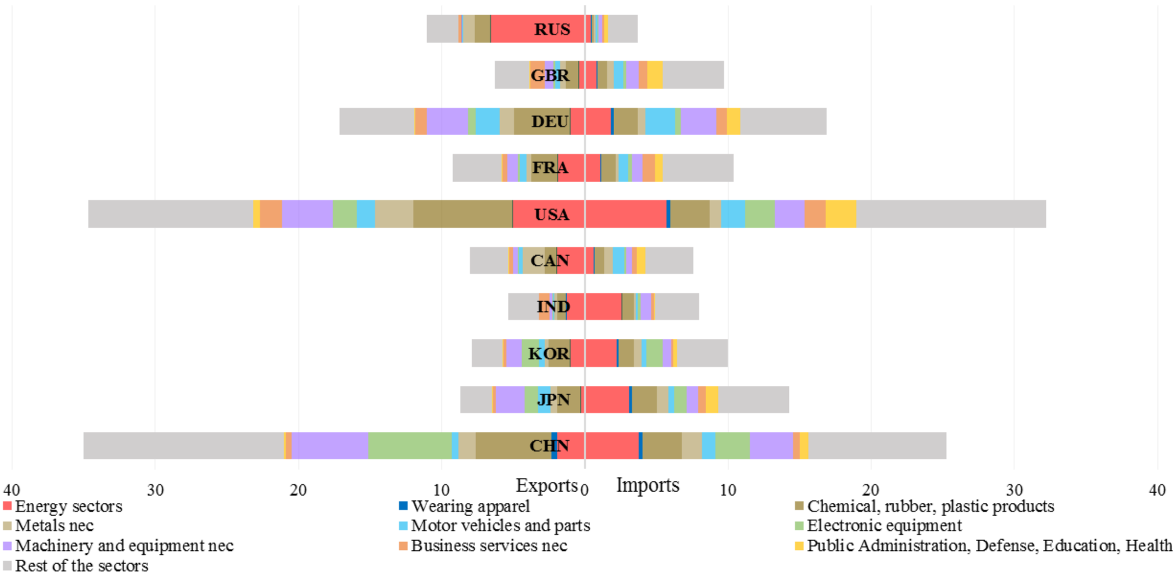
(b) Energy-related water use embodied in final trade



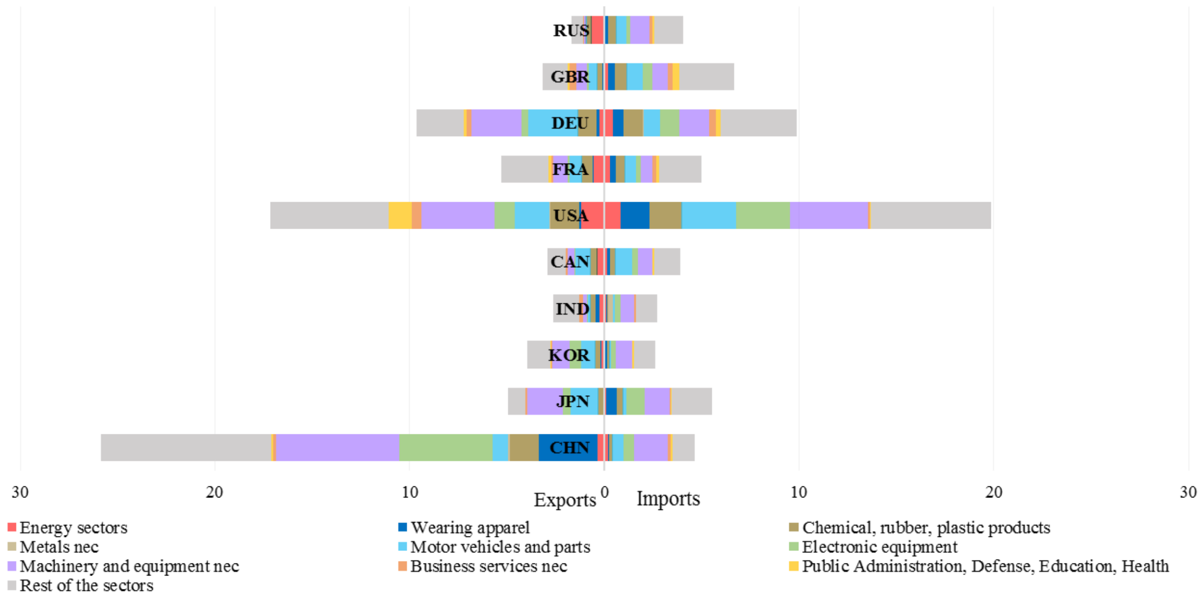
(c) Energy-related water use embodied in total international energy and non-energy trade

Figure 3. Intertwined relations of energy-related water use embodied in intermediate trade (a) and final trade (b) between the fourteen economies, and (c) major flows of energy-related water embodied in total international energy and non-energy trade (unit: bcm). (C&W Asia is Central & Western Asia, S&C America is South & Central

America, WSI is water stress index derived from Pfister et al.'s study [111].)



(a)



(b)

Figure 4. The sectoral contributions of energy-related water embodied in intermediate trade (a) and final trade (b) of the top traders (unit: bcm).

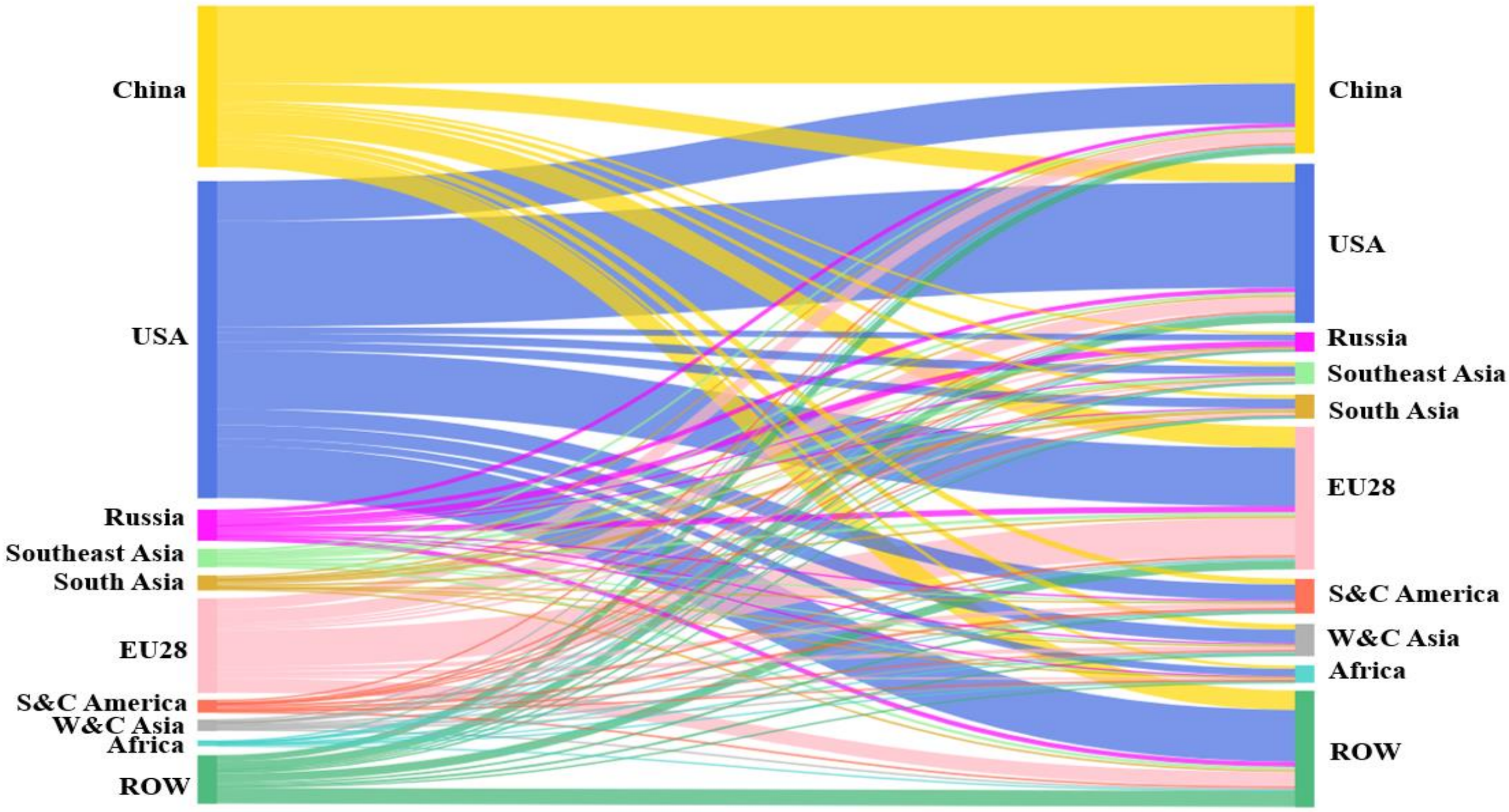
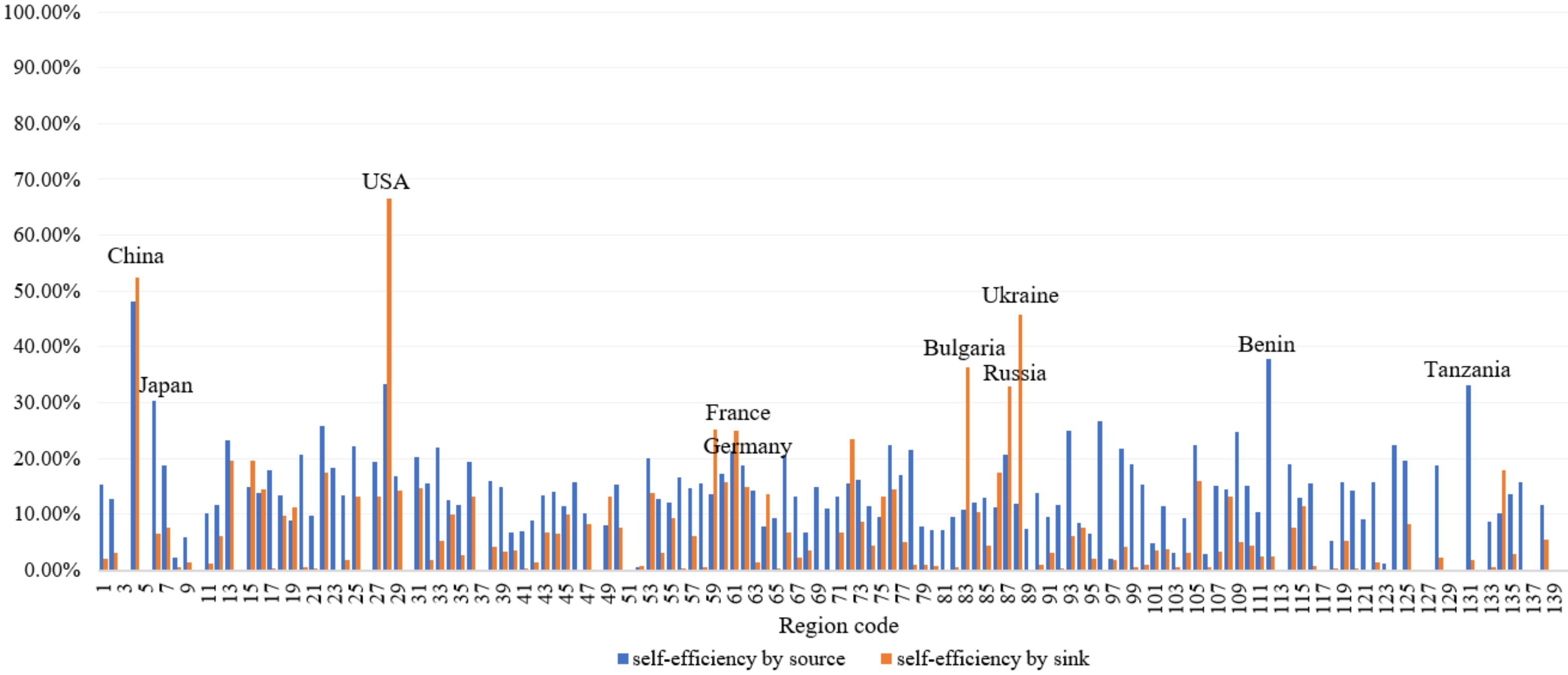


Figure 5. Source-sink relations of energy-related water use between major economies.



(C&W Asia is Central & Western Asia; S&C America is South & Central America)

Figure 6. Energy-related water use self-sufficiency rate by source and sink for each

region.

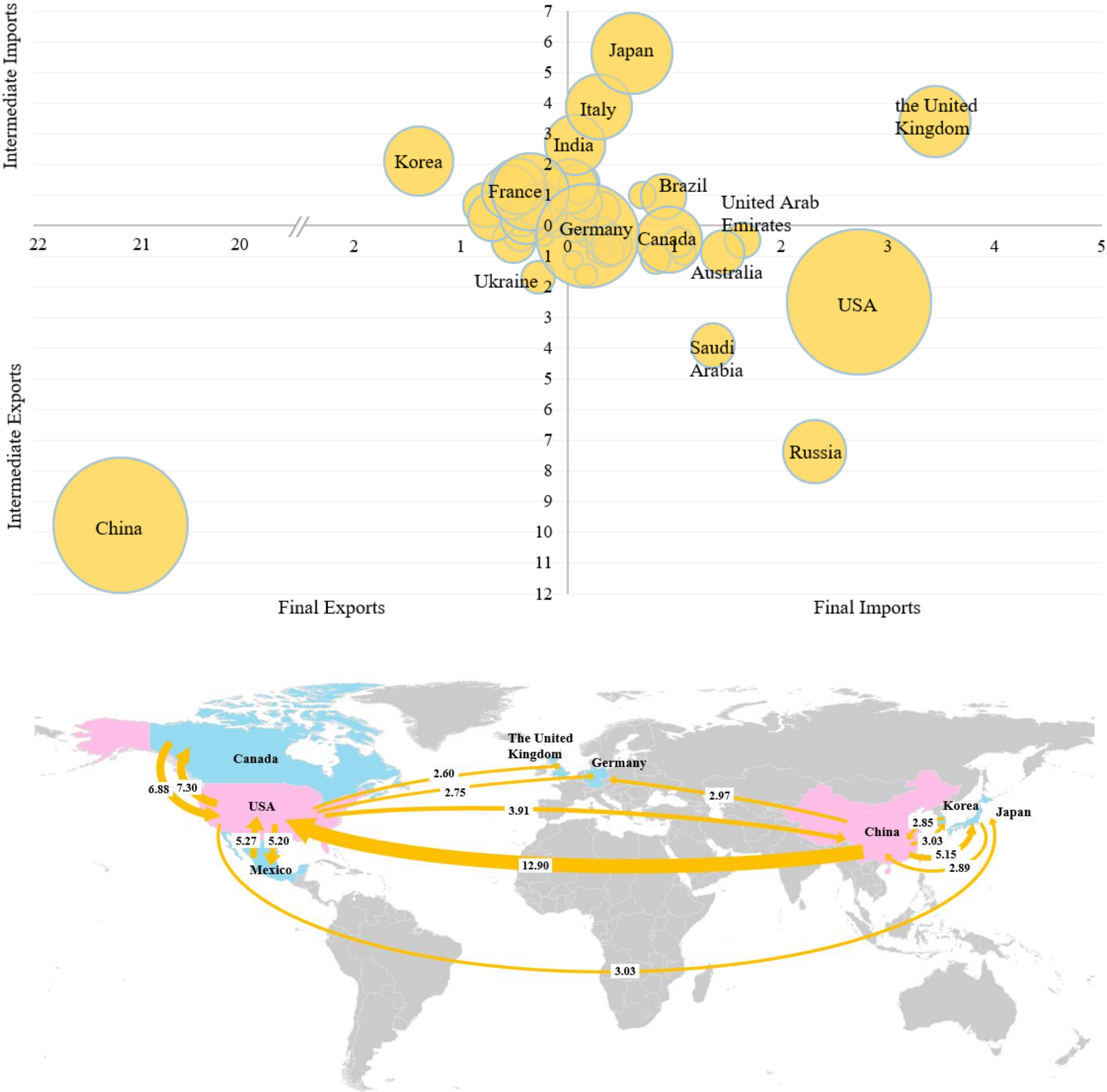
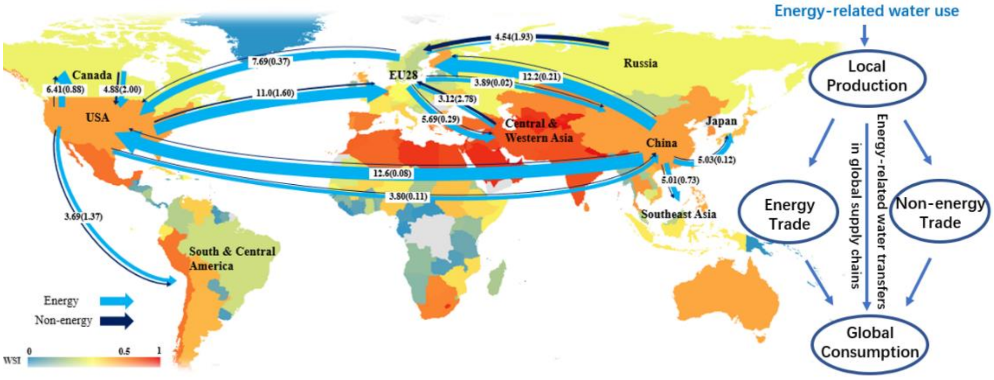


Figure 7. Trade imbalances of energy-related water use for regions (unit: bcm).

Figure 8. Major flows of energy-related water use for the United States and Mainland China (unit: bcm).

Graphical Abstract



Highlights

Systems accounting model is developed to track energy-related water use via global supply chains.

Over 1/4 of energy-related water embodied in China's final consumption originates from the USA.

Non-energy commodities trade dominates energy-related water transfer via international trade.

Major embodied water flows are from China to the USA, USA to EU28, and China to EU28.

Energy-water nexus policy-making must consider regional endowment and global supply chain.