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Multiple metrics for quantifying the intensity of water consumption of energy production

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Abstract

Discussion of the environmental implications of worldwide energy demand is currently dominated by the effects of carbon dioxide (CO_2) emissions on global climate. At the regional scale, however, water resource challenges associated with energy systems are a growing concern. This paper, based on an inventory of national energy portfolios, posits an indicator-based framework for characterizing regional energy portfolios' relative water intensity. These calculations extend upon a previous paper that established a method for calculating the national water consumption of energy production (WCEP) at the global level. Intensity indicators are based on normalizing the WCEP results with a set of additional indicators (including population, gross domestic product, total energy production, and regional water availability). The results show great variability in water consumption across nations, as well as across the various water intensity measures that were applied. Therefore, it is best to apply this full suite of indicators to each country to develop an integrated understanding of the intensity of water use for energy across countries.

S Online supplementary data available from stacks.iop.org/ERL/9/105003/mmedia

Keywords: water–energy nexus, energy portfolio, water intensity

1. Introduction

Many high-level reports have emphasized the dynamic and integrated nature of coupled water–energy systems (DOE 2006, WEC 2010, IEA 2012). While both sides of the water–energy nexus merit increased attention, this research focuses specifically on the water requirements of energy systems. Fundamentally, water is consumed in nearly all energy production processes within four main categories: fossil fuel extraction and processing, uranium mining and processing, biofuel cultivation and processing, and electricity production. A number of reports have sought to calculate current and projected water use by energy systems at the regional and national levels (Grubert *et al* 2012, Macknick *et al* 2012, Clemmer *et al* 2013), but this paper extends on this literature by focusing on the intensity of water consumption by energy systems at the international scale.

In the companion paper to this study (Spang *et al* 2014), existing national energy portfolio data were synthesized with a consolidated set of water consumption factors for energy technologies to estimate the water consumption of energy (WCEP) production for over 150 countries. Applying these water consumption estimates to existing national energy production data allowed for cross-country comparisons of the relative magnitude of WCEP systems, both by individual energy production process and by total energy portfolio. By definition, WCEP focuses on the *consumption* of water for energy production (e.g. water that is removed entirely from a source water system, as in the case of evaporation) as opposed

Table 1. Water consumption intensity of energy production: indicator overview.

Indicator	Units	Purpose
WCEP	Million cubic meters (m^3)	The total water consumed by the energy system
Per capita WCEP	m^3/person	Total water consumption for energy divided by population to normalize consumption by country size
Economic WCEP intensity	m^3/GDP ($1000, 2008)	Total water consumed by the energy system normalized by the country's total economic productivity
Technological WCEP intensity	m^3/gigajoule (GJ)	Total water consumption divided by total energy produced, showing the relative water intensity of the energy portfolio
Physical WCEP intensity	%	Total water consumed for energy system as percentage of total internal renewable water resources, reflecting the proportion of water consumed for energy in terms of total available water

to water *withdrawals* (the total amount of water removed but also may be returned to the source water system, as in the case of once-through cooling systems.) While gaps in the data were a significant obstacle to estimating actual water consumption for energy production, a standardized approach allowed for consistent comparability of the water intensity in terms of national technology portfolios for energy production.

In this paper, the original WCEP estimates are normalized by a set of additional national-level indicators (including population, gross domestic product (GDP), total energy production, and regional water availability) to highlight specifically the energy sector's intensity of water consumption. This suite of metrics helps to capture the multiple dimensions of WCEP intensity and to identify locations where energy production may be placing an undue burden on the national water system.

1.1. Comparability of water intensity of energy at the national level

While many publications have made the case that the water and energy sectors are closely intertwined (Gleick 1994, DOE 2006, WEC 2010), the simple understanding that water requires energy and energy requires water is insufficient for understanding the issue's scale at the international level. To do this, we must understand how best to measure the interrelationships between water and energy; then compare these measurements across regions and over time. This paper develops metrics to quantify the global intensity of the energy production sector's demand for water, using the best available data.

Building on previous research that defined the calculation of total WCEP (Spang *et al* 2014), this paper introduces additional indicators to relate the original WCEP estimates to other key national-level indicators, including population, the economy, energy production, and available water. While the original formulation and calculation of WCEP provided insight about these countries' absolute consumption of water for energy, it did not address the *intensity* of water consumption for energy production. In other words, normalizing the estimated water consumption by other national characteristics provides a sense of how efficiently countries use water for energy production. This parallels previous work on metrics to define the intensity of CO_2 emissions (Raupach *et al* 2007) based on similar normalization calculations. WCEP intensity indicators are listed in table 1.

Each indicator provides a view of a particular dimension of the intensity of water consumption for energy, including the magnitude of water consumption (total water consumption), intensity of water consumption normalized by population (per capita water consumption), intensity of water consumption per unit of economic output (economic water intensity), intensity of water consumption per unit of total energy produced (technological water intensity), and intensity of water consumption as a percentage of total available water resources in the country (physical water intensity).

1.2. A geographic approach

While existing literature has been foundational in defining the concept of the 'water–energy nexus' (Gleick 1994, DOE 2006), many of these reports do not address energy systems' water consumption impacts within a geographic context. Every country uses a unique mix of energy processes to supply energy within and across its borders. Because some technologies are significantly more water-intensive than others, the energy technology portfolio has direct implications on the total water required to produce energy in the region. Our objective is to produce results directly relevant to improved policy-making for the regional management of water resources for energy production.

The actual water consumption for energy production is influenced by the age of the energy infrastructure, local climate, quality of source water, and many other factors (Yang and Dziegielewski 2007, Mekonnen and Hoekstra 2010, Macknick *et al* 2011). Due to its global scale, however, this paper cannot provide this level of spatial resolution. Rather, this research focuses specifically on the relative water intensity associated with the technology composition of national energy production portfolios.

Parallel to the spatial distribution of *demand* for water resources is the spatial distribution of water resource *supply*. For nations that have the fewest local water and energy resources, efficient use of these resources is imperative. Indeed, many countries are already operating at the limits of their local energy and water systems. By identifying countries

Table 2. Energy categories and technology/processing subcategories.

Fossil fuel extraction and production	Nuclear fuel extraction and processing	Biofuel cultivation and processing	Electricity generation[a]	
Coal	Uranium ore mining	Rapeseed biodiesel	Steam turbine	Combined cycle
Crude oil	Uranium milling	Soybean biodiesel	Coal	Gas turbine
Oil sands	Uranium conversion	Palm oil biodiesel	Oil and gas	Photovoltaic
Heavy oil	Uranium enrichment	Biodiesel processing	Nuclear	Wind
Oil shale	Fuel fabrication	Sugarcane ethanol	Waste heat	
Oil refining	Fuel reprocessing	Maize ethanol	Biomass	
Dry gas		Sugar beet ethanol	Geothermal	
Shale gas		Ethanol processing	Solar thermal	

[a] Hydropower is not included as a water-consuming energy production technology in this study.

where energy systems' demand for water is out of balance with national supplies, this research highlights regions that merit more detailed examination to prevent future tensions in the water–energy resource space.

2. Methodology

This analysis builds on the WCEP results from a previous study (Spang *et al* 2014), where water consumption for each of the four energy categories (fossil fuels, nuclear fuel, biofuels, and electricity) was calculated, then summed to produce a value for total water consumption of national energy production. Water consumption is treated as a national environmental impact from the deployment of technologies on the supply side of the energy equation (regardless of where that energy is eventually consumed), so it includes the water implications of energy exports but not energy imports.

As discussed in the original WCEP calculation, water consumption for hydropower, which is estimated as the evaporation from the reservoir behind the dam (Gleick 1994, Torcellini *et al* 2003), is ambiguous in its attribution to energy production because most dams serve multiple benefits beyond hydropower, most notably water storage and flood control. Hence, all the WCEP intensity metrics do not include evaporative water consumption for hydropower—an approach accepted in the existing literature (Elcock 2010, Macknick *et al* 2012). A review of energy production processes and technologies included in the original WCEP calculations is given in table 2. This study expands on these results by normalizing the WCEP values for each energy category by population, economy, energy production, and physical water resources to generate four WCEP 'intensity indicators' for each country.

The per capita WCEP captures the intensity of national water consumption for energy, normalized by population. This normalization allows for a more direct comparison of the intensity of WCEP between countries with large and small populations. Per capita water consumption calculations for total energy production are based on dividing WCEP values (Spang *et al* 2014) for each of the four major energy categories (i) by 2008 population data from the World Bank (2011) for each country (j) as listed in (1).

$$\text{Per capita WCEP intensity}_{i,j}\ (\text{m}^3/\text{person}) = \text{WCEP}_{i,j}(\text{m}^3)/\text{population (person)}_j. \qquad (1)$$

Economic WCEP intensity was calculated by dividing the national WCEP estimate by total GDP[5] for each country i as shown in (2). The 2008 GDP data were sourced from the World Bank Data Page (World Bank 2011). This metric provides improved comparability between countries by normalizing the WCEP by the size of the countries on economic terms instead of by population.

$$\text{Economic WCEP intensity}_{i,j}\ (\text{m}^3/\$1000) = \text{WCEP}_{i,j}\ (\text{m}^3)/\text{GDP}_i\ (\$1000). \qquad (2)$$

Technological WCEP intensity is a measure of the overall efficiency of water consumption for energy production, enabling direct comparison national energy production technology portfolios' water consumption intensity. This indicator is calculated by dividing the WCEP value for every country, *i,* by the total energy (fuels and electricity) produced in that country (3).

$$\text{Technological WCEP intensity}_{i,j}\ (\text{m}^3/\text{GJ}) = \text{WCEP}_{i,j}\ (\text{m}^3)\big/\text{Total energy produced}_i\ (\text{GJ}). \qquad (3)$$

The final metric is a measure of physical WCEP intensity, comparing WCEP values to the country's physical water resources to provide a sense of the pressure that water consumption for energy production places on regional water supplies.

Data on available water in each country were taken from the AQUASTAT database (FAO 2011) of the United Nations Food and Agricultural Organization (FAO), which provides a measure of the total actual renewable water resources ($\text{TRWR}_{\text{actual}}$) in each country. $\text{TRWR}_{\text{actual}}$ refers to the 'maximum theoretical yearly amount of water actually available for a country at a given moment' based on internal sources adjusted by flow agreements with any upstream or downstream countries, formal or informal (FAO 2012). The term *renewable* reflects the quantity of water that can be

[5] In this paper, GDP is given using purchasing power parity (PPP)-adjusted 2008 US dollars.

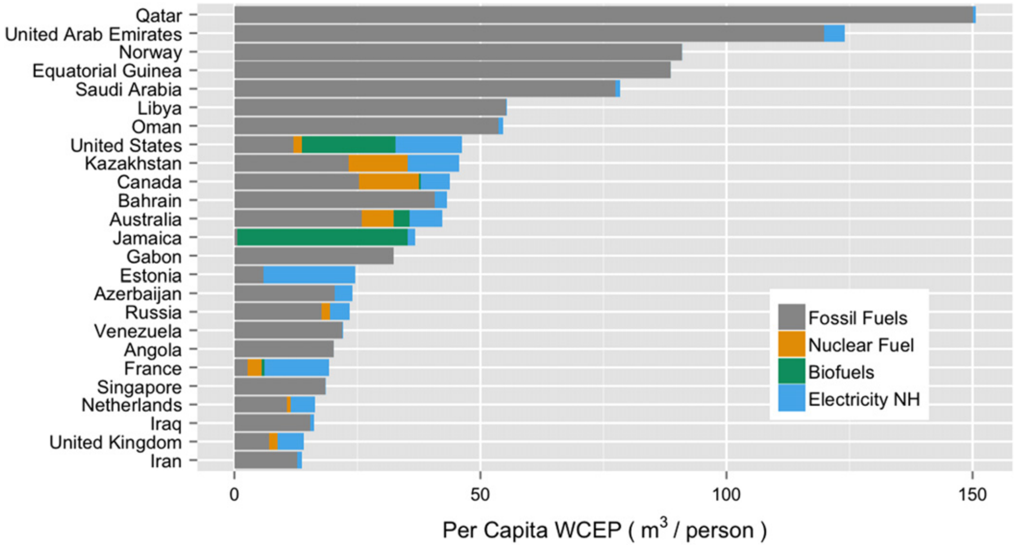

Figure 1. Per capita WCEP intensity by energy category, 2008.

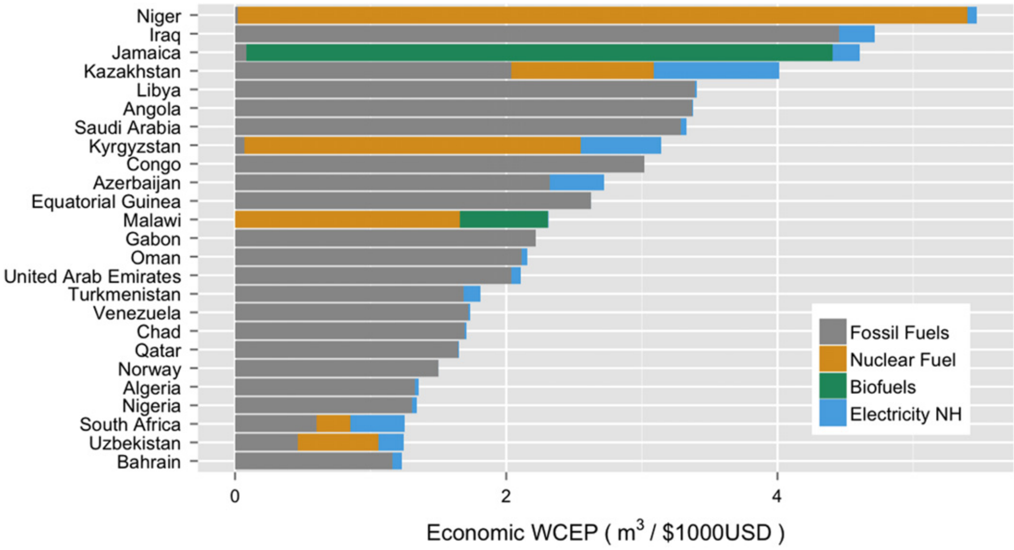

Figure 2. Economic WCEP intensity by energy category, 2008.

naturally regenerated each year and, hence, does not include water sources such as fossil aquifers that have minimal capacity for renewal.

Physical WCEP intensity is calculated by dividing the WCEP estimate for each country, i, by the total actual renewable water resources in each country (4).

$$\text{Physical WCEP intensity}_{i,j}\,(\%) = \text{WCEP}_{i,j}\,(\text{m}^3)/\text{total actual renewable water}_i\,(\text{m}^3)\,. \quad (4)$$

The results of the calculations for all four WCEP intensity metrics are provided in the following section and presented graphically as bar charts of the 25 top-ranked nations for each indicator (figures 1–5). Global maps of WCEP intensity for each indicator (maps SI-1–SI-4) are also provided in supplemental information, available at stacks.iop.org/ERL/9/105003/mmedia, where a complete table of all calculated values can be found (table SI-1).

3. Results and discussion

The ranking of nations' WCEP intensity varies significantly depending on the intensity indicator applied. The following sections detail the calculations for each of the four water consumption intensity indicators (per capita, economic, technological, and physical) for total non-hydro energy production within each country, as described in the methodology.

3.1. Per capita WCEP intensity results

Per capita country rankings for water consumption of non-hydro energy portfolios, shown in figure 1, highlight the intensity of water use in many smaller countries that did not show up in the original rankings of total WCEP (Spang *et al* 2014). The top five slots are dominated by the oil-rich countries of Qatar, United Arab Emirates, Norway, Equatorial Guinea, and Saudi Arabia. Indeed, seven of the top eight

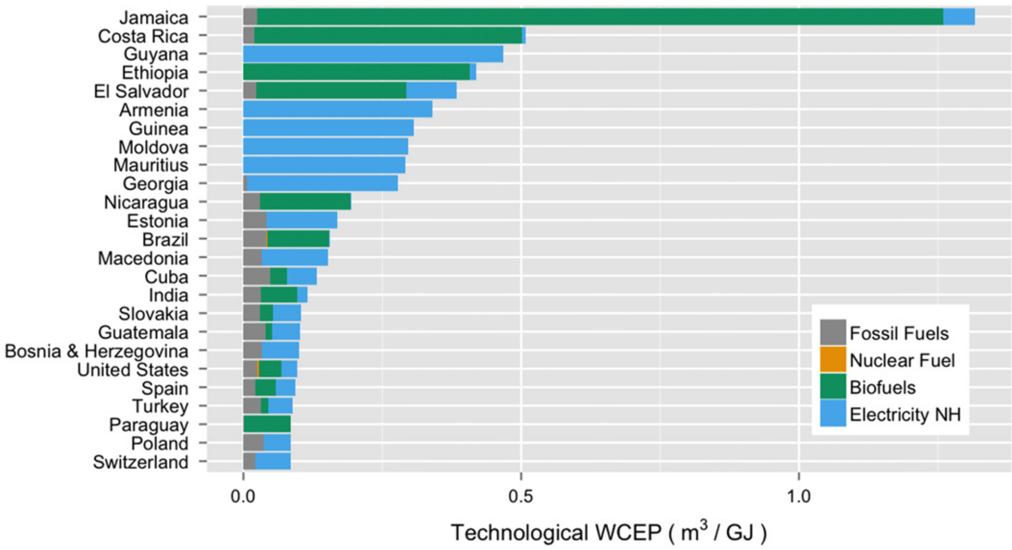

Figure 3. Technological WCEP intensity by energy category, 2008.

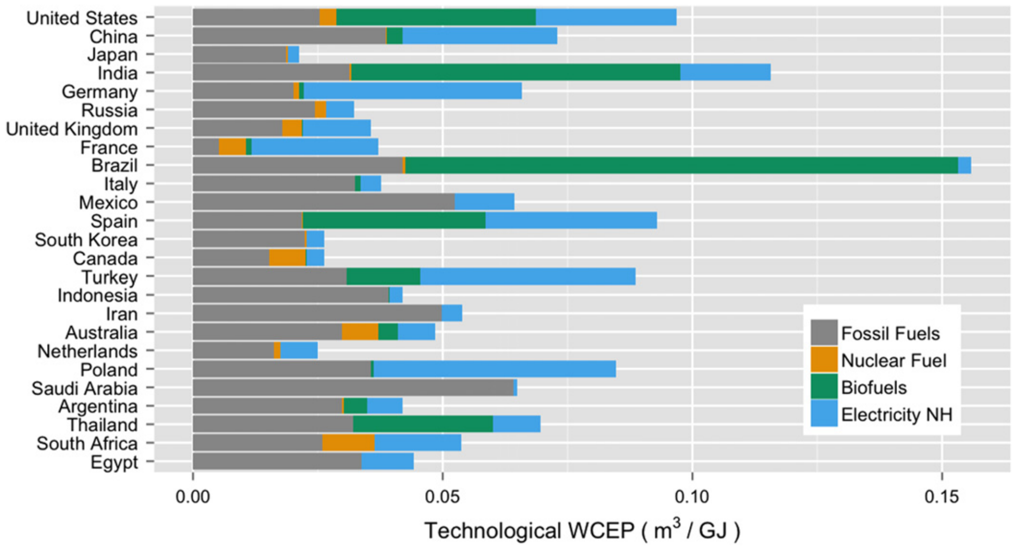

Figure 4. Technological WCEP intensity with countries ranked by PPP-adjusted GDP, 2008.

ranked countries for per capita WCEP have energy portfolios dominated by fossil fuel production and processing. This suggests that availability of fossil fuel resources within the borders of a country is a major driver for intensive per capita WCEP. Further, many top-rated countries are in the arid Middle East (including Qatar, the United Arab Emirates, Saudi Arabia, Oman, and Bahrain), where water use in the fossil fuel category is predominantly for oil extraction and production. Given their dry climate, these countries are likely to be more vulnerable to intensive water use for energy production.

After fossil fuels, biofuels production plays a significant role in elevating per capita WCEP intensity in the United States and Jamaica. Nuclear fuel production contributes noticeably to the per capita WCEP for Kazakhstan, Canada, Australia, and France. Meanwhile, electricity generation plays a role in higher per capita WCEP for Estonia and France. Both of these countries have a disproportionate amount of electricity production from the water-intensive technologies of fuel oil-based (Estonia) and nuclear fuel-based (France) thermoelectricity generation (Macknick *et al* 2011, Meldrum *et al* 2013, Spang *et al* 2014).

Unsurprisingly, many heavily populated countries that appeared high in the total WCEP rankings (Spang *et al* 2014), including China, India, and Russia, fall out of the rankings when their large populations are placed in the denominator of a normalization equation, as in (1). Though these countries consume huge amounts of water for energy production in absolute terms, in global comparison they use less water for energy production per resident.

3.2. Economic WCEP intensity results

Figure 2 shows the results of calculating economic WCEP intensity, which provides an estimate of WCEP per $1000 of national GDP. Normalizing water consumption by economic

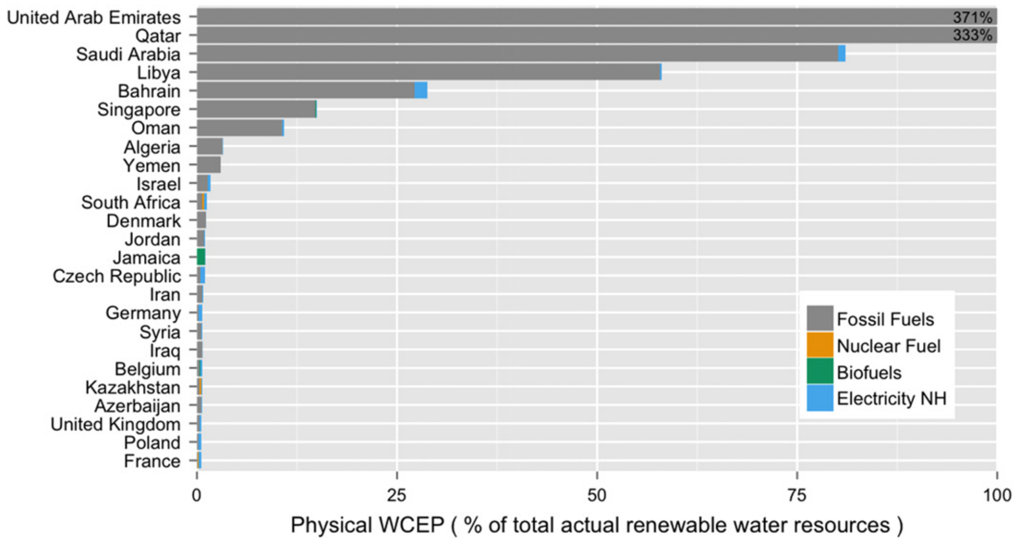

Figure 5. Physical WCEP intensity by energy category, 2008.

productivity gives a sense of the economic efficiency of resource use at the macro scale. For example, if fossil fuel production requires high levels of water consumption but generates significant income for the country, the relative economic WCEP 'intensity' decreases, reflecting the economic value of the water consumption.

Economic WCEP intensity indicators tend to be magnified for poor countries. With a lower GDP value in the denominator to normalize total WCEP, poor countries have a relatively higher intensity of energy-based water consumption, per (2). This trend is shown clearly in figure 2, where less developed countries with relatively water-intensive energy systems dominate the rankings, while wealthier North American and European countries fall from the rankings completely.

Fossil fuel production consistently drives high economic water intensity for most countries in the rankings, but nuclear fuel production plays a notable role in Niger, Kazakhstan, Kyrgyzstan, and Malawi, while biofuel production drives higher economic WCEP intensity in Jamaica and Malawi.

3.3. Technological WCEP intensity results

The technological intensity of water consumption is calculated by dividing the WCEP by the total amount of energy produced. For this calculation, hydropower produced is included in the denominator as part of total energy production, but not in the numerator as a water-consuming technology (since reservoir evaporation cannot be strictly attributed to energy production). As shown in figure 3, the results highlight countries with a disproportionate share of biofuels in their energy portfolio, but water-intensive electricity production also shows up consistently in the rankings. Smaller countries with less diverse energy portfolios are overly represented in this ranking because their minimal overall energy production quickly amplifies the impact of any water-intensive technologies.

Figure 4 compares technological WCEP intensity across countries with the largest economies (ranked by PPP-adjusted GDP, 2008). Because these countries tend to have more diverse energy portfolios, there is less bias toward small, biofuel-intensive energy producers. There is large variation in the technological intensity of water consumption for energy across these top economic producers. For example, even though the United States' economy is approximately nine times that of Brazil, Brazil's technological intensity of water consumption for energy is nearly twice that of the United States.

Clearly, the level of a country's commitment to biofuels significantly impacts its technological intensity of water consumption for energy. This makes sense, as biofuel cultivation and processing consume 10–100 times more water than other energy processes. Without biofuels in the mix, variation in the technological intensity of water consumption for energy decreases significantly.

Japan stands out in the rankings as the third largest economy (in 2008), but with significantly lower water consumption for energy systems. This is attributable to Japan's lack of biofuel production and its reliance on seawater cooling at most power plants (Platts 2010), which is not counted toward *freshwater* consumption for energy production, as WCEP is defined by Spang *et al* (2014).

Brazil exhibits by far the greatest technological intensity of water consumption, approximately $0.16\ m^3\ GJ^{-1}$. The United States, India, Spain, Turkey, and Poland show similar levels of technological intensity of water consumption for energy, ranging from roughly 0.075 to $0.125\ m^3\ GJ^{-1}$, while China, Germany, Mexico, Iran, Saudi Arabia, Thailand, and South Africa fall in the range of 0.050 to $0.075\ m^3\ GJ^{-1}$. The most important conclusion to draw from this is that water consumption for energy is not necessarily tethered to economic development directly, but can be decoupled to allow economic productivity without intensive water for energy demands.

3.4. Physical WCEP intensity results

Physical WCEP intensity assesses countries' water consumption for energy in terms of water available within its national boundaries. This intensity indicator is useful for linking energy systems' water requirements to the regional water resource context and allows for the identification of 'hot spot' countries that use an unusually high percentage of regional water resources for energy production.

Physical WCEP intensity is calculated by dividing national WCEP by the total actual renewable water resources in a country to calculate a percentage value for the energy-based use of existing water supplies (see table 1). Country rankings for physical WCEP intensity are provided in figure 5.

Figure 5 shows seven countries using more than 10% of total renewable water supplies for energy production—significantly more than all other countries in the ranking. These countries can be considered 'hot spot' countries considering their disproportionate consumption of national water resources for energy production. The Middle East/North Africa region has the most countries classified as hot spots: six of the seven hot-spot countries (the UAE, Qatar, Saudi Arabia, Libya, Bahrain, and Oman) are in this region. The remaining country, Singapore, ranks highly because of its oil refinery production in the context of minimal renewable water supplies.

Fossil fuel-intensive countries dominate the rankings. This makes sense, as many of the largest oil-producing nations are in the arid Middle East and the economic imperative to exploit oil and other fossil fuel resources may surmount concerns about regional water availability. Many Middle Eastern countries avoid the direct conflict between energy production and water shortages by desalinating brackish water and seawater (a highly energy-intensive process) to use as an input for the oil recovery process (Wu *et al* 2009, FAO 2011). In these countries, fossil fuels are effectively turned into water (via desalination), to facilitate the production of more fossil fuels—a robust example of a tightly coupled water–energy nexus.

In the most extreme circumstances, the WCEP amount significantly exceeds the total available water resources in the country, as is case for the two highest-ranked nations in figure 5. Both the United Arab Emirates (UAE) and Qatar use roughly 3.3–3.7 times (~350%) their total available internal water resources for fossil fuel production. While it may seem impossible to use over three times more water than is actually available in the country, this overshoot can be explained in terms of the definition of total actual renewable water. This definition of water supply does not include unconventional sources of water (such as recycled or desalinated water), and desalination plays a fundamental role as a water source in both Qatar and the UAE, where it supplements the naturally renewable water supply by more than three and six times, respectively (FAO 2011).

Additionally, the quality of the available data may lead to elevated estimates of water consumption for fossil fuel production. The quality of source water (brackish versus fresh water) for oil extraction is not specified in the global data, nor is the method of oil extraction (conventional pumping versus enhanced oil recovery (EOR), such as water flooding). The water consumption estimate for oil production used in this study was a universal average of freshwater consumption for conventional and EOR methods, which could exaggerate consumption in countries using mostly conventional methods or primarily brackish water.

4. Conclusion

To understand the global distribution of the intensity of water consumption for energy at the national level, the results of WCEP calculations from a previous study (Spang *et al* 2014) were used to produce four different WCEP 'intensity' metrics: per capita, economic, technological, and physical. Normalizing the original WCEP estimates by other national-level indicators allows for direct comparison between countries on the relative efficiency of water consumption for energy production. For the indicators, the absolute magnitude of water use represents the scale of the pressure on the regional water system, and the intensity of use (provided by the additional four indicators) highlights regions where water is not used efficiently. The results demonstrate significant variation in water consumption by country, energy type, and indicator, underscoring the idea that water consumption for national energy production is a multidimensional issue requiring multiple metrics to assess.

Because the volume of water consumed varies significantly by energy technology and process, the composition of national energy portfolios drives the intensity of energy system water consumption. Looking across the four metrics of intensity, the two energy categories consistently driving higher WCEP intensity were fossil fuel and biofuel production. In other words, both fossil fuel and biofuel production have key impacts on the intensity of water use by energy systems.

Fossil fuel production drives intensive water consumption in many countries because the intrinsic economic value of these fuels transcends local water limitations. Indeed, the majority of countries identified as hot spots (in terms of WCEP representing more than 10% of total water resources in the country) were major oil-producing nations in the Middle East and North Africa. Many of these countries use desalinated water for industrial fossil fuel production, thereby are effectively manufacturing water to continue producing fossil fuels beyond local regional water limitations.

A national commitment to biofuel production leads to intensive water consumption for energy across multiple indicators because of the fundamentally high water requirements to cultivate biofuel feedstocks. However, with the exception of Brazilian ethanol, biofuels have not yet proven themselves economically viable at a large scale (Mekonnen and Hoekstra 2010), so unlike fossil fuels, the economic imperative to override local water limitations for biofuel production does not appear to be a dominant global trend. Meanwhile, biofuels' high water requirements also serve as a barrier to entry for most countries already experiencing significant water stress, as demonstrated by the relative absence of this technology in the physical WCEP rankings.

While fossil fuels and biofuels play leading roles in driving country-level WCEP intensity, electricity production also contributes significantly to overall national water use. However, given the diversity of technologies available to produce electricity and the associated range of water input requirements, the countries identified above as having high water consumption for electricity have multiple options to reduce water consumption while still meeting electricity demand. A better mix of technologies might reduce their impact on already limited water systems as well as reduce their electricity systems' vulnerability to potential interruptions from water shortages.

Further, remembering that the WCEP indicator focuses solely on energy production (including exports, but not imports), the metric will show countries with a high reliance on energy imports as having a low intensity of water consumption. This relationship demonstrates an important tradeoff between traditional concerns about water and energy security. Whereas a high reliance on energy imports might represent a potential energy security concern, it also reflects a reduced burden on local water supplies for energy production, i.e. improved water security. Hence, this tradeoff may offer opportunities for nations to actively influence their energy trade balance in response to the dynamic local context of energy security, water security, or both.

Finally, while it is useful to compare WCEP intensity internationally, one of the limits to a global study of this nature is a lack of granularity in the indicators. This is especially important when trying to place water use in the context of regional water scarcity. The availability of water varies significantly between countries, but also across the local and regional scales within countries. For example, China is not classified as water-stressed at the national level, but in certain regions of China, water scarcity is profound (IWMI 2008). Future research on WCEP intensity should incorporate higher-resolution data on both energy production and water use for a more robust identification of regional WCEP hot spots around the world. Producing higher-resolution assessments of WCEP intensity should lead to both improved policies and more clearly identified market opportunities. Any advances in hot spot regions to decouple energy systems from vulnerable water supplies could drive technological change that spills over to other countries, and possibly other sectors.

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