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A framework for understanding energy for water

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ABSTRACT

This article offers a framework for understanding how energy is used to meet water demand in countries. Specifically, the relationships between energy use and water scarcity, the location of renewable water resources, and aggregate water demand are explored. The article also examines how policy options such as water price reforms, agriculture subsidies and crop elimination may influence the energy use and energy intensity of water withdrawals. Conclusions suggest that while policy options exist, certain uncontrollable factors such as severe water scarcity or substantial freshwater abundance limit the ability of some countries to significantly improve the aggregate energy efficiency of water provision.

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Introduction

Oceans cover 71% of the earth's surface and represent over 96% of the world's total water resources. Of the remaining water, half is frozen in glaciers or ice caps and a quarter is locked in saline underground aquifers. This leaves less than 1% of the world's total water resources available for consumption by life on earth, a small percentage in relative terms, but a figure representing 10.6 million km³, or 1.5 million m³ per person (own calculations, data from Gleick, 1993). As the hydrological cycle results in much of the world's freshwater being recycled after consumption, the current stock of water is more than enough to sustain life on earth.

While there is enough freshwater on earth, nearly 20% of the world's population faces physical water scarcity, a situation in which there is insufficient water to meet the demands of the ecosystem. The United Nations estimates that if population and economic growth continue to strain the world's water resources, roughly two-thirds of the world's population could be living in water-stressed regions by 2025 (United Nations Department of Economic & Social Affairs [UNDESA], 2014).

One of the fundamental components in addressing physical water scarcity is energy. This is because energy is a primary input for moving water from areas of relative abundance to areas of relative scarcity. For example, in California, water from the abundant north of the state travels hundreds of kilometres over the eastern Sierra Nevada mountain range in order to meet demand in Los Angeles, a region of increasing physical water scarcity. The energy

required to transport water this distance is estimated to be 1.6 kWh/m³, or three times the energy required to extract and treat water withdrawn from sources in Los Angeles (Wilkinson, 2000). The need for energy-intensive interbasin water transfers is expected to increase as the population and economy of the city grow.

In Jordan, a severely water-scarce country, a different sort of water transport occurs. Groundwater from aquifers located more than 1 km below the earth's surface is extracted for use by municipalities and agriculture. This extraction comes at a tremendous energy cost. Hayek (2014) estimates that the average energy required to extract groundwater in Jordan is roughly 1.2 kWh/m³, or nine times the energy required to withdraw groundwater in the Netherlands, a country also reliant on groundwater, but with much shallower bores (Imperial Irrigation District, 2015). The case of Jordan is important because the country imports 97% of its energy from neighbouring countries, and these energy supplies are largely in the form of non-renewable fossil fuels that can experience large fluctuations in price (Talozi, Al Sakaji, & Altz-Stamm, 2015).

In rare cases, such as Spain, Australia and the Gulf region, seawater is desalinated, as neither interbasin transfers nor deep aquifer extraction are sufficient to meet water demand. Desalination represents the most energy-intensive option for meeting water demand, and often entails significant financial and environmental costs.

Exploring the relationship between energy and water demand is important for two reasons. First, a significant amount of energy is used for direct water services. For example, Sanders and Webber (2012) have estimated that 8.3% of 2010 annual primary energy consumption in the United States was used for the heating, chilling, treating, pressurizing and pumping of water by the municipal, industrial and agricultural sectors. Thus, water conservation can have a direct effect on energy use, which can help improve energy security and climate change objectives, particularly when fossil fuels are used as the energy source.

Second, while water and energy are inextricably linked, they are typically governed in silos, which can lead to policy fragmentation and a misalignment of incentives. In general, the energy sector considers water only as it relates to hydropower and water requirements for thermal power plants. Similarly, water planners are typically more concerned with supply augmentation and management, as opposed to energy issues (Malik, 2002). Improving coordination of the management of water and energy resources can increase efficiency in both areas. For example, Kumar, Scott, and Singh (2013) have shown that power tariff reform that includes pro rata pricing and higher unit rates for electricity would likely lead to improved efficiency and sustainability of groundwater use by farmers in India. This is an important consideration given that in 2010 India extracted 684 km³ of water for agriculture, a figure representing 90% of total extractions (<http://www.fao.org/nr/water/aquastat/data/query/>).

This article offers a framework for understanding how energy is used to meet water demand in both water-scarce and water-abundant countries. Specifically, the supply and demand of water, and the energy required to withdraw that water, are disaggregated: supply is disaggregated by source and treatment process, while demand is disaggregated by user. This approach helps policy makers understand the ways decisions in one domain can affect the other, thus building the case for more integrated management of the water–energy nexus. Through a detailed examination of how energy is used for water supply, and how water is used in the economy, the framework also provides policy makers with a tool for assessing the possibilities (and limits) of efficiency improvements in both domains.

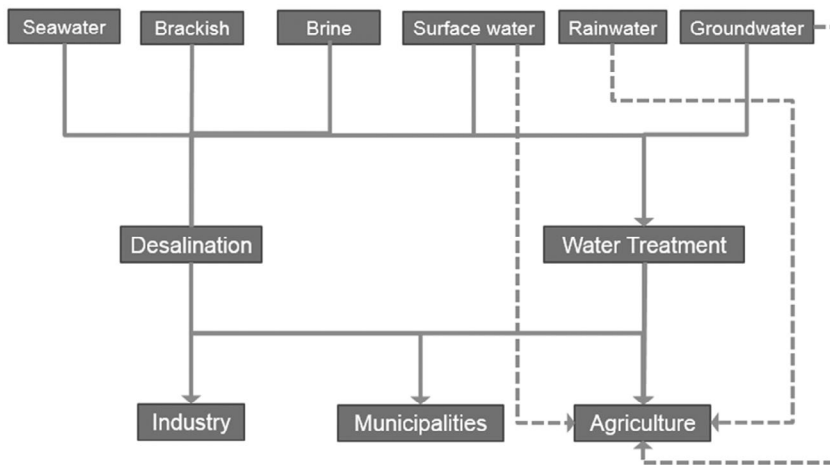


Figure 1. Sources and uses of water.

The article's conclusions are threefold. First, energy use for water is a function of not only water scarcity, but also the location of renewable water resources: countries with abundant renewable water resources that are located in deep aquifers, or far from demand centres, may still require substantial energy resources to meet water demand. Second, while economic solutions for managing water resources exist, they can be politically sensitive, and therefore difficult to implement. This often results in the overuse of water, which can lead to increases in both aggregate energy use and overall energy intensity of water extraction. Last, while some countries can reduce the energy used for water by eliminating water-intensive agricultural crops, certain uncontrollable factors, such as severe water scarcity or high water abundance, reduce the efficacy of this option. By disaggregating and exploring how supply and demand for water can affect energy use, this article offers a theoretical framework through which to examine the case studies on managing energy for water presented in this special issue.

The supply of water: implications for energy

As described in Figure 1, water can come from both conventional and unconventional sources. *Conventional sources* refers to surface water, groundwater and rainwater, all of which may be treated and then consumed, or sent directly from the source to the final consumer. *Unconventional sources* refers to seawater, brackish water, brine and wastewater, which must be purified by advanced treatment technologies prior to consumption.

The energy required to meet water demand is dependent on the type of water used, whether it is treated, and the technology used for treatment. In almost all cases, water used for agriculture is untreated, and thus consumes the least energy. For example, rainwater consumed directly by agriculture incurs effectively no energy footprint; and untreated surface water requires only minimal energy for extraction. As farmers begin to extract water from underground bores or use desalinated water, energy requirements increase.

Water extracted for municipal and industrial use is typically purified prior to consumption. This can increase energy requirements. Surface water is often contaminated and must be pumped through numerous filters and disinfected with chlorine and other chemicals before

being distributed to the water grid. Groundwater, in contrast, is typically cleaner, and does not require much treatment aside from the addition of chlorine and other purifying chemicals. As a result, most of the energy required to withdraw and purify groundwater is used for extraction (Burton, 1996; Copeland, 2014; Plappally & Lienhard, 2012).

The energy required for unconventional water withdrawals is a function of three factors: the type of water withdrawn; the quantity of water withdrawn; and the desalination technology used. Two primary types of desalination technologies exist: thermal and membrane. Thermal desalination is a process in which saline water is vaporized, thus separating pure water from any salts, minerals and other contaminants (Tonner, 2008). Membrane desalination is a process whereby saline water is passed through one or more semipermeable membranes. The membranes separate pure water from salts and other impurities. The energy required for thermal desalination processes such as multistage flash distillation (MSF) and multiple-effect distillation (MED) is higher, and is independent of the salinity or the source of water. In contrast, the energy required for membrane technology, such as reverse osmosis (RO) and electrodialysis (ED), is generally less, and varies with the salinity of water: the more saline the water, the more energy-intensive the extraction and treatment. In addition to the specific technology used, other factors will affect the energy required for desalination, including output capacity of the plant, thermal design, membrane type (for membrane technologies), efficiency of the plant, and system configuration. The latter is important to consider for dual-purpose plants (i.e. plants designed for power and water production). While global online seawater desalination capacity increased significantly between 2000 and 2014, from 0.72 km³ to 13.73 km³ (Global Water Intelligence, 2015), given its high capital and energy costs, the technology contributes only a small fraction to overall water supplied.

Figure 2 describes how energy use increases with different water sources and extraction technologies. With the exception of rainfall, untreated surface water requires the least energy for extraction, with the variance in energy required due primarily to the varying efficiency of pumps for extraction. In emerging economies, where pumps are often less efficient and energy costs are lower, energy intensity is generally higher. The figure also shows that while some water sources are more energy-intensive than others, each source has a large range of possible energy intensities. For example, while it is generally assumed that treated wastewater is more energy-intensive than groundwater extraction, this may not be the case when groundwater bores are deep and pumps are inefficient. This is an important consideration in water-scarce countries that must rely on deep groundwater aquifers. Wastewater treatment may also offer a less energy-intensive alternative to desalination. In Saudi Arabia, a severely water-scarce country, the government has begun to encourage the reuse of wastewater, and plans have been put in place to expand wastewater collection and treatment systems to cover about 60% of urban areas by 2014 – up from 42% in 2010 (Ouda, 2014). To date, much of the recycled water has been used for urban-area landscaping and, to a lesser extent, crop irrigation (Ouda, 2014). It is hoped that wastewater will help alleviate stress on non-renewable aquifers through less energy-intensive, cheaper means than can be offered by desalination. The case of Saudi Arabia shows that when countries understand the economic and energy implications of different water sources, it is feasible for strategies to be implemented that minimize these costs.

An important source of water that is not considered in Figure 2 is water transported over long distances. Lack of data and extreme differences in the characteristics of water transport networks make it difficult to establish useful energy-intensity ranges for water transport at

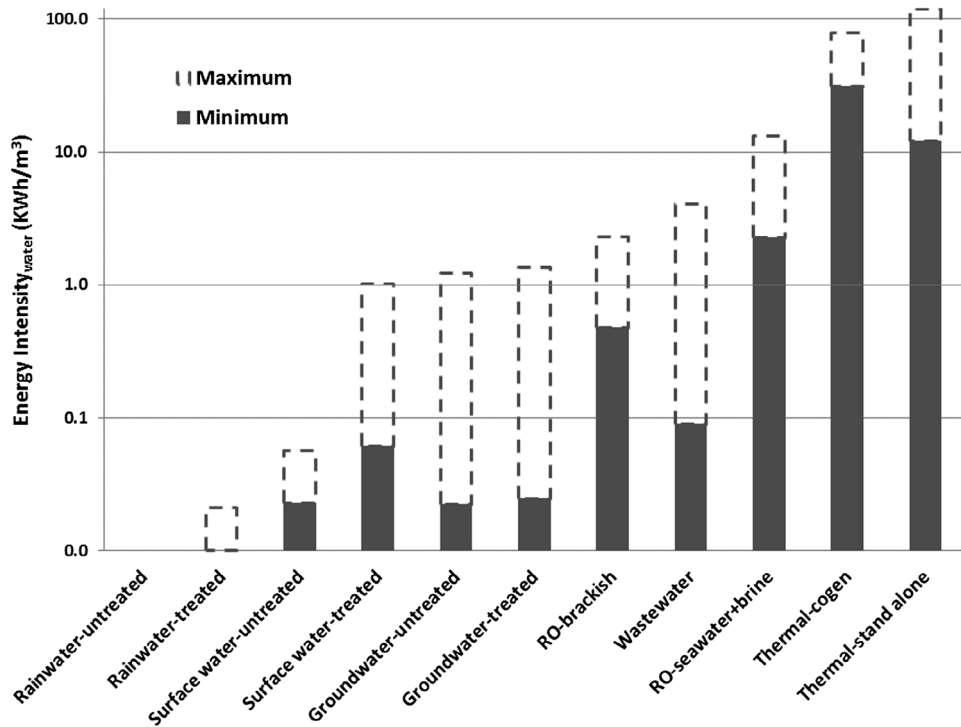


Figure 2. Energy required for different types of water. Sources: Al-Karaghoul and Kazmerski (2013), Abdel-Jawad (2001), Buenomena (2013), Darwish, Al-Najem, and Lior (2009), Drewes (2011), Global Water Intelligence (2015), Hamed (2004), Hayek (2014), Ludwig (2010), Matar, Murphy, Pierru, and Rioux (2014), Plappally and Lienhard (2012), Veera (2011), Vieira, Beal, Ghisi, and Stewart (2014). Note: Vapour compression (VC) desalination is a modified form of the MED process where the evaporation of seawater is obtained by the application of heat through a mechanical compressor. In this unique process, the energy requirements are lower than MSF/MED thermal cogeneration technologies, which is why the 'thermal stand-alone' technology has lower potential minimum energy requirements. In general, thermal cogeneration processes are less energy-intensive than thermal stand-alone processes.

the national level. For example, when water transport systems are gravity-fed, such as the All-American Canal, located in Southern California adjacent to the Mexican border, energy can be produced from hydroelectric power plants. The All-American Canal is used to transport 3.8 km³ of water 82 miles from the Colorado River to the Imperial Valley (Imperial Irrigation District, 2015), and the process generates more than 253 million kWh of electricity on an annual basis. In contrast, the proposed Ebro project in Spain that sought to transfer 860 GL/y of water from the Ebro River a distance of 745 km to the south of the country was predicted to require roughly 4 kWh/m³ (Marcuello, Capilla, Murillo, Barcones, & Meyer, 2003; Plappally & Lienhard, 2012). The Ebro water transfer project was cancelled in 2004 due to social, environmental and economic concerns. Studies suggested that the project would have led to the disappearance of the Ebro Delta, an important wetland in Spain, and that the economic costs would have been higher than initial government estimates (World Wide Fund for Nature [WWF], 2003).

According to Plappally and Lienhard (2012), energy intensity of water transport systems is location-specific, and dependent on factors such as pipeline grade, the soil's seepage or percolation properties, solar radiation and climatic behaviour in a given geographical

region. Although difficult to generalize, energy for water transport can represent a significant proportion of the total energy required to meet water demand. For example, Hardy, Garrido, and Juana (2012) have estimated that 21% of the total energy used to meet water demand in Spain goes to distribution and water transport. It should be noted that while historically water transport was primarily used to address municipal water-scarcity challenges, it is increasingly being used for agriculture and industry.

Water scarcity and energy use

The water scarcity of a country is traditionally measured as the ratio of its water withdrawals to total renewable water resources (Brown & Matlock, 2011). If a country withdraws less than 20% of its total renewable water resources it is considered water-abundant. When a country withdraws between 20% and 40% of total renewable water resources it is considered water-scarce; and when the ratio exceeds 40%, the country is considered severely water-scarce.

Figure 3 estimates the relationship between water scarcity and the aggregate energy intensity required to provide a cubic metre of water in a sample of countries. Water-scarcity ratios were obtained from Aquastat (<http://www.fao.org/nr/water/aquastat/data/query/>) and national accounts. Energy data were compiled by estimating three sources: untreated surface and groundwater, treated surface and groundwater, and desalinated unconventional water. Given data limitations for numerous countries, energy for interbasin water transport and wastewater treatment were not included in the calculations, and so the energy intensity is probably underestimated, particularly in water-scarce regions where large interbasin water transfers occur or where substantial wastewater treatment occurs.

The energy required to extract untreated surface water was estimated to be 0.023 kWh/m³ for OECD countries and 0.034 kWh/m³ for non-OECD countries. These values were calculated based on a theoretical lift parameter (l , 2.73 kWh to lift 1000 m³ a height of 1 m), a hydraulic head (h) of 5 m, and a pump efficiency (ϵ) of 40% for non-OECD countries and 60% for OECD countries, and described in the equation below.

$$e_{GW} = \frac{l * h}{\epsilon}$$

This equation has been used to estimate energy for water extraction in a number of studies, notably that of Nelson et al. (2008). While the efficiencies of pumps can vary within and between countries, particularly when both electrical and diesel pumps are used, the assumptions and results obtained are in line with case studies from both developed and emerging economies (Abadia, Rocamora, Ruiz, & Puerto, 2008; Japikse, Marscher, & Furst, 1997; Moreno, Carrion, Planells, Ortega, & Tarjuelo, 2007; Shah, 2009). Energy for untreated groundwater was estimated in the same manner, with groundwater depths coming from a variety of government figures and academic studies. Energy for treated water in countries came from academic studies and reports from utilities, while energy for desalinated water was derived from numerous academic and government sources (see sources section of Figures 3 and 6). Despite the use of aggregated data, sensitivity analysis in which pump efficiencies and energy requirements for water treatment were varied under multiple scenarios did not greatly alter the aggregate relationships between countries. Given this, one can assume that the analysis above offers a reasonable estimate of the relationship between water scarcity and energy intensity for water in the sample of countries.

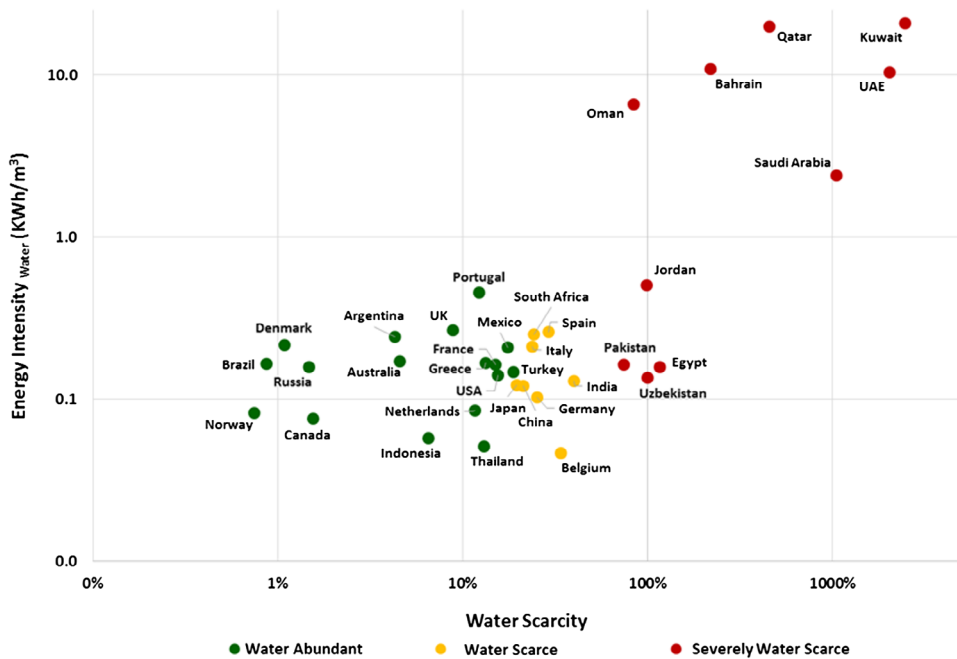


Figure 3. Energy intensity of water (extraction and treatment) and water scarcity in a sample of countries. Sources: Abderrahman (2001), Agenda 21 Della Terra d'Arneo (n.d), Al-Karaghouli & Kazmerski (2013), Al-Mashaikhi (2011), Al-Mooji, Hofstetter, & Renck (2013), Abdel-Jawad (2001), Aqualogy (<http://www.aqualogy.net>), Aquastat (<http://www.fao.org/nr/water/aquastat/data/query/>), Association of Private Water Operators (2013), Australian Bureau of Statistics (2014), Basharat (2012), British Geological Survey (2015), Buenomena (2013), Bundesanstalt für Geowissenschaften und Rohstoffe (2015), Burton (1996), Campanelli, Foladori, and Vaccari (2013), Chan (2013), China Urban Water Association (2012), Chudaeva et al. (2008), CONAGUA (2014), CONUEE (2011), Copeland (2014), Darwish et al. (2009), Department for Environmental, Food and Rural Affairs (2008), Department of Environment, Water and Natural Resources (2014), Dimakis, Colleuille, & Wong (2005), Drewes (2011), ECRA (2011), El Tahlawi, Farrag, and Ahmed (2008), Encyclopedia of Desalination and Water Resources (2014), Entidade Reguladora dos Serviços de Águas e Resíduos [ERSAR], (2012), Environmental Agency Abu Dhabi (2014), European Benchmarking Cooperation (2014), European Environment Agency (2014), Frijns, Mulder, and Roorda (2008), Gaut (2010), Global Water Intelligence (2015), Godskesen, Hauschild, Rygaard, Zambrano, and Albrechtsen (2013), Hadian, Mardiana, Abdurahman, and Iman (2006), Hamed (2004), Hardy et al. (2012), Hayek (2014), Hernández-Mora, Martínez-Corona, Llamas-Madurga, and Custodio-Gimena (2010), Imperial Irrigation District (2015), International Groundwater Resources Assessment Centre [IGRAC] (<https://ggmn.unigrac.org>), Japan Waterworks Association (2014), Lemos, Dias, Gabarrell, and Arroja (2013), Ludwig (2011), Karimov et al. (2015), Kenway et al. (2008), Kumar (2013), Kwanyuen, Mainuddin, and Cherdchanpipat (2003), Li, Liu, Zheng, Han, and Hoff (2015), Maas (2009), MacHarg and McClellan (2004), Matar et al. (2014), McLay (2005), McMahon and Price (2011), Margat and van der Gun (2013), Ministry of Water & Electricity (2010), Ministry of Water and Irrigation (2015), Nelson et al. (2008), Natural Resources Canada Database (2014), Papapetrou, Wieghaus, & Biercamp (2010), Pearce (2007), Peng (2014), Plappally and Lienhard (2012), Portela and Cohim (2011), Qatar General Electricity and Water Corporation (2014), Queensland Department of Natural Resources and Mines (2014), Raucher et al. (2010), Reboucas (1999), Renzoni and Germanin (2007), Saatçı (2015), Shah (2009), Tao (2012), Tech Archival (2014), Trans Adriatic Pipeline-TAP (2015), Shimizu, Dejima, and Toyosada (2012), Veera, Nirmalakhandan, and Deng (2010), Veera (2011), Venkatesh (2011), Vince (2007), Wang et al. (2012), Water in the West (2013), Water Resources Policy Division, Land and Water Bureau (2006), World Health Organization and UN ICF (2014).

It is often assumed that energy intensity and water scarcity are positively correlated. As Figure 3 shows, this is true when the severely water-scarce countries of the Gulf region are considered. The Gulf countries contain almost no surface water, and so they rely on desalination and deep underground fossil aquifers in order to meet water demand. For example, the United Arab Emirates obtains 24% of its water from desalination, while 70% comes from fossil aquifers, and only 6% from surface water. Fossil aquifers take thousands of years to form, and when water is withdrawn from them, the total water available for future generations decreases. The Environment Agency of Abu Dhabi estimates that water levels in the agricultural region of Al Khazna fell from 56 m to 96 m between 1999 and January 2014, while water levels just north, in Sweihan, fell from 46 m to 104 m between 1998 and 2013 (Malek, 2015). The non-renewable nature of these aquifers causes them to fall when water is extracted; and as water levels drop, the energy costs for extraction rise.

When excluding the Gulf region, however, there is effectively no correlation between the energy intensity of water extraction and water scarcity. For example, the severely water-scarce countries of Pakistan and Egypt use less energy per unit of water extracted than Portugal, a water-abundant country. The primary differences between these countries are twofold. First, while Portugal enjoys abundant renewable freshwater resources, these resources exist as groundwater, which, as stated, requires more energy for extraction compared to surface water. In Portugal, 74% of the total water supply comes from underground aquifers. In contrast, Egypt obtains 89% of its water from the surface, primarily the Nile Delta, while Pakistan obtains 65% of its water from lakes and rivers. Thus, while the total renewable water resources in Egypt and Pakistan are being exhausted more quickly than in Portugal, the energy requirements for this extraction are lower, as the water is being extracted from more accessible sources.

Second, water scarcity estimated at the national level can be misleading. This is because regional differences within a country can have a profound impact on actual water resources readily available to the populace. Portugal is not considered a water-scarce country because of the abundant water resources in the country's north. Much of the country's population and agricultural activity, however, are located south of the city of Porto, where water resources are scarcer, and so groundwater from deeper sources must be withdrawn. In Egypt and Pakistan, while renewable water resources are scarcer at the national level, they are much more accessible to the population, and thus require less energy. The situation is similar in Australia, a country considered water-abundant due to the extensive water resources located in the tropical north, despite the fact that an estimated 65% of the population live in water-scarce regions (own calculations, data from Australian Bureau of Statistics, 2015; Chartres & Williams, 2006; *The Economist*, 2007; World Bank, 2015). While imperfect, national water-scarcity calculations are still useful as they offer a theoretical indication of the water resources that can be mobilized by the state for extraction and consumption.

An additional factor that can affect the relationship between water scarcity and energy intensity is total water withdrawals. Consider the cases of the United Kingdom and Spain. The two countries have similar energy intensities despite the fact that Spain is a more water-scarce country, uses far more desalination, has deeper average groundwater bores, and extracts more than twice the groundwater (roughly 5.7 km³ compared to 2.16 km³; <http://www.fao.org/nr/water/aquastat/data/query/>). The similarities in energy intensity are due to the way water is used in agriculture. In the UK, the total value added by agriculture in 2013 was only USD 12 billion, or 0.5% of the nation's total GDP (in constant 2005 USD; United

Nations Statistics Division, 2015). The UK enjoys ample rainfall, and so it only extracts roughly 1.3 km³ of water to achieve that agriculture production. Spain is a far dryer country, but in 2013 its agriculture sector contributed 3% to the GDP, a figure representing USD 35 billion. Because of the sector's size and the country's climate, Spain must extract 20 km³ of water for agriculture. While Spain extracts far more water for agriculture than the UK, over 79% of this water comes from the surface. This significantly reduces the *average energy intensity* required to meet water demand. This result, however, is somewhat misleading because Spain uses far more *total energy* to meet water demand given the higher overall levels of water extraction.

This section has assessed the supply of water resources. It has demonstrated that water comes from a number of different sources that have varying energy requirements. In theory, water-abundant countries will have lower energy intensities for water withdrawals. In practice, this relationship is complicated by factors such as regional water scarcity, the location of total renewable water resources, and total water use. The analysis also suggests that as countries exhaust easily obtainable water resources they are likely to move to more expensive, and energy-intensive, water resources. This phenomenon is prevalent in the Gulf region. It should be noted that energy-intensive water sources are, in general, also the most costly, and so as countries move up the marginal cost of energy curve, the total costs of water often increase (Figure 2).

The extent to which countries must shift to more energy-intensive water resources is a function of not only water supply but also how water is used by the population and the economy. The demand for water is addressed in the following section.

The determinants of water demand

Only a small percentage of water extracted is consumed *directly* by the population. Globally, roughly 70% of all water withdrawn is used for agriculture, while 19% is an input for industrial processes (<http://www.fao.org/nr/water/aquastat/data/query/>). Of the remaining 11% of water allocated to municipalities, much is used either by firms (local companies connected to the municipal grid) or for irrigation in residential communities. Given that so much extracted water is used as an input for production, it is appropriate to consider the resource from the perspective of production theory, whereby output (Y) will be some function of a combination of inputs, such as capital (K), labour (L), land (H) and water (W):

$$Y = F(K, L, H, W)$$

The relative contribution of each factor of production to output is determined by comparative productivity. Productivity is defined as output (typically represented in physical or monetary terms) per unit input (represented in terms of monetary costs or input units). In the short run, it is almost always possible to increase the productivity of an individual input. Without technological innovation, however, this increase will come at the expense of the productivity of other factors. For example, a farmer could reduce the amount of extracted water required to produce crops (i.e. increase water productivity) by investing in drip-irrigation technologies (i.e. increasing capital expenditures, and thus decreasing capital productivity) or employing more labour to irrigate plants directly by hand (i.e. increasing labour expenditures, and thus decreasing labour productivity). A farmer will only choose to substitute water for capital or labour if the cost savings from using less water are greater than the increased expenditures from employing more capital or labour. In cases where the costs of installing

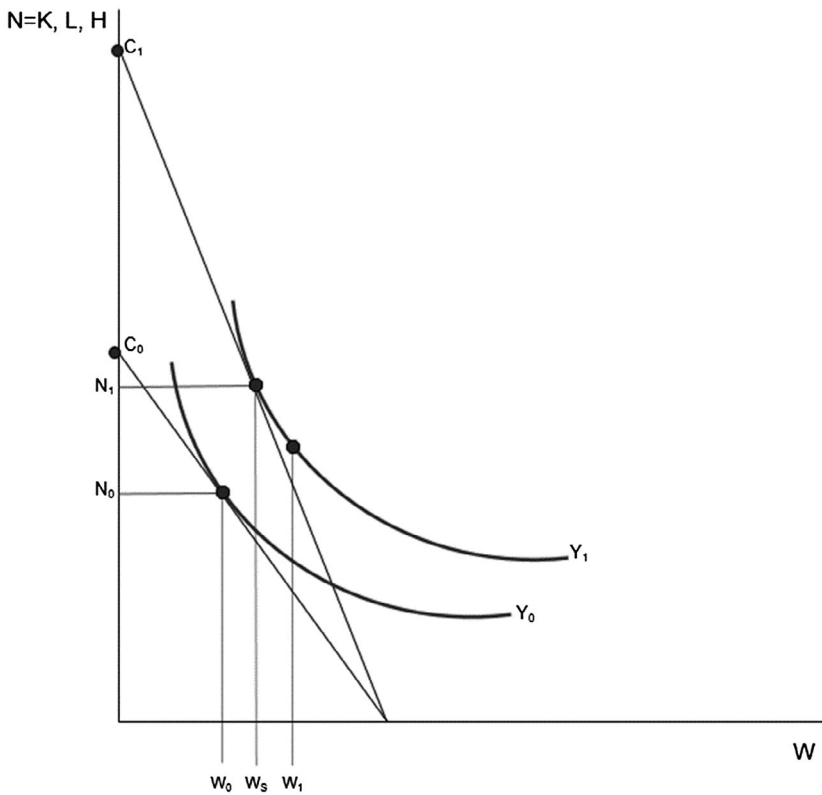


Figure 4. Potential effects of capital and labour subsidies on water consumption. Adapted from Sorrell (2014).

drip irrigation or increasing labour use are higher than the savings from using less water, the investment will not make economic sense, as it will increase the total costs of production. It should be noted that, because energy can represent up to 25% of groundwater system production costs (Dhuyvetter, O'Brien, Haag, & Holman, 2014; Zilberman, Sproul, Rajagopal, Sexton, & Hellegers, 2008), the cost of water use for agriculture may vary considerably with fluctuations in energy costs: the higher the energy costs, the more incentive there may be for a farmer to invest in water savings.

The amount of water used for production is a function of the relational costs between water and other factors of production. Water is used excessively in production when it is valued less than substitute inputs. Malik (2002) has argued that “inefficient use of both water and electricity in large part is also the result of non-metering of the consumption and the non-remunerative tariff structures for these services”. The effects of this inefficiency are not restricted to producers, but can also affect how embodied water is consumed. Allan, Keulertz, and Woertz (2015) have noted that the true values of water and energy are not reflected in the prices of food and manufactured commodities paid by consumers in private-sector markets. As a result, the quantity demanded of these products, and thus the total water and energy used in their production, can rise.

If policy makers seek to change the relative contributions of each input to production, there are effectively two options: decrease the costs of substitute inputs (such as labour

and capital) or increase the cost of water. The first option is achieved through subsidies. For example, farmers could be offered more efficient drip-irrigation technologies at subsidized prices, or be offered tax rebates for employing more labour. The second option is achieved through increasing the price of water, either by introducing a tax or increasing the prices of water inputs, namely energy, which, as stated, is often the largest single cost for water provision.

Both options have drawbacks. Figure 4 shows the potential effects of a capital or labour subsidy on water consumption. In the figure, vector C represents the total costs of agricultural production while isoquant Y , which is assumed to be homothetic, represents the possible mix of water W and the nest, N , of land, labour and capital, for production. In the scenario, prior to the introduction of the subsidy the point of tangency is $\{Y_0, C_0\}$. This intersection represents the chosen mix of factors of production given cost constraints. A subsidy on land, labour, and/or capital decreases the total costs of N , which leads to an outward shift of the total cost curve, from C_0 to C_1 . This movement has two effects.

First, there is an overall increase in production, as cheaper inputs allow for increased production for the same costs. This increase in production leads to a shift in water use from W_0 to W_1 . Second, there is a substitution of W for N , which leads to a movement upward along the Y isoquant, from W_1 to W_S , where S represents subsidy. The net effect of the subsidy on aggregate water consumption will depend on the relationship between the substitution and cost effects. In instances where the cost effect is greater than the substitution effect ($W_1 - W_0 > W_1 - W_S$), the subsidy will lead to an increase in aggregate water consumption, from W_0 to W_S , as demonstrated in Figure 4.

In practice, this effect could be described as follows. When labour or capital is subsidized, the total costs of production are reduced. While this may reduce water usage per unit of output, it may also increase the profitability of the industry, thus encouraging more production (either by incumbents or new entrants), and increasing aggregate water use. Also, if producers are operating in a competitive market, cost reductions may cause end prices for consumers to decrease, which can increase quantity demanded. The lack of aggregate savings from technologies meant to raise efficiency is known as Jevons' paradox (Alcott, 2005), or the rebound effect. Empirical studies suggest that irrigation modernization may lead to a rebound effect that negates efforts to improve water productivity. Pfeiffer and Lin (2014) found that irrigation efficiency in western Kansas from 1995 to 2005 led to increases in groundwater extraction of over 100%. The results were due primarily to switching to more profitable, but also more water-intensive, crops. Similarly, Ward and Pulido-Velázquez (2008) showed that water conservation subsidies in the Rio Grande Basin have not reduced aggregate water use, as farmers have simply increased yields. Because energy use is directly related to water use, when water consumption increases so does aggregate energy consumption.

The second option, increasing the price of water, offers a better economic solution for improving water productivity and decreasing energy consumption. As Figure 5 shows, a water tax leads to increased costs for water, causing an inward shift from C_0 to C_1 . This shift also has two effects. First, lower production reduces total water use, from W_0 to W_1 . Second, higher water costs make other factors more attractive, leading to a substitution effect equal to $W_1 - W_T$, where T represents tax. Thus, the total reduction of water resulting from the tax is $W_0 - W_T$.

In practice, the effect of a tax could be described as follows. An increase in the price of water will raise the total costs of production, which will result in reduced production and/

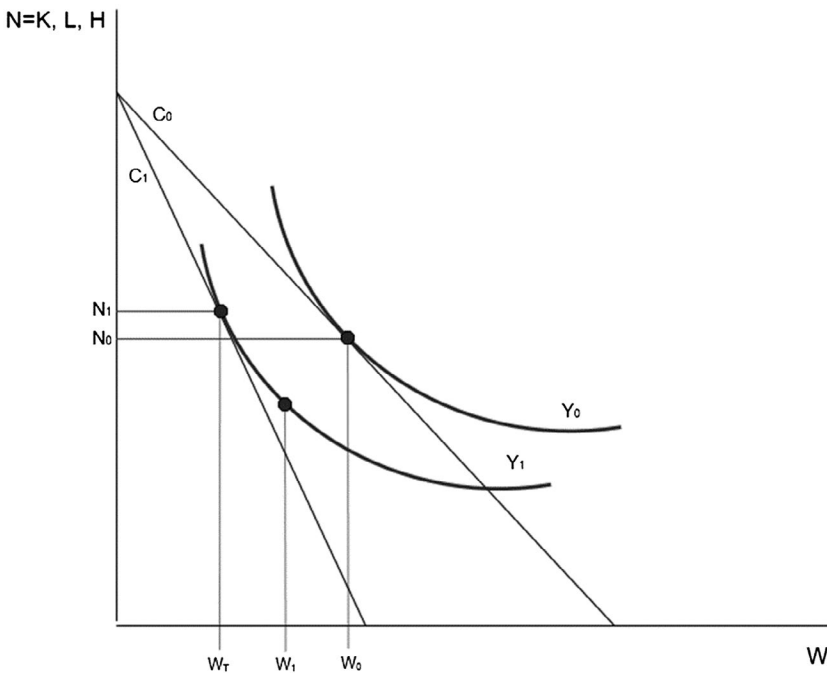


Figure 5. Potential effects of a water tax on water consumption. Adapted from Sorrell (2014).

or lower quantity demanded of products. In principle, this reduction in water use will lead to lower energy consumption for the provision of that water. While a tax may be an economically favourable solution, it is rarely implemented, as it is politically sensitive given the reductions it would entail in firm profitability as well as consumer welfare.

It should be noted that the logic above also applies to households using municipal water supplies. Households could be incentivized to reduce water use (for example by adopting low-flow faucets and showerheads) either by increasing the price of water or by subsidizing the prices of water-conserving technologies. The effects of household water reductions on energy are significant. This is because the energy savings related to the reduction of water use by household items such as washing machines, dishwashers and showers, although often overlooked, can be as high as 11.2 times the energy used to deliver water services (Kenway et al., 2008). As with water use for production, however, subsidies can lead to a rebound effect (i.e. increases in aggregate water use), while taxes can lead to cost increases (i.e. a decrease in welfare). It should be noted that even though taxes may be preferable, finding the correct level of tax can be difficult. Easter and Liu (2007) have suggested that one reason private and social costs of water are not included in tariffs is that they are difficult to estimate and may be beyond the knowledge of many countries. The authors argue for additional reforms to complement increases in water tariffs. For example, volumetric pricing, as opposed to simply charging farmers per hectare irrigated, could improve the efficiency of water used. Likewise, water quotas can be used to force water use reductions.

The analysis above suggests that while economic solutions for managing water resources exist, they can be politically sensitive, and therefore difficult to implement. This often results in overuse of water by households, industry and agriculture. Overuse has two implications for

energy. First, it increases overall energy consumption, as energy use is a function of total water withdrawn. Second, and perhaps more importantly, high water use can necessitate a movement to more energy-intensive water sources, thus increasing the average energy required to meet water demand. This is exemplified in Figure 6. The figure shows the per capita energy required to meet water demand in a sample of countries under two scenarios. The first scenario is a baseline, showing per capita energy for water under current consumption practices. The second scenario shows how this per capita energy use could change if the three most water-consuming crops in each country were removed from production. The top of the dotted bar (referred to as the Crop Reduction Scenario) assumes a reduction in the crop's actual water source, while the top of the solid bar (referred to as the Crop Reduction + Zero Desalination Scenario) assumes that water reductions occur in the most costly and energy-intensive sources, such as desalination and deep groundwater withdrawals. Any level within the dotted area represents some combination of a reduction in actual water sources and the most energy-intensive water sources.

Figure 6 suggests that crop elimination has the potential to dramatically reduce energy intensity for water extraction in some countries. For example, in 2010 Saudi Arabia used 2301 kWh per capita to extract and treat water for municipalities, industry and agriculture. If the country's three most water-intensive crops – alfalfa, dates and wheat – were eliminated in that year, total freshwater withdrawals would have been reduced from 25 km³ to 15 km³. If reductions occurred from each crop's actual source (typically deep groundwater aquifers), per capita energy consumption for water would have been reduced to 2094 kWh. Saudi Arabia, however, desalinated roughly 1.3 km³ of water in 2010. Eliminating the three crops would reduce the need for this expensive and energy-intensive desalination, as the desalinated water could be replaced in part or in full by conventional water, effectively allowing the country to move down the marginal cost of energy curve. If all of the country's desalinated water were replaced by conventional groundwater, this would reduce the average energy required to meet water demand by 87%. It should be noted that the water reductions from eliminating these crops would decrease total freshwater consumption by 41%, which would still result in Saudi Arabia being a severely water-scarce country, but non-renewable water resources would be depleted at a much lower pace. The situation is similar in Oman. Eliminating the three most water-intensive crops in 2010 would have significantly reduced the average energy intensity of water extraction, as well as reducing water scarcity by 53%. As with a water tax, eliminating crops is a politically sensitive topic, as some countries consider this a surrendering of food security. Despite this, recent developments suggest that it is possible. The government of Saudi Arabia has mandated the elimination of wheat production by 2016, and Almarai, the country's largest dairy producer, is employing a strategy to import all of the alfalfa it uses as fodder (Almarai, 2014). In 2008, Almarai used roughly 400,000 tons of domestically produced alfalfa as fodder (Almarai, 2009). This figure represented 20% of the total fodder used by the company that year, and roughly 16% of the total alfalfa that was produced in Saudi Arabia. Eliminating this alfalfa would reduce water consumption by 0.9 km³. If similar commitments were made by other agriculture producers that rely on alfalfa as feed, and domestic alfalfa production were eliminated, this would reduce water consumption by an estimated 6 km³ (FAOStat, <http://faostat3.fao.org/home/E>; Ministry of Agriculture, 2014; Multsch, Al-Rumaikhani, Frede, & Breuer, 2013). While dates are more politically and culturally sensitive, the elimination of both fodder and wheat would reduce water consumption by 7.3 km³ (FAOStat, 2015; Ministry of Agriculture, 2014; Multsch et al., 2013), which is far more than the current production of desalinated water. These types of

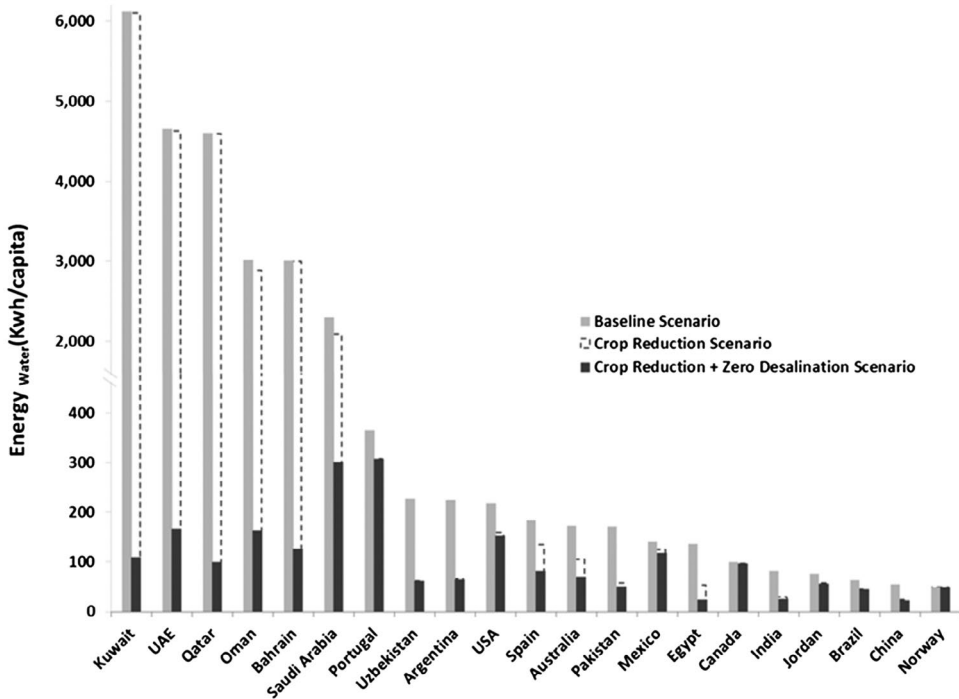


Figure 6. Energy for water per capita, baseline and crop elimination. Sources: Abderrahman (2001), Agenda 21 Della Terra d'Arneo (n.d), Al-Karaghoulis & Kazmerski (2013), Al-Mashaikhi (2011), Al-Mooji, Hofstetter, & Renck (2013), Abdel-Jawad (2001), Aqualogy (<http://www.aqualogy.net>), Aquastat (<http://www.fao.org/nr/water/aquastat/data/query/>), Association of Private Water Operators (n.d), Australian Bureau of Statistics (2014), Basharat (2012), British Geological Survey (2015), Buenomena (2013), Bundesanstalt für Geowissenschaften und Rohstoffe (2015), Burton (1996), Campanelli et al. (2013), Chan (2013), Chudaeva et al. (2008), CONAGUA (2014), CONUEE (2011), Copeland (2014), Darwish et al. (2009), Department for Environmental, Food and Rural Affairs (2008), Department of Environment, Water and Natural Resources (2014), Dimakis, Colleuille, & Wong (2005), Drewes (2011), ECRA (2011), El Tahlawi et al. (2008), Encyclopedia of Desalination and Water Resources (2014), Environmental Agency Abu Dhabi (2014), European Benchmarking Cooperation (2014), European Environment Agency (2014), Frijns et al. (2008), Gaut (2010), Global Water Intelligence (2015), Godskesen et al. (2013), Hadian et al. (2006), Hamed (2004), Hardy et al. (2012), Hayek (2014), Hernández-Mora et al. (2010), Imperial Irrigation District (2015), International Groundwater Resources Assessment Centre [IGRAC] (<https://ggmn.unigrac.org>), Japan Waterworks Association (2014), Lemos et al. (2013), Ludwig (2011), Karimov et al. (2015), Kenway et al. (2008), Kumar (2013), Kwanyuen et al. (2003), Li et al. (2015), Maas (2009), MacHarg and McClellan (2004), Matar et al. (2014), McLay (2005), McMahon and Price (2011), Margat and van der Gun (2013), Ministry of Water & Electricity (2010), Nelson et al. (2008), Natural Resources Canada Database (2014), Papapetrou, Wieghaus, & Biercamp (2010), Pearce (2007), Peng (2014), Plappally and Lienhard (2012), Portela and Cohim (2011), Qatar General Electricity and Water Corporation (2014), Queensland Department of Natural Resources and Mines (2014), Raucher et al. (2010), Reboucas (1999), Renzoni and Germanin (2007), Saatçı (2015), Shah (2009), Tao (2012), Tech Archival (2014), Trans Adriatic Pipeline-TAP (2015), Shimizu et al. (2012), Veera et al. (2010), Veera (2011), Venkatesh (2011), Vince (2007), Wang et al. (2012), Water in the West (2013), Water Resources Policy Division, Land and Water Bureau (2006), World Health Organization and UNICEF (2014). Note: Energy values from KAPSARC analysis on energy for surface water abstraction, groundwater abstraction and desalination. Crop water use data from the Water Footprint Network (average values between 1996 and 2005). Crop production data from FAOSTAT for the year 2011 (<http://faostat3.fao.org/home/E>).

initiatives are necessary to help the country reach its goal of reducing water withdrawals by 30% by 2030, and if coupled with reductions in energy-intensive water supplies, could also lead to energy reductions.

In addition to estimating the potential benefits from crop elimination in some countries, there are two other important findings from the figure. First, in the four other Gulf Cooperation Council (GCC) countries, Kuwait, the United Arab Emirates, Qatar and Bahrain, eliminating water-intensive crops has effectively no impact on average energy used for water, as no water-intensive crops are grown on a large scale in these countries. For energy intensity reductions to occur, crop elimination must be coupled with a movement away from desalination towards conventional water. This strategy is unfavourable, however, because a shift away from desalinated water would increase aggregate groundwater use, which would raise the overall water scarcity of the countries. For these severely water-scarce countries, where desalination is required, two options exist for reducing energy use: reducing municipal water consumption; and/or adopting more energy-efficient desalination technologies (i.e. a movement from thermal technologies to membrane technologies). Second, some countries, like Mexico, Canada and Norway, would enjoy only minimal reductions in average energy consumption with the elimination of water-intensive crops. This is because most crops in these countries rely on rainwater, and so energy use for extracted water is marginal. For example, over 99% of the water used to grow wheat in Canada and Norway comes from rainfall (own calculations, data from Mekonnen & Hoekstra, 2011). In cases where crop elimination does not affect energy intensity, countries may consider reducing municipal water consumption, or adopting more efficient pumps for extraction.

Virtual trade in water: implications for water and energy savings

Allan (1998) has defined the virtual-water content of a commodity, good or service as the volume of water used in its production. The trade in virtual water, therefore, represents the amount of water embedded in products traded internationally. Using this framework, Allan's work has explored how food trade may affect the water economies and policies in water-scarce countries (Allan, 2003). He has argued that importing water-intensive crops offers a policy option for countries with water deficits, which may even be particularly valuable for preventing 'hydropolitics' from sparking full-scale conflicts (Allan, 2002).

Building on Allan's insights, Hoekstra and Hung (2002) examined the volume of virtual water trade flows between countries, putting national water trade balances in the context of domestic water requirements and resources. This work offers an empirical assessment of the way countries are water-dependent on others. More recent work in this area has suggested that "about one-fifth of both global cropland and agricultural water use is allocated to the production of agricultural commodities consumed abroad" (Hoekstra & Mekonnen, 2012, quoted in MacDonald et al., 2015).

The high potential for virtual water trade to improve the sustainability of water resources in water-scarce countries should be complemented with an analysis of energy savings. As shown in Figure 6, crop elimination, which is effectively a substitution away from domestic production to imports, could lead to significant reductions in both total energy use and, in some cases, the intensity of energy used to meet water demand, both of which would have positive effects on sustainability and the environment.

Conclusion

This article offers a framework for evaluating how energy is used to meet water demand. The supply of and demand for water, and the energy required to withdraw that water, were disaggregated. The supply analysis demonstrates that water comes from a number of different sources that have varying energy requirements. In theory, water-abundant countries will have lower energy intensities for water withdrawals. In practice, this relationship is complicated by factors such as regional water scarcity, the location of total renewable water resources, and total water use. The analysis also suggests that as countries exhaust easily obtainable water resources they are likely to move to more expensive, and energy-intensive, water resources. This phenomenon is prevalent in the Gulf region as well as water-scarce regions in developed countries like Spain, Australia and parts of the United States.

Regarding demand, while economic solutions for managing water resources exist, such as raising water prices or mandating the elimination of some agriculture crops, they can be politically sensitive, and therefore difficult to implement. It should be noted that some countries have made progress in these areas. For example, in the mid-1970s, Denmark experienced two years of drought, in which city water supplies were virtually exhausted. This resulted in campaigns to conserve water as well as the introduction of water taxes, which led to a decrease in aggregate municipal water consumption from 605 million m³ in 1980 to 400 million m³ in 2005 (Geological Survey of Denmark & Greenland, [GEUS], 2006). In addition, as stated, Saudi Arabia has reduced its wheat production since 2008, and plans to rely solely on imported wheat by 2016. The decision was made because of the negative impact domestic wheat production has on water resources. The country is trying to meet its food security goals through other means, such as the creation of the Saudi Agricultural and Livestock Investment Co. (SALIC), which has been endowed with USD 800 million to improve food security in the country through foreign purchases. In 2013, SALIC purchased 40,000 hectares of active farmland in Poland and the Ukraine; and in 2015 the group became a majority investor in the Canadian Wheat Board. Should these initiatives lower agricultural water use in the country, there may be potential reductions in the aggregate energy used for water, as well as average energy intensity for water withdrawals.

The article has suggested that while supply and demand management can reduce the energy required for water resources, uncontrollable factors may limit the potential efficacy of certain policy options. For example, in severely water-scarce regions, it is likely that desalinated and/or deep aquifer water are necessary components of the water portfolio, and so these regions will always have a higher overall energy intensity than countries with abundant, clean surface water. Similarly, it is difficult for water-abundant countries that already rely on rainwater and surface water to make significant improvements to energy intensity. In both cases, focus should be placed on reducing water consumption, as this will lower overall energy expenditures for water.

Last, it should be noted that the analysis in this article is based on aggregated data from multiple sources. In some countries, water and energy data are granular and current, while in others water resources and energy use are based on estimates. Moving forward, it behoves countries to improve the way water and energy data are collected and published so that more cross-country research can be done. It is hoped that this special issue contributes, in part, to this initiative.

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