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Energy Intensity of Water End-Uses

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Abstract

Water end-use, in buildings, industrial facilities, and farms, often has the highest energy intensity. This review highlights key findings on energy intensity of water end-use in urban and agricultural sectors. In the domestic sector, energy used for water heating constitutes 14-25% of total energy use in US households. Heat pumps for energy recovery from hot grey water in residential buildings, and micro-turbines operating from grey water in tall buildings are being increasingly explored. In agriculture, groundwater pumping consumes most of the on-farm energy, and water efficient pressurized delivery systems have higher energy consumption. Rainwater harvesting systems are being deployed in many regions. The energy intensity range for residential rainwater harvesting has been reported to be 0.6 – 5.3 kWh/m³ in Australia, however with improved pump efficiency the intensity can be lowered to 1.5 kWh/m³ which would be less than other non-conventional sources such as seawater desalination or indirect potable reuse

Keywords

water end-use; energy intensity; water-energy nexus; urban water; hot water energy use; rainwater harvesting; water use efficiency; energy efficiency; irrigation; groundwater pumping; water sector GHG emissions; life cycle analysis

Introduction

The linkages between energy and water have been extensively investigated; however, some aspects of energy use in the water sector are often excluded due to differences in definition of boundaries within the water sector. In particular, the end-use segment (wherein water is used for various purposes within buildings, residences, industrial facilities, and farms) is frequently overlooked since this process occurs outside the water industry [1**] and often state and federal jurisdictions [2]. The importance of the end-use segment within the cycle of abstraction, conveyance, treatment, distribution, end-use, and disposal (see Figure 1), however, has been identified to have the highest energy intensity relative to other processes in many parts of the world ([3-7*]). Many researchers have worked to identify and quantify the energy intensity of

water end-uses (energy consumed per unit of water), and in this study we conduct a review of this research over the last three years with a focus on the residential and agricultural sectors.

Water end-use in urban areas is the type of usage that is measured via metered water consumption at the building, facility, or lot scale in a city. For end-use, there is energy required for on-site pumping (e.g. in the case of high rise buildings) and heating (to obtain a hot water supply in the building). In residential water use applications, energy is used in appliances such as clothes washers and dishwashers. In landscaping applications, some additional pumps and electrical control equipment (motors and valves) maybe used that add to the energy consumption. For buildings with on-site wastewater recycling units, energy is consumed in running the units to treat and pump the recycled water. Industrial facilities use water in various operations and have associated energy requirements typically in terms of pumping, pressurization, heating, cooling and treatment of water.

Agriculture has the highest water consumption of any sector including the domestic and industrial sectors, and the energy consumed for pumping irrigation water constitutes a large fraction of total energy use in several agrarian regions [8*-9]. Energy use for pumping groundwater depends on the geology, pumping equipment technology, and volume of abstracted water. Energy is also used in pressurized irrigation systems such as drip and sprinkler systems.

In the following sections of this paper, we present a review of studies conducted on energy intensity of water end-use in urban and agricultural sectors published during 2011-2014. We summarize their regional and topical focus, and present reported data of energy intensity in various end-uses. We also summarize methods employed for analyzing and quantifying the energy intensity and discuss existing knowledge gaps in this area.

Trends in Energy Intensity of Water End-Use Studies

In order to obtain an overview of key trends in publications on energy intensity of water end-use, we compiled data for English language journal articles in the Web of Science (Science Citation Index and Social Science Citation Index) during the 2011-2014 period. We conducted a topic search of the terms: water, energy, and end-use. This search provided results of publications that have these terms in their title, abstract or keywords list. We tabulated the results by research area and by country of authors. Research areas are defined in the Web of Science database to categorize publications according to a particular discipline (details of which can be found at [10]). The country of authors was determined by the address provided by the authors of the papers. It should be noted, however, that the address of the author does not necessarily correspond with the region analyzed in the paper. For instance, in several papers authors based in the US have investigated other regions including Mexico, Pakistan, and others.

Figure 2 summarizes the results (obtained in November 2014). The top research areas of publications were energy fuels, engineering, environmental sciences, and construction building technology. The literature is dominated by a focus on energy (it is interesting to note that environmental science and ecology rank third and water resources ranks fifth in number of total journal articles).

We also find that USA, Australia, Canada, and England are the leading countries where researchers have published work on this topic. Note that we combined several small shares of countries into the 'other' category in the pie chart to improve clarity of the figure. It is interesting to note that from a regional perspective, the research has been driven by local resource scarcity.

The Australian work is more from a water security perspective while in the US and many other countries it has largely been motivated from an energy security perspective [11]. A number of studies in countries such as India and China focus on the agricultural sector where energy use in groundwater pumping constitutes a large fraction of total energy use in some states and provinces.

The papers reviewed in this study were primarily of three types: 1) reports of measurement and field-data collection, 2) theoretical analysis, modeling and estimation, and 3) review papers that compiled and discussed data reported elsewhere. The first type of papers employed instrumentation and data collection methods, including use of smart meters, data acquisition systems and analytical software for monitoring and field-data collection (such as that reported in [12*]) and data collection through field-interviews and surveys [13*-14*]. The second type included a range of methodologies (depending on the focus of the paper) that included both widely known and used methods as well as custom tools and new methods developed by the authors. Some of the known methodologies included life cycle analysis [15*], probabilistic modeling, Monte Carlo simulations and regressions [16*]. Some new tools included the Water-Energy Nexus (WEN) tool [5] and quantitative modeling approaches [9, 17-19]. The third type presented compiled data reported elsewhere and discussed research and policy implications such as in [1,6, 20, 21**] and others.

Energy Consumption in Residential Water Use

The energy intensity varies with the type of source and supply architecture of the water system, the local climate and temperature conditions, as well as behavioral factors. It has been reported that end-use energy requirements associated with municipal, industrial, and self-supplied sectors (such as agriculture, mining, and power plants) represents 5% or more of the national energy consumption in the US [22], and energy consumed for household water use in Beijing is ~1% of the city's total energy consumption [17]. A number of studies have sought to compile previous work and report on energy intensity of residential water end-uses. One of the most comprehensive reviews is from Plappally and Lienhard [6**]. Their work, a compilation of data from a number of sources, provides a detailed report of energy use in water heating, appliances (such as dish washers and clothes washers), and cooking. Their study finds that the range of energy intensity for hot water heating varies significantly, with estimates ranging from 2.7 to 73 kWh/m³. Several factors account for this large range. Differences in building types such as homes, apartment buildings, offices, and hospitals, and the external temperature (local weather conditions) influence how much energy is used. Furthermore, individual appliances vary significantly. Electric water heaters have higher end-use efficiencies than natural gas water heaters, but significant electrical losses make the primary energy use greater. The same conclusions are found in [23], and it was determined that over the full fuel cycle, natural gas water heaters are about twice as efficient. It should be noted that the amount of water heated in residences varies significantly with geography, so the energy intensity of the appliance does not capture the full picture of the energy efficiency of water use. Overall, water heating accounts for 97% of energy use for water end-uses in households in Australia [20], and it has been reported that water heating accounts for 75% of the residential sector's direct water-related energy in the US [24]. At a national scale, 14-25% of energy supplied to residences is used for heating water in the US [6**]. Table 1 summarizes reported data of energy intensity for residential water heating and other water-related end-uses.

Abdallah and Rosenberg analyzed a large water use dataset of 11 cities in the US and determined that water and energy distributions among households are skewed with largest 12% of the users consuming 21% and 24% of water and energy respectively [16*]. Their results showed that water heater set point temperature, intake temperature, heater efficiency, and shower hot water fraction were among the factors with highest relative effect on household energy use.

While efficiency of appliances and technology are key factors in reducing energy intensity of water end-uses, user behavior is likely the most important factor. The results in [16*] and other studies before it [13*, 21**, 30] have highlighted the importance of end-user behavior on impacting both amount of water used as well as the energy consumed with water use. The water heater set point temperature, and shower hot water fraction are factors controlled by the human end-users, and efforts to reduce energy intensity of water end-use need to include measures of influencing end-user choices. The cost of energy for water end-use is borne directly by the users [31], unlike other segments where water utilities or other agencies pay for the energy costs. These cost implications should be highlighted to influence end-user behavior and expand conservation efforts.

A number of studies, mostly based in Australia, have focused on assessing the energy intensity of alternative water systems and comparisons with conventional water supply in residences. The increasing freshwater scarcity in Australia has driven state and local governments to mandate internally plumbed rainwater tanks [12*]. There is an increasing shift to decentralized water sources (that include rooftop rainwater harvesting, water recycling and reuse, etc.) in the region. Researchers have noted that the net impact on energy use is not considered nor has been fully investigated in designing and implementing policies that encourage users to use these sources. There is also a gap in understanding the environmental implications of decentralized water supply and use systems [20].

The rainwater harvesting systems are alternatives to conventional reticulated water supply, and are installed at individual residences to supply water for specific non-potable end-uses such as toilet flushing and clothes washing. The reported literature has used a combination of modeling and empirical observation to estimate the energy intensity of rainwater harvesting systems. Most papers reported a range for the energy intensities, between 0.6 and 5.3 kWh/m³ (see Table 1). Some present small case studies on a few in-home systems using smart meters and other new technologies that allow for detailed data collection of water use events and associated energy use in residences [12*, 25-26]). The authors note that efforts to match more appropriately sized pumps with each system could lower the energy intensity. Vieira et al., have provided a detailed review of energy intensity of rainwater harvesting systems [27*]. They note that the median energy intensity of theoretical studies was 0.2 kWh/m³, and was considerably lower than that reported in empirical studies of 1.4 kWh/m³. The lower theoretical estimates could be due to lack of full accounting of energy losses and inefficiencies. Tjandraatmadja et al. note that rainwater harvesting has much higher energy intensity than conventional reticulated supplies for the same uses in Australia, which are 0.21 kWh/m³ and 0.67 kWh/m³ in Melbourne and Brisbane, respectively [26]. More data collection is needed as these systems become both more abundant and more efficient. They also note that with improved pump matching with end-use needs (that vary for washing machines, dishwashers, faucets, and toilets) the energy intensity can be reduced to less than 1.5 kWh/m³ which would make rainwater harvesting more energy efficient than other non-conventional sources such as seawater desalination (3.6 kWh/m³) or indirect potable reuse (2.8 – 3.8 kWh/m³).

Most of the studies have focused on single residence scale, but there is now focus on assessing rainwater supply at a larger scale. Cook, Sharma, and Chong report on communal use of

rainwater harvesting systems that can supply potable water to a small urban development, albeit at higher energy usage (estimated at 4.01 kWh/m³) as compared to large centralized water supply [25]. Their analysis shows that rainwater use can be expanded beyond the single household to larger community level use in certain regional contexts.

Energy Intensity in Agricultural End-Uses

Water-energy linkage studies across different water sectors in many developing countries are predominantly focused on energy use in the provision of irrigation water [20]. The energy consumption in water-related end-use in agriculture (that occurs at the farm level) is primarily associated with on-farm groundwater pumping and energy used in pressurized water distribution and application systems at the field level.

Facing increasing competition for water, many regions have started to shift to pressurized irrigation systems that are more water efficient [18]. The water efficiency can be increased by replacing gravity-fed systems such as border check and furrow with pressurized center pivot and drip systems that can provide significant reduction in water application at the field scale. These water efficient systems, however, are more energy intensive. The overall farm-level energy intensity of water use depends on both the irrigation water source and field application technology. For farms using pumped groundwater for irrigation, water efficient application technologies (such as drip and sprinklers) allow for less pumping and overall energy savings at the farm-level. However, farms receiving surface water for irrigation can have an increase in energy consumption with the use of pressurized irrigation systems [28].

An approach that can mitigate this tradeoff is the reuse of grey water in irrigation systems. Matos et al. find that grey water decentralized reuse system consumed between 11.8 to 37.5% of the energy of a wastewater centralized reuse system [29].

In many parts of the world, there is an increasing trend to replace open channels that distribute irrigation water with pressurized pipes in order to reduce water losses due to evaporation and seepage. Some recent papers describe methods to optimize pressurized irrigation networks to minimize the energy consumption in irrigation water distribution in Spain [19, 32]. Abadia, Rocamora, and Vera, apply these methods to a real system in Spain and achieve a 34% reduction in energy consumption [33].

The water and energy tradeoffs at farm level production are ultimately connected with agricultural output and economic benefit at local and regional scales. A number of studies focusing on different parts of the world have quantified energy use in irrigation and water and energy productivity in irrigated agriculture.

Hafeez et al. conducted a study to analyze water productivity with water reuse at five different spatial scales in a rice-dominated irrigated region in Central Luzon in the Philippines [34]. The water reuse was through groundwater pumping in downstream regions of the area under study where water reaches through percolation from upstream irrigation. They found that water productivity (US \$/m³) with water reuse was higher than without water reuse, however total energy inputs of water reuse were 28% higher than energy inputs without water reuse. Thus, while reuse contributed to increasing water productivity, it also increased energy use (due to pumping) – indicating a tradeoff between yield and energy use.

Siddiqi and Wescoat found a similar trend in the Punjab province of Pakistan [9]. Using annual production, agricultural machinery census data, and water pumping estimates, they estimated that while there was a 31% increase in crop production between 1995 and 2010, the direct on-farm energy intensity (mega joules per kilogram) increased 80% over this period. This increase in energy was primarily driven by groundwater pumping by farmers that constituted 61% of direct on-farm energy consumption. Shah et al. observed similar results based on a nine-country survey in sub-Saharan Africa [14*]. Small farmers using motor-pump irrigation (as compared to rain fed, gravity flow, and manual lift irrigation) reported the highest net value added per acre and per family worker. This added value is achieved through increased energy intensity that has implications for greenhouse gas (GHG) emissions (93% of the irrigation pumps used petrol and diesel). It is reported that subsidized tariffs for agricultural water pumping in Mexico have led to increased groundwater abstraction, and irrigation constitutes over 25% of all electricity consumption in the state of Chihuahua [8**]. Several studies have also reported that in some regions of India, almost half of the electricity produced is used for irrigation [1**].

Environmental Impacts of Energy Consumption in Water End-Use

Several papers have focused in whole or in part on the energy intensity issue motivated from an environmental impact perspective. Domestic water heating accounts for 5.5% of total GHG emissions in the UK ([1**]), and in Mexico [8**] reports that agricultural pumping accounts for an estimated 3.6% of total national emissions and are equivalent to emissions from transporting the same produce to market.

Elias-Maxil et al. have summarized measures for reducing energy consumption related to water use in urban areas in the Netherlands [35]. They discuss actions for reducing energy expenditure including reducing demand, using renewable energy sources to substitute fossil fuels consumed for operating the urban water cycle, and technological options for recovering energy from hot wastewater. They report that in modern Dutch houses, 40% of the total energy loss is through waste hot water and describe a number of case studies on reclaiming waste heat for residential space heating.

Ghimire et al. presented a life cycle assessment (LCA) of domestic rainwater harvesting (DRWH) systems and agricultural rainwater harvesting (ARWH) systems, in the Back Creek watershed in Virginia, US, to understand the environmental implications of rainwater harvesting relative to conventional water delivery [15]. The results found that a pumped DRWH system performed worse than municipal supply in seven of fourteen impact categories that included worse impact on energy demand and global warming. However, if there is no pumping in the DRWH, it performs better than the municipal supply system. In the agricultural case, the ARWH system performed better than well water in most LCA categories, and an ARWH that required no pumping performed better than well water in all fourteen LCA categories.

Discussion and Conclusions

This review of recent work on the energy intensity of water end-uses in the domestic and agricultural sectors highlights the need for continued research in this area. With increasing urbanization, changing climatic conditions, and shifting technological implementation, the energy consumption for water end-use is likely to change over time. It is important that the synergies and tradeoffs between water end-use, energy consumption, economic implications and environmental impacts are holistically understood and carefully used in policy. Otherwise, partial solutions can

have unintended effects – such as reported in [8**] where night-time subsidized power for agricultural groundwater use has driven increased pumping, reversing past gains in water and electricity conservation, or the cases where mandated rainwater harvesting has increased energy intensity in some regions in Australia [12*]. The national and regional hydro-geological and socio-ecological context should be included in designing policy interventions that ensure water and energy security while preventing resource depletion and deterioration [36]. This consideration of context is particularly important in the agricultural sector where measures for water efficiency (such as use of pressurized systems) should be also be evaluated for impacts on overall energy use and carbon emissions.

Within the urban domestic sector, several studies underscored the significance of hot water, and its importance in the overall energy intensity of water end-use. While space heating and cooling receives attention in regards to energy use in buildings, water heating also needs to be considered as an important component to be included in efforts to reduce energy consumption in buildings. Since a reduction in the energy intensity for water end-use can allow for direct cost savings for users, and municipal and state governments should highlight this to incentivize synergistic water and energy conservation schemes. There is work being done on investigating use of solar hot water heaters (SHWH) to reduce electricity and gas consumption for hot water [38], however detailed assessments are needed that go beyond technology prescription and include key factors of hot water demand, tank sizes, and electricity tariff levels etc. to determine choice of optimal system design [39]. Several countries have implemented policies to incentivize the SHWH installation in residential buildings. Israel has mandated SHWH since 1980 in response to rising oil prices and has achieved an installation base of 77%; Australia and China have more moderate SHWH incentive policies and have achieved 7.6% and 11% installation bases respectively [43]. Another nascent research area is the potential for grey water in residential buildings to reduce energy consumption for hot water heating in buildings, either by harnessing the heat content of grey water using heat pumps [44, 45] or using the potential energy of grey water in tall buildings to power turbines [46]. While additional research is needed and results will vary based on key factors including climate, heat pump sizing, and hot water demand profile, the energy savings for hot water heating could be as high as 17%-34% [45].

The impact of changing architecture in water supply systems (from centralized to an increasing degree of decentralization) as well as changing urban form (with high density residences and high rises requiring booster pumping, etc.) on energy consumption are not completely known nor fully incorporated into planning. Additionally, the continued migration from rural to urban communities has implications for increased urban water demand that have comparatively higher associated energy for end-use [40]. Water reuse will also play an important role in meeting future water demands – particularly in water scarce regions - and energy implications will need to be better understood [41-42].

Compliance with Ethics Guidelines

Conflict of Interest

Afreen Siddiqi and Sarah Fletcher declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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** Of major importance

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Figure 1: Key segments of the water use cycle. The end-use is the most energy intensive in many regions.

Figure 2: Research areas and country of authors of journal articles published between 2011 and 2014 with the terms: water, energy, and end-use in the paper's title, abstract, or keywords.

Table 1: Energy intensity ranges reported for domestic and agricultural end use

	Energy intensity	Reference	Notes
Residential End Use	[kWh/m³]		
	0 - 54	[1**]	Residential water heating
	35	[6**]	Natural gas water heaters
	73	[6**]	Electric water heaters
	47-50	[6**]	Hot water residential use in 6 cities in Australia
	53	[6**]	Hot water domestic use in Finland
	30-80	[6**]	Hot water in apartment buildings in Estonia
Rainwater Harvesting	[kWh/m³]		
	4.01	[25]	Specific energy for centralized communal rainwater supply
	0.83-2.26	[12**]	Single residence rainwater harvesting system
	0.6-5.3	[26]	household rainwater harvesting system
Irrigation	[kWh/ha]		
	455-1901	[37]	Pressurized irrigation system in 10 representative districts in Spain
	833- 36,101	[1**]	Range of energy use for irrigation



