

International energy trade impacts on water resource crises: an embodied water flows perspective

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LETTER

International energy trade impacts on water resource crises: an embodied water flows perspective

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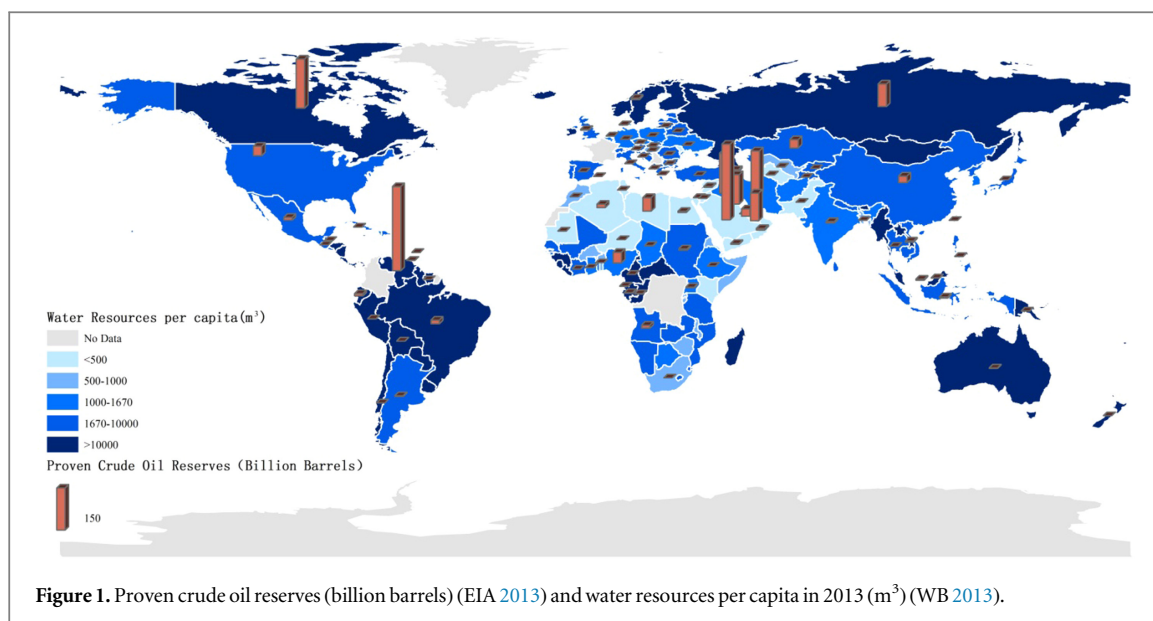
Water and energy are coupled in intimate ways (Siddiqi and Anadon 2011 *Energy Policy* **39** 4529–40), which is amplified by international energy trade. The study shows that the total volume of energy related international embodied water flows averaged $6298 \text{ Mm}^3 \text{ yr}^{-1}$ from 1992–2010, which represents 10% of the water used for energy production including oil, coal, gas and electricity production. This study calculates embodied water import and export status of 219 countries from 1992 to 2010 and embodied water flow changes of seven regions over time (1992/2000/2010). In addition, the embodied water net export risk-crisis index and net embodied water import benefit index are established. According to the index system, 33 countries export vast amounts of water who have a water shortage, which causes water risk and crisis related to energy trade. While 29 countries abate this risk due to their rich water resource, 45 countries import embodied water linked to energy imports. Based on the different status of countries studied, the countries were classified into six groups with different policy recommendations.

1. Introduction

Extracting, delivering and disposing of water requires energy. Similarly, processes related to extracting and refining various fuel sources and producing electricity use water. This so-called 'water-energy nexus' has become a high-priority issue in sustainability assessments. Despite the interconnections, these two sectors have historically been independently regulated and managed. Traditionally, energy supply planning has rarely considered water supply issues. However, water supply planning seldom considers the associated energy requirements (Stillwell *et al* 2011). Increased awareness has been placed on the fact that the water sector is energy intensive and that innovative energy sources require stable water supplies. These issues have generated increased interest in evaluating both sectors in a more integrated framework (CEC 2005, Cabrera *et al* 2010, Pate *et al* 2007, WEF 2009).

Since 2010, the energy-water nexus has gained wide attention. Although Aqeduct conducted water risk assessment on a global scale based on water supply

and water use indexes etc (WRI 2015), to the best of our knowledge, there is little research on international energy trade impacts on water resource from an embodied water flows perspective. Freshwater withdrawals for energy production, which currently account for 15% of the world's total (WWAP 2014), are expected to increase by 20% through to 2035 (IEA 2012). A study was performed in the Middle East and South Africa on the country-level. It quantitatively assessed the water-energy nexus (Siddiqi and Anadon 2011), which showed a strong dependence between water extraction and energy production systems, and some other research on water-energy nexus focused on individual drainage basins and sub-basins (Ashlynn *et al* 2010, Liang and Zhang 2011, Sabrina *et al* 2011). Estimates of operational water withdrawal and water consumption factors for electricity generating technologies were conducted in the United States (Macknick *et al* 2012). Spang *et al* (2014) defined and calculated an indicator to compare the water consumption of energy production for over 150 countries based on exploring the geographic distribution of



water use by national energy portfolios, and the results showed that approximately 52 billion cubic meters of freshwater is consumed annually for global energy production.

As essential global resources, energy and water are unevenly distributed, as summarized in figure 1. Figure 1 shows the distribution of crude oil reserves (Hao and Zhao 2010) and water resources per capita, with grades based on a common method (Falkenmark and Widstrand 1992). Although some countries in North Africa or the Middle East have abundant energy resources, they have limited water resources. On the contrary, most countries in Latin America or Oceania have abundant water resources, but limited energy resources. It is the uneven distribution of energy that drives international energy trade to some extent, and meanwhile brings water resource flows in the form of embodied water.

Global scale energy flows have dramatically increased (Ruta and Venables 2012), which has changed water resource allocations and intensified the global water and energy crisis. Definitions of ‘virtual water’ have been debated in recent decades and have received significant attention in the field of agricultural trade (Hoekstra and Hung 2005, Lenzen 2009). The volume of virtual water that is ‘hidden’ or ‘embodied’ in a particular product is defined as the volume of water used in the production process of a product (Allan 1997, Hoekstra 1998). Thus, studying the virtual water trade between nations or continents provides an approach for improving global water use efficiency and achieving water security in water-poor countries. In addition to agricultural products, energy also contains virtual water. However, the volume of virtual water embodied in energy is difficult to calculate. Few studies have focused on the virtual water of energy, except for biofuel production (Elena and Esther 2010). In this study, water utilized in the energy

extraction and transformation process is defined as ‘embodied water’, which represents water consumption during the energy production process.

This study aims to add to the water-energy nexus knowledge in the context of global energy trade. This letter focuses on the following topics: (1) quantifying the volumes of embodied water flows between nations from 1992–2010; (2) estimating the risk and crisis states introduced by energy embodied water flows; and (3) classifying countries into six groups by the impact degree of energy embodied water flows on water scarcity resource and offering energy trade and water resource management suggestion to each group. To our knowledge, this is the first global study to report risk and crisis states based on international energy embodied water flows. In addition, it is the first to cluster countries into categories based on different resource management approaches. Our analysis of the global water-energy nexus could provide better supporting evidence for water and energy resource management, which also contributes to the world resource balance.

2. Methods

2.1. Calculation of specific water demand per energy type

Recently, research institutions, such as the Harvard Kennedy School and Lawrence Berkeley National Laboratory, have focused on average specific water demand per energy type (Baker *et al* 2014, McMahon and Price 2011, Mielke *et al* 2010). Many factors have significantly influenced the energy production water demand, such as the production process, productivity, regional climate variations and other factors. Thus, the value of specific water demand (SWD) is a critical variable.

Table 1. The specific water demand of traditional oil, coal and traditional gas.

| Fuel type | Liters/gigajoule | | |
|-----------------|------------------|------------------|-------------|
| | Rawmaterials | Transformation | Total (SWD) |
| Traditional oil | 3–7 | 25–65 (refining) | 28–72 |
| Coal | 5–70 | | 5–70 |
| Traditional gas | Minimal | 7 (processing) | 7 |

We integrated research results from the United States, the Middle East, China and other areas in table 1, including traditional oil, coal and traditional gas data (Kahrl and Roland-Holst 2008, McMahon *et al* 2011, Siddiqi *et al* 2011). Three types of electricity generation are considered: conventional thermal generation, nuclear generation and hydroelectric generation, as listed in table 2. The conventional thermal electricity and nuclear data were based on a review by Macknick *et al* (2012). The hydroelectric generation data are based on a study from California (Gleick 1994, Macknick *et al* 2012). Wind, solar, tidal and wave electricity generation essentially have little water demand. It should be specially explained that the data used in table 1 is consumptive use data and that in table 2 it is withdrawals data (except hydroelectricity due to lack of withdrawals data). With consumption, water is transformed into another state such that it cannot be later used for other purposes within the natural annual water cycle of the region (Siddiqi *et al* 2011). Withdrawal involves returning the water to its original source, such as a lake or a river, albeit often in a slightly altered state such as at a higher temperature (Siddiqi *et al* 2011). Power generation is dominated by thermal electricity, which accounts for over 80% of global electricity production (UN Water 2015). While the quantity of water required for thermal power is dependent on the type of cooling system. Open-loop cooling requires more water withdrawals but is less consumptive, whereas closed-loop systems require less water to operate but nearly all of this water is consumed (UN Water 2015). In addition, there is little difference between water withdrawal and consumption for oil, gas and coal production (IEA 2012). Given this, we used withdrawals for conventional thermal and nuclear electricity, and used consumptive data for hydroelectricity and types in table 1 due to lack of withdrawals data and the small gap between consumptive and withdrawals data of these types.

2.2. Calculation of embodied water flows and the national embodied water balance

Embodied water flows between nations were calculated by multiplying the international energy flows by their associated embodied water content. We considered 219 countries that have statistics data. And embodied water flows were calculated by:

$$\begin{aligned} & EWF(n, e, t) \\ & = [EP(n, e, t) - EC(n, e, t)] * SWD(e) \quad (1) \end{aligned}$$

where $EWF(n, e, t)$ denotes the embodied water flows (Mm^3) of country n in the year t as a result of energy type, e , flows. $EP(n, e, t)$ represents the total energy, e , production of country n in year t . $EC(n, e, t)$ represents the total energy, e , consumption of country n in year t . $SWD(e)$ is the specific water demand of energy e .

2.3. Calculation of embodied water export risk and crisis indexes

Countries lacking water resources will potentially suffer significant water shortages if a large amount of energy is exported because it is accompanied by a loss of embodied water. In order to evaluate the influence quantitatively, an index system is needed. So we established the embodied water export risk and crisis indexes (EWERCI) which consider both energy flows and the state of water resources.

EWERCI is designed to assess the impact that energy exports exert on the water resources of countries or regions. In addition, it allows for assessment of potential water scarcity. EWERCI is calculated by equation (2):

$$\begin{aligned} & EWERCI(n, e, t) \\ & = [EWERI(n, e, t) * WCI(n, t)]^{1/2} \quad (2) \end{aligned}$$

where the embodied water export risk index (EWERI) denotes the risk of international embodied water exports from country n in year t as a result of energy, e , flows. The water crisis (WCI) is the water scarcity crisis index of country n in year t . $EWERCI(n, e, t)$ is an integrated index of $EWERI(n, e, t)$ and $WCI(n, t)$.

$EWERI(n, e, t)$ is calculated based on the average energy embodied water export percentage of freshwater withdrawals (x) of country n in year t . Due to lack of partial data of total freshwater withdrawals, we calculated 185 countries that have valid data. After sorting all values of x , we selected the top 20% countries as high risk ones, namely, $EWERI = 1$, if $x \geq 5\%$ and $EWERI = 0$ if $x \leq 0.01\%$. The index is defined by equation (3):

$$EWERI(n, e, t) = \begin{cases} 1, & x \geq 5 \\ \frac{x - 0.01}{4.99}, & 0.01 < x < 5 \\ 0, & x \leq 0.01 \end{cases} \quad (3)$$

$WCI(y)$ is related to water resources per capita (y) of country n in year t , per equation (4). Water resources per capita can be used as a water scarcity index (Falkenmark and Widstrand 1992). Therefore, we set $WCI = 1$ when $y \leq 500$, indicating severe water scarcity, and $WCI = 0$ when y is equal to or greater than the world average water resources per capita ($6962 m^3$).

Table 2. The specific water demand of several electricity types.

| Electricity type | Detailed | Water demand (m ³ MWh ⁻¹) | SWD (m ³ MWh ⁻¹) |
|----------------------------------|------------------------|--|---|
| Conventional thermal electricity | cooling tower(generic) | 1.89–4.54 (withdrawals) 3.03–9.84 (withdrawals) | 1.89–4.54 |
| Nuclear electricity | cooling tower(generic) | | 3.03–9.84 |
| Hydroelectricity | | 5.39–68.13 (consumption) | 5.39–68.13 |
| Wind electricity | | Minimal | 0 |
| Solar, tide and wave electricity | | Minimal | 0 |

$$WCI(y) = \begin{cases} 1, & y \leq 500 \\ \frac{6962 - y}{6462}, & 500 < y < 6962 \\ 0, & y \geq 6962 \end{cases} \quad (4)$$

2.4. Calculation of the embodied water import benefit index for water resources

A significant amount of embodied water linked to energy imports may mitigate water crises in some water-stressed countries. The embodied water import benefit index for water resources (EWIBIWR) is designed to measure the impact of energy imports on the water resource scarcity of a country or region. The index is calculated via equation (5):

$$EWIBIWR(n, e, t) = [EWIBI(n, e, t) * WCI(n, t)]^{1/2} \quad (5)$$

where the embodied water import benefit index (EWIBI) denotes the risk of international embodied water imports of county n in year t as a result of energy, e , flows. WCI is a measurement of the water scarcity crisis of country n in year t . $EWIBIWR(n, e, t)$ is the integrated index of $EWIBI(n, e, t)$ and $WCI(n, t)$.

$EWIBI(n, e, t)$ gives the relationship between embodied water imports and the total freshwater withdrawal of some countries. It is calculated as the average embodied water import divided by the percentage of freshwater withdrawals (x) of county n in year t . Similarly, the index is defined based on equation (6) and after sorting values of x , top 20% countries are chosen as high benefits whose EWIBI is defined as 1. ($EWIBI = 1$, if $x \geq 5\%$ or $EWIBI = 0$, if $x \leq 0.5\%$):

$$EWIBI(n, e, t) = \begin{cases} 1, & x \geq 5 \\ \frac{x - 0.5}{4.5}, & 0.5 < x < 5 \\ 0, & x \leq 0.5 \end{cases} \quad (6)$$

2.5. Data sources

Energy production and consumption data were obtained from the EIA (2013). Continuous data from 1992 to 2010 were used for this study. The internal renewable freshwater resources per capita and annual freshwater withdrawals data from 1992, 1997, 2002, 2007 and 2009 were first collected from the World Bank World Development Indicators, namely annual freshwater withdrawals (total) (WB 2012). The

remaining data were collected from OECD Environment Database Freshwater abstractions (OECD 2012), ESCAP Statistical Database Total freshwater withdrawal (ESCAP 2011), UNEP Yearbook 2012 (UNEP 2012), Environment Statistics Database from United Nations Statistics Division (UN 2011), The World Factbook 2006–2011 Data, report of the CIA (WF 2006–2011). However, a lack of data exists for certain countries and years, so only recent data were used.

3. Results and discussion

3.1. Global embodied water flows

3.1.1. Global embodied water flows in energy sectors

The EWF calculation results show that the global volume of energy-related international embodied water flows averaged 6298 Mm³ yr⁻¹ from 1992–2010. For comparison, the global water consumption by the energy sector was 66 Bm³ yr⁻¹ in 2010 (IEA 2012). Therefore, approximately 10% of the water used for world energy production was not used for domestic consumption, but for exports (embodied form).

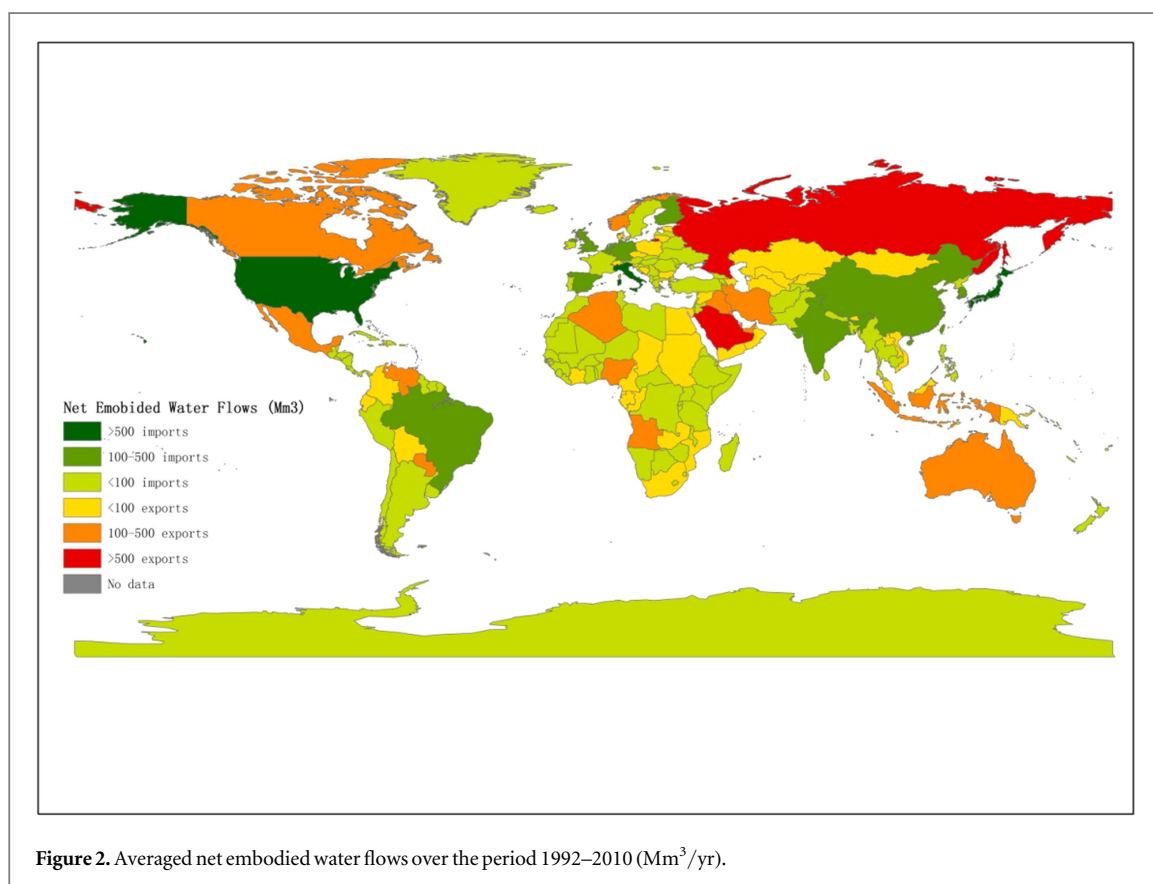
Table 3 shows that about 60% of the total volume of energy-related international embodied water from 1992 to 2010 was related to the oil trade. Gas and electricity account for 2.44% and 31.64% of global energy-related embodied water flows, respectively. It shows the dominance of petroleum which is known as ‘black gold’, ‘blood of industry’ and the necessary strategic material. Despite natural gas has shown the least percentage so far, it shows potential effect in the energy trade.

3.1.2. Net embodied water flows between regions

National embodied water balances from 1992–2010 are shown in figure 2. Countries with net embodied water exports are shown in red, and countries with net embodied water imports are illustrated in green. Note that some countries, such as Uzbekistan and Indonesia, are net embodied water exporters from 1992–2010, but are net embodied water importers in one or more particular years during this period. Other countries exhibit the opposite trend, such as the United Kingdom, Belize and Brazil. The reasons may be that some countries were influenced by some international economy factors like oil price big

Table 3. Global embodied water flows between nations by types of energy (Mm^3).

| Energy | 1992 | 1997 | 2002 | 2007 | 2010 | Average |
|-------------|-------|-------|-------|-------|-------|---------|
| petroleum | 3225 | 3845 | 4046 | 4557 | 4547 | |
| % | 58.74 | 59.13 | 56.12 | 56.21 | 57.70 | 57.58 |
| coal | 359 | 471 | 625 | 799 | 828 | |
| % | 6.54 | 7.12 | 8.67 | 9.86 | 10.51 | 8.54 |
| gas | 126 | 144 | 173 | 212 | 215 | |
| % | 2.29 | 2.18 | 2.40 | 2.62 | 2.73 | 2.44 |
| electricity | 1781 | 2154 | 2366 | 2539 | 2290 | |
| % | 32.43 | 32.57 | 32.81 | 31.31 | 29.06 | 31.64 |
| total | 5491 | 6614 | 7210 | 8107 | 7880 | |

**Figure 2.** Averaged net embodied water flows over the period 1992–2010 (Mm^3/yr).

volatility, exploitation of new energy, economic and environmental policy and strategy adjustment and so on, which causes the switch between exporters and importers.

To show embodied water flows between major world regions, the world was classified into seven regions (EIA 2013): North America, Central and South America, Africa, Europe, Eurasia, Middle East and Asia and Oceania. Net embodied water flows between regions from 1992–2010 are presented in figure 3.

Regions with significantly large net embodied water imports are Asia and Oceania, Europe and North America. Regions with substantial net embodied water exports are the Middle East, Eurasia and Africa. Another region with less substantial net

embodied water exports is Central and South America. Asia and Oceania, the largest embodied water importing region, increased its embodied water imports from $837 \text{ Mm}^3 \text{ yr}^{-1}$ in 1992 to $1863 \text{ Mm}^3 \text{ yr}^{-1}$ in 2010. In Europe and North America, the volume remains relatively stable over the study period, averaging $1275 \text{ Mm}^3 \text{ yr}^{-1}$ and $657 \text{ Mm}^3 \text{ yr}^{-1}$. The Middle East is the largest embodied water exporter. Net embodied water exports from the Middle East regularly surpass $1800 \text{ Mm}^3 \text{ yr}^{-1}$, accounting for 50% of all export regions. As a significant exporter of energy products, the Middle East exhibits the significant collective effects of embodied water exports. We can see energy exporters overlap with oil-rich countries to some extent. And although exports from Eurasia and

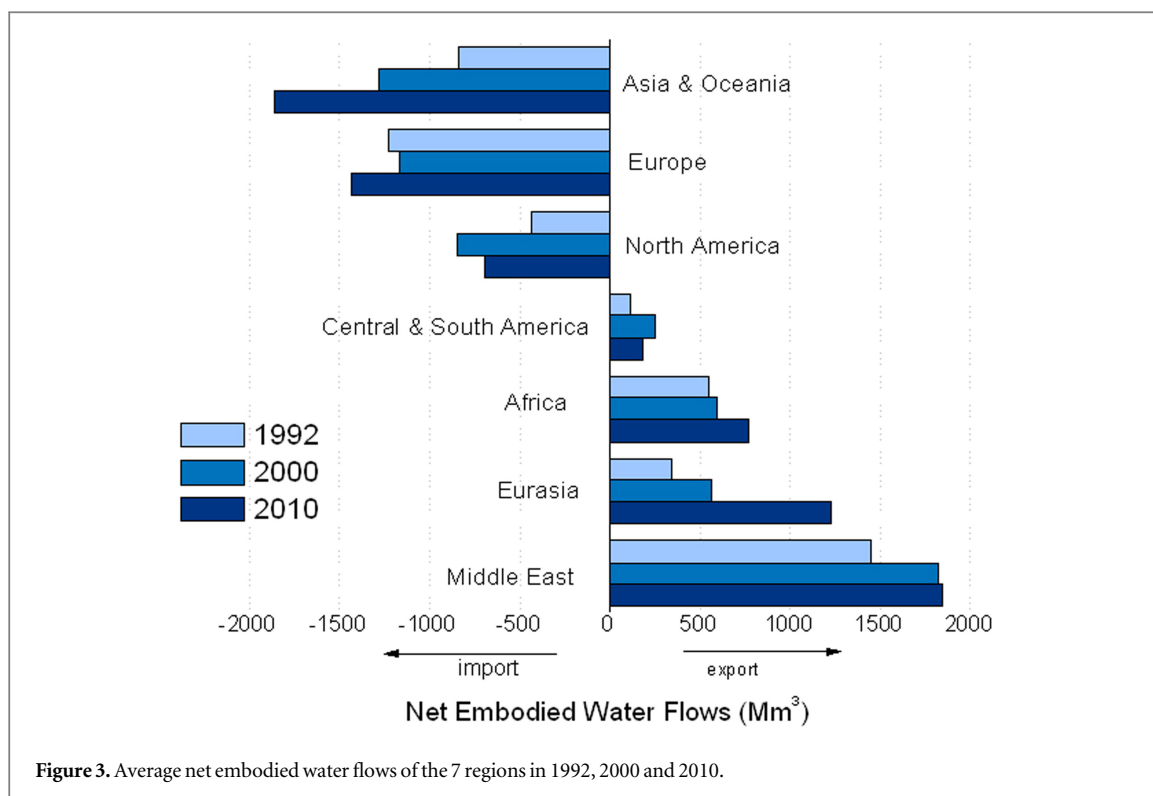


Figure 3. Average net embodied water flows of the 7 regions in 1992, 2000 and 2010.

Africa are not overly high, they exhibited an increasing trend. In addition, although the electricity embodied water accounts for about 30% of four main types energy embodied water flows, it only occupies at most 10% in each region, which implicates that electricity trade in global scale is still undeveloped.

3.2. The influence of embodied water flow on countries

3.2.1. The water resource risk and crisis states caused by embodied water exports

The risks and crises related to embodied water exports, and energy trade (EWERCI – energy) were calculated via equation (2). Many countries were found to be at risk due to embodied water exports.

Among the 185 analyzed, 33 countries faced water resource dangers linked to embodied water exports from 1992 to 2010. The EWERCI (energy) of these countries are shown in figure 4. Among these countries, only Angola have higher risks caused by large embodied water exports far more than water shortage, as calculated via EWERCI. On the contrary, countries in group (b) exhibit larger water resource scarcities, which amplifies the impact of embodied water export on water resource. Kuwait, Qatar, Oman and Saudi Arabia face both severe water shortages and large energy embodied water losses.

The time variation histogram of the EWERCI (energy) over the last two decades was analyzed and shown in figure 5. According to the bar chart, EWERCI (energy) always equals 1 in Kuwait, Saudi Arabia and Qatar. This signifies that these three

countries have been in embodied water export extreme crisis states for a long period of time. The crises are reflected not only in their water resource scarcities but also in their large amounts of energy exports. The situations in Nigeria, Oman, Algeria, Libya, United Arab Emirates and Chad are also not optimistic, as each country exhibits an EWERCI (energy) value greater than 0.5 over a long period of time. Sudan and South Sudan, Azerbaijan, Denmark and Kazakhstan show an increasing trend. These trends are mainly a result of sharp increases in energy embodied water exports.

The risk and crisis states of embodied water exports can be classified into specific energy categories. Figure 6 shows the values of EWERCI (oil), EWERCI (coal), EWERCI (gas) and EWERCI (electricity) from 1992 to 2010. The signs of these values express the same meanings as in figure 4.

Overall, the risk and crisis states of energy embodied water exports in these countries are strongly oil-oriented, and the embodied water of coal exports is much less. The risk and crisis states in Kuwait, Saudi Arabia, United Arab Emirates, Bahrain, Angola, Syria, Mexico, Chad, Iraq, Azerbaijan and Sudan and South Sudan are entirely generated by crude oil exports. In Libya, Algeria, Denmark and other countries, crises are also related to natural gas exports, but still dominated by crude oil exports. In France, Cote d'Ivoire, Bulgaria, Zambia, Czech Republic and Mozambique, the risk is dominated by electricity embodied water exports. By understanding the dominant factors that export embodied water, strategies could be set for a

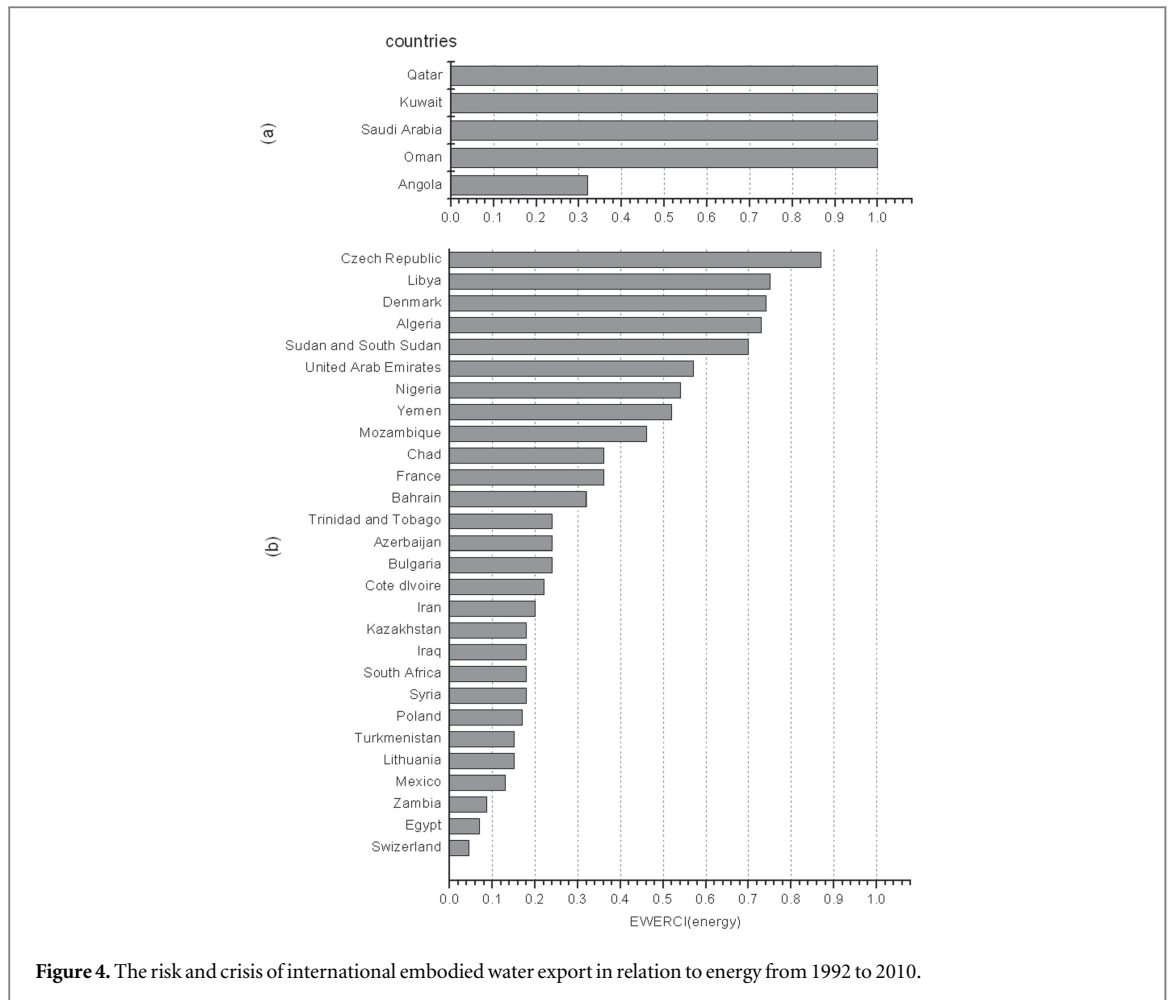


Figure 4. The risk and crisis of international embodied water export in relation to energy from 1992 to 2010.

certain energy, which is one of the great significance of this study.

3.2.2. The benefits of water resources linked to embodied water imports

Among the 219 countries and regions, 157 countries import embodied water linked to energy imports. Furthermore, some countries and regions suffering from water scarcity significantly benefited from energy imports.

Figure 7 presents all of the countries that gained embodied water import benefits due to international energy trade (EWIBIWR—energy), as calculated by equation (5). 45 countries were found to have benefited, of which most were developed countries. In Singapore, Maldives, Djibouti, Malta, Antigua and Barbuda, Bermuda, Luxembourg, Saint Lucia and Grenada, the EWERC I(energy) values were basically stable at a high level over the past two decades. And Korea.Rep (Republic of Korea), Thailand, Malta and Maldives maintained growth, which may be related to the rapid economic development and increased demand for energy. Overall, these countries benefited most from international embodied water imports in relation to oil, whereas coal and electricity yielded less contributions.

3.3. Recommendations for different country groups

According to the embodied water flow and water resource scarcity states, countries can be classified into six groups, as shown in table 4.

The countries in the first group, such as Azerbaijan and Kazakhstan, exhibit increasing embodied water flow crisis states. To relieve rising trend crisis related to energy embodied water, the countries in this group could protect water resource from an embodied water perspective, for instance, replacing water-intensive energy with other not water-intensive products, or importing other water-intensive energy to try to reach a balance of embodied water.

The second group, which includes Kuwait and Saudi Arabia, also exhibits embodied water flow risks. During the last two decades, their crises exhibited downward or stable trends within a certain range (the embodied water exports increased, however the growth rate was below the increase in total water withdrawal). Policymakers should pay more attention to the energy-water nexus and avoid water resource issues caused by energy exports.

The third group is characterized by having significant energy embodied water exports, but rich water resources, such as Canada and Venezuela. Although these countries export a large amount of energy, their water resource balances are not

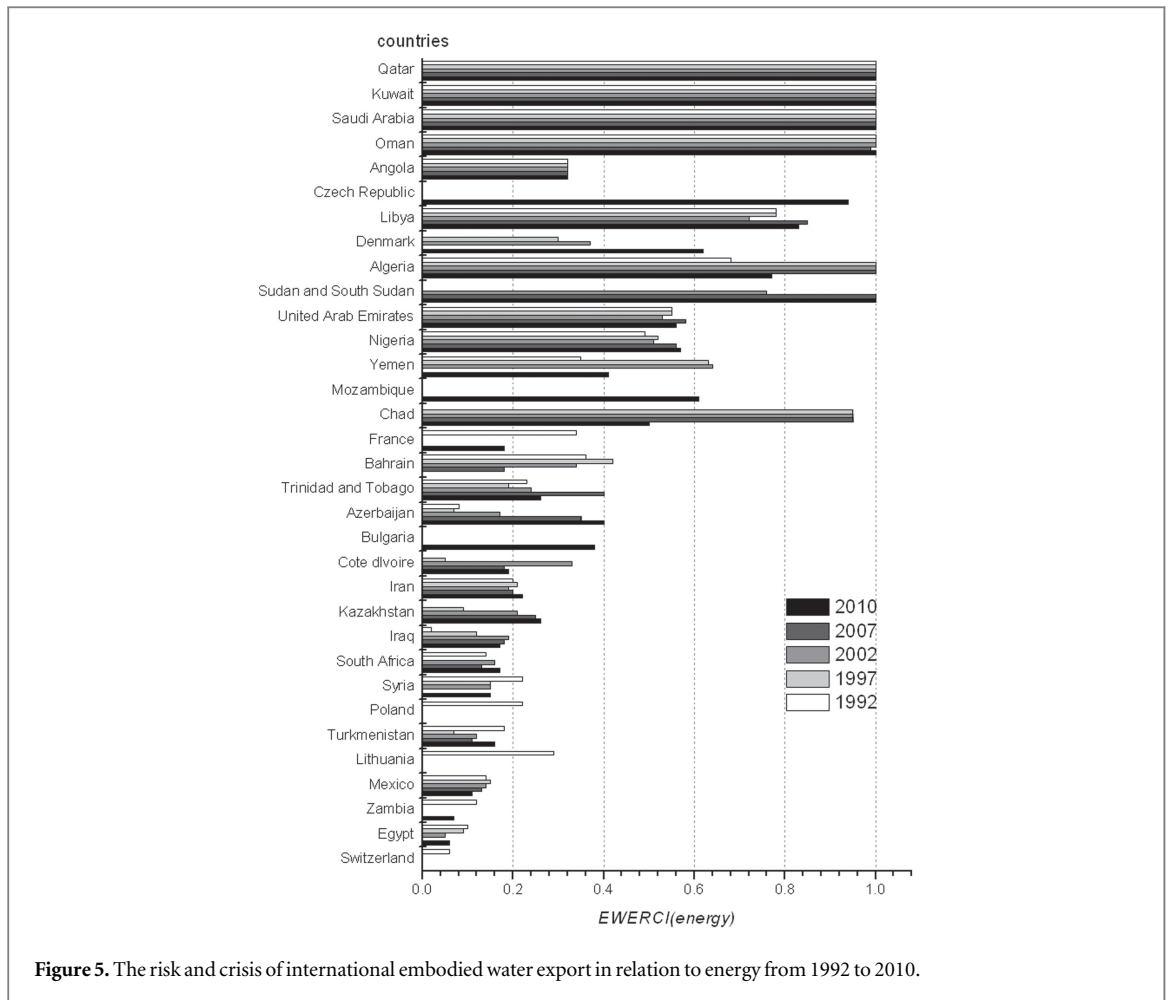


Figure 5. The risk and crisis of international embodied water export in relation to energy from 1992 to 2010.

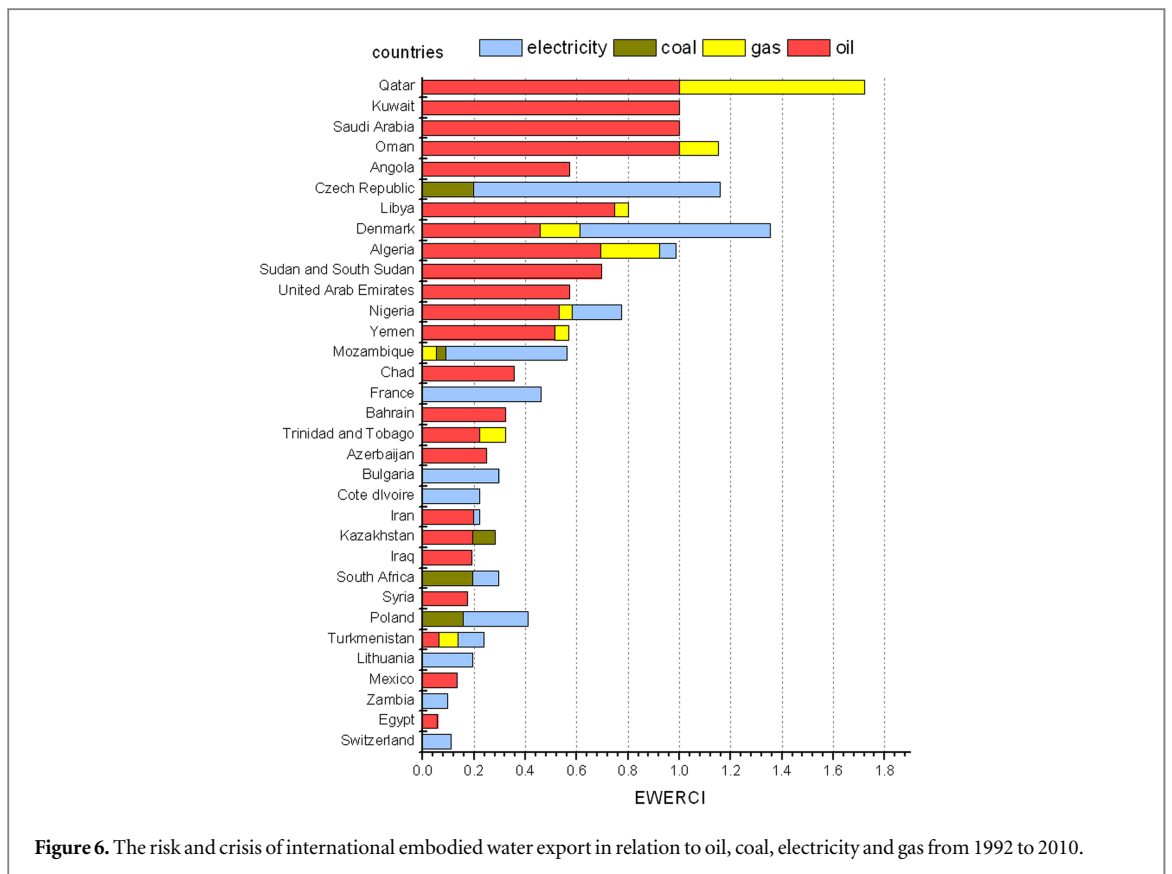


Figure 6. The risk and crisis of international embodied water export in relation to oil, coal, electricity and gas from 1992 to 2010.

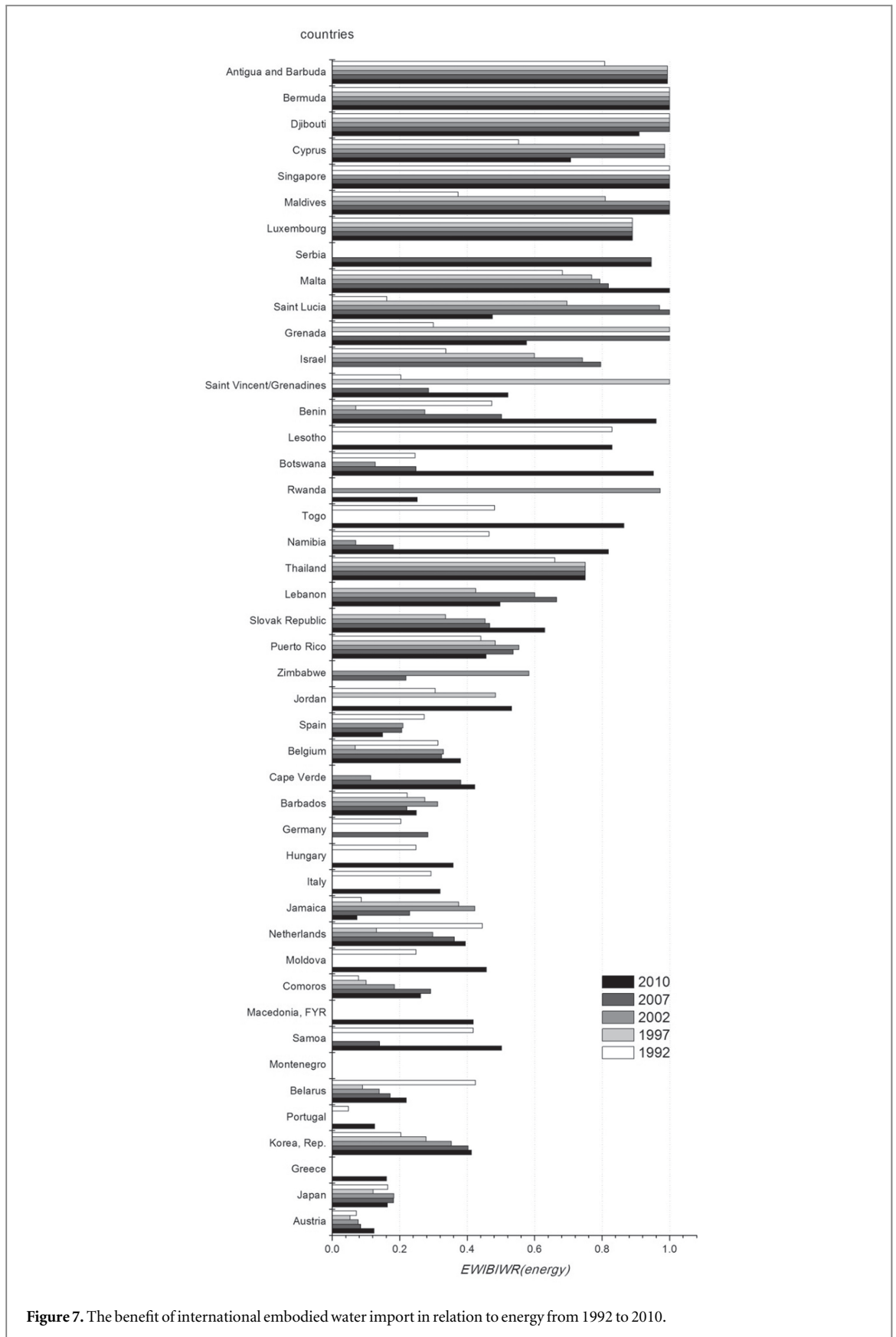


Figure 7. The benefit of international embodied water import in relation to energy from 1992 to 2010.

threatened. Increased energy demands, rapid population growth, climate change and other factors will cause the distribution and supply of resources to change. However, the energy-water nexus should be utilized to solve problems at an early stage.

The fourth group benefits from global energy flows. These 45 countries are experiencing water resource scarcities. Importing water intensive energy was found to be an effective way to increase the water resources of a country. In addition, water can be saved

Table 4. Six groups of countries classified by energy embodied water flows and water scarcity.

| Sort and Feature | | | Amount | Countries List |
|---------------------------------|-------------|--|--------|--|
| <i>Exporters</i> | EWERCI > 0 | EWERCI (energy) > 0 and with a ascendant tendency | 4 | Azerbaijan, Denmark, Kazakhstan, Sudan and South Sudan |
| | | EWERCI (energy) > 0 and with a downward or stable tendency | 29 | Algeria, Angola, Bahrain, Bulgaria, Chad, Cote d'Ivoire, Czech Republic, Egypt, France, Iran, Iraq, Kuwait, Libya, Lithuania, Mexico, Mozambique, Nigeria, Oman, Poland, Qatar, Saudi Arabia, South Africa, Switzerland, Syria, Trinidad and Tobago, Turkmenistan, United Arab Emirates, Yemen, Zambia |
| | EWERCI = 0 | EWERCI (energy) > 0 and WCI = 0 | 26 | Australia, Bhutan, Bolivia, Bosnia and Herzegovina, Brunei, Cameroon, Canada, Colombia, Congo (Brazzaville), Congo (Kinshasa), Ecuador, Equatorial Guinea, Estonia, Gabon, Indonesia, Kyrgyzstan, Laos, Malaysia, Mongolia, Norway, Papua New Guinea, Paraguay, Russia, Slovenia, Timor-Leste, Venezuela, |
| <i>Importers</i> | EWIBIWC > 0 | EWIBI (energy) > 0 and WCI > 0 | 45 | Antigua and Barbuda, Austria, Barbados, Belarus, Belgium, Benin, Bermuda, Botswana, Cape Verde, Comoros, Cyprus, Djibouti, Germany, Greece, Grenada, Hungary, Israel, Italy, Jamaica, Japan, Jordan, Korea, South, Lebanon, Lesotho, Luxembourg, Macedonia, Maldives, Malta, Moldova, Montenegro, Namibia, Netherlands, Portugal, Puerto Rico, Rwanda, Saint Lucia, Saint Vincent/Grenadines, Samoa, Serbia, Singapore, Slovakia, Spain, Thailand, Togo, Zimbabwe |
| | EWIBIWC = 0 | EWIBI (energy) > 0 and WCI = 0 | 12 | Albania, Belize, Brazil, Croatia, Fiji, Finland, Iceland, Ireland, Latvia, Panama, Sweden, United States |
| <i>The micro flow countries</i> | | EWERI (energy) = 0 and EWIBI (energy) = 0 | 69 | Afghanistan, Argentina, Armenia, Bangladesh, Burkina Faso, Burma (Myanmar), Burundi, Cambodia, Central African Republic, Chile, China, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Eritrea, Ethiopia, Gambia, The, Georgia, Ghana, Guatemala, Guinea, Guinea Bissau, Guyana, Haiti, Honduras, India, Kenya, Korea, North, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Nepal, Netherlands Antilles, New Zealand, Nicaragua, Niger, Pakistan, Peru, Philippines, Reunion, Romania, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Solomon Islands, Somalia, Sri Lanka, Suriname, Swaziland, Tajikistan, Tanzania, Tonga, Tunisia, Turkey, Turks and Caicos Islands, Uganda, Ukraine, United Kingdom, Uruguay, Uzbekistan, Vanuatu, Virgin Islands, US |

via reducing local energy production. Therefore, policymakers should utilize these findings for energy and trade related decision making.

The countries in the fifth group also import international embodied water, as linked to energy imports. However, imports in these countries do not significantly impact their water resources. Therefore, policymakers must note and balance global energy and water resource distributions and variations.

Finally, in the sixth group, embodied water flows related to international energy trade are un conspicuous, and energy trade almost doesn't have impact on countries' water resource. The water scarce countries in this group should base their policy on the water-energy nexus. Specifically, they should avoid water resource crises and avoid risks from embodied water exports linked to international energy trade. In addition, policymakers must consider the ideal balance of international embodied water imports and exports related to energy.

4. Conclusions

As global economic development and population increase, so too will energy demand. Water resource shortages are becoming increasingly prominent. In this letter, we reviewed and evaluated the energy and water nexus from a global energy flow perspective. This approach illustrated the connections and interactions between water and energy resources. In international energy trade, energy flows have a significant influence on the water resources of various countries. A greater emphasis should be placed on the water-energy nexus in water resources management and trade policy.

In this study, we found that 10% of the water used for energy production in the world is not used for domestic consumption, but instead for exports. Some countries benefit from energy embodied water flows while some get more crisis. By calculating the risk and crisis states of countries in relation to energy trade, we found 33 countries suffer more serious water resource crisis because of energy embodied water export. On the contrary, importing water intensive energy which brings embodied water flows will relieve some countries' water resource tension.

Based on established index systems, countries are divided into six groups. Policymakers should properly refer to this result and reconsider energy trade policy from an energy embodied water perspective. In the countries with high or increasing risk and crisis states linked to embodied water flows, it is necessary to take corresponding measures to alleviate natural resource crises. Reducing energy production and exportation is the most direct and effective way, especially in oil-producing countries because oil production is associated with a high water demand. However, policymakers must decide between economic development and resource protection. Other comprises, which are often

based on scientific and technological innovations, must also be made, including developing water saving technology, substituting for high water demand energy sources and managing innovation with various energy sectors. During our study, we also discovered an interesting fact that water exports grow with growing levels of development, which needs further research.

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