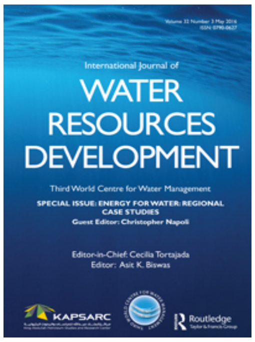

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Energy for freshwater supply, use and disposal in the Netherlands: a case study of Dutch households

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ABSTRACT
This study presents energy requirements for Dutch household water: 10.2 GJ per capita per year, which includes 9.3 GJ (92%) for heating water, 0.6 GJ (6%) for water supply, and 0.2 GJ for wastewater treatment (2%). The top three energy consumers include shower water (58%), dishwasher water (9%) and washing machine water (8%). The Netherlands, a water-abundant country, expends far more energy to heat water for households than to supply municipal water, or to treat and dispose of wastewater. Policies to make water chains more sustainable should focus on use, rather than supply and disposal.

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Water-energy nexus; energy footprint; water chain; Netherlands; household water use

Introduction

The interrelationships between water and energy issues, often referred to as the 'water-energy nexus', have received much attention in the last decades. There are strong connections between the demand for and use of energy and water, with strong parallels between the growing water crises and conflicts over energy sources (Biswas & Tortajada, 2009; Gleick, 1994; Liu, Zhao, Gerbens-Leenes, & Guan, 2015; Mekonnen, Gerbens-Leenes, & Hoekstra, 2015; NETL, 2006). In 2005, a seminar on water and energy, organized within the overall framework of the World Water Week in Stockholm, addressed the interlinkages between energy and water (Tortajada & Varis, 2006). The seminar showed that water affects energy, and energy in turn is affected by water. Detailed studies on the energy requirements to supply water include those by Barrios, Siebel, van der Helm, Bosklopper, and Gijzen (2008) and Frijns, Mulder, and Roorda (2008), who gave an overview of energy requirements to supply freshwater and to dispose of wastewater in the Netherlands; Buckley, Friedrich, and Von Bloonitz (2011), who reviewed South African water sector life-cycle assessments; Plappally and Lienhard (2012), who gave an in-depth overview of energy requirements of water supply in the complete water chain, including energy for wastewater treatment, for the agricultural and municipal sectors in various countries; Sanders and Webber (2012), who evaluated the energy consumed for water use in the United States; and Williams and Simmons (2013), who gave an estimate of the energy requirements to supply water, including an estimate of the

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energy requirements for global water supply. In spite of the close interrelationships, however, the water profession as a whole has given inadequate attention to the energy sector (Tortajada & Varis, 2006). The provision of basic infrastructure services, such as water and sanitation, plays a vital part in the economic growth of a country and is essential for development (Tortajada, 2014). At present, the benefits of clean water and effective wastewater treatment are not available everywhere, as a consequence of the amount of both capital and energy needed to build and operate such systems (Plappally & Lienhard, 2012; Williams & Simmons, 2013). Estimates suggest that today the delivery of suitable water and the treatment of wastewater uses about 3% of the world's primary energy (Williams & Simmons, 2013). Further, end uses of water, such as water heating for the shower or dishwasher, also consume energy (Barrios et al., 2008; Frijns et al., 2008; Plappally & Lienhard, 2012).

Energy is required in the complete water chain. For example, energy is required to withdraw water (e.g. to pump groundwater), to purify water to the required quality level, to distribute water, to heat water in the use phase, to collect and treat wastewater, and to dispose of wastewater. Often, if water becomes scarcer or if the quality decreases, more energy is needed per unit of water supplied: water-scarce regions must often withdraw water from deep aquifers, and when water quality is low, energy-intensive treatment may be required. This means that local circumstances and choices made in every link of the water chain have a large impact on energy requirements of freshwater supply, use and disposal and therefore differ between locations. Case studies of specific countries and locations might contribute to better insight into the 'water-energy nexus' and show similarities and differences for energy requirements for freshwater supply, use and disposal. The Netherlands is a well-developed country with excellent water and energy infrastructure. Moreover, data on energy and water use are available. This makes it a good subject for a case study of the energy requirements for freshwater supply, use and disposal of its households.

Even though in some countries water is abundant, this does not necessarily mean that there is always enough freshwater of sufficient quality available for household supply, because sometimes droughts occur, or the water quality is insufficient. Although the Netherlands is located in the delta of large rivers, with roughly one-fifth of the country's surface consisting of water, it must consider freshwater availability for municipal water supply, because of the temporal variability of river runoff and changes in water quality. The occurrence of droughts or low-quality surface water sometimes constrains the ability to supply municipal water to households (Wolters-Noordhoff Atlas Productions, 2007). Moreover, demand for water is increasing. In the Netherlands between 1920 and 1990, the annual municipal freshwater use per capita increased from 17 to 70 m^3 per year (Wolters-Noordhoff Atlas Productions, 2007). Also, if total water use increases, more energy is needed to supply freshwater, to treat wastewater and to heat the water in the use phase.

Energy use has received much attention in the Netherlands. Especially in the last decade of the twentieth century, many studies have analyzed energy use by Dutch households (e.g. Falkena, Moll, Noorman, Kok, & Benders, 2003; Kramer & Moll, 1995; Kramer, Wiersma, Gatersleben, Noorman, & Biesiot, 1998). While those studies have given an in-depth overview of energy use in Dutch households, they have not specifically addressed the energy required for freshwater use. The water utilities in the Netherlands have also assessed energy use of the sector (Barrios et al., 2008; Frijns et al., 2008), providing detailed information on the energy requirements for municipal water for the Netherlands, including energy requirements for specific water treatment activities for municipal water. This article expands on these previous studies by estimating the energy embodied in 'water use' in addition to water extraction and treatment. The aim of this case study is to assess energy requirements related to Dutch household water supply, use and disposal for all components of the freshwater chain, including energy use in the household for heating, and to compare energy for water with total household energy use. Next, it compares the results with earlier studies to find general trends. By including energy for water use, the study provides a robust estimate of the total energy footprint associated with municipal water demand in the Netherlands.

Municipal water supply and wastewater treatment in the Netherlands

The Netherlands is a flat country in the delta of the Rhine, Meuse and Scheldt Rivers. It is water-abundant, as most of the renewable water resources it receives are never extracted: 77.8% flow to the sea, 17.6% evaporate and only 4.5% are consumed by humans (Wolters-Noordhoff Atlas Productions, 2007). Ten Dutch water utilities provide drinking water for municipal supply. They are located close to municipalities, and withdraw water from sources nearby. The purpose of this strategy is to ensure that costly, energy-intensive water transport systems are not required to meet municipal water demand (Rijksinstituut voor Volksgezondheid en Milieu, 2011). The water utilities select the highest-quality source for drinking water production (Smeets, Medema, & Van Dijk, 2009). The preferred source is groundwater, because it is microbiologically safe. In some parts of the country, however, groundwater is brackish and so surface water is used for drinking. Figure A1 (in the supplemental online material at http://dx.doi.org/10.1080/07900627.2015.1127216) shows the source water types for drinking water in the Netherlands (Smeets et al., 2009).

The purification processes used by each utility depend on the quality of the water source, the type of water extracted (ground or surface) and the drinking water standards required. Figure A1 shows that groundwater is used for drinking in most parts of the Netherlands. Groundwater in the Netherlands is high-quality water that is only minimally treated for substances such as ammonium, iron, manganese and oxygen. It is extracted from restricted areas owned by the water utilities. This decreases the risk of groundwater contamination (Smeets et al., 2009). For the purification of surface water, more treatment is needed, such as storage in a water reservoir, slow sand filtration, coagulation, UV disinfection or ozonation, and activated carbon filtration (Rijksinstituut voor Volksgezondheid en Milieu [RIVM], 2011). The quality of surface water in the Netherlands is determined by human activities upstream of the sources of extraction, e.g. wastewater discharges and industrial and agricultural activities. This upstream pollution can occur purposely through sanctioned industrial or agricultural activity or by accident. When water is accidentally contaminated, and the system is too heavily polluted to be used as a source of drinking water, water utilities use storage systems, including dunes. After persistent problems with polluted and brackish drinking water in the nineteenth century, the major towns in the west of the Netherlands eventually went to the groundwater reserves in the coastal dune belt for their water supply (De Vries, 2007). Figure A1 (in the supplemental online material) shows that in some areas surface water is used directly, and in other areas it is infiltrated in the dunes. Although most of the time the Rhine and Meuse provide sufficient water quantities, the water quality is not always sufficient. The surface water from the Meuse and Rhine is pretreated, transported to the dunes and infiltrated to improve its quality. The dunes form a natural filter for pathogenic micro-organisms, contribute to constant water quality and temperature, and have a large storage capacity to overcome pollution waves in the rivers (Smeets et al., 2009; RIVM, 2011).

In the Netherlands, the standards for surface water for drinking derive from a 1975 European Union directive (75/440/EEG) that gives critical concentrations for pesticides, polyaromatic hydrocarbons and chloride (RIVM, 2011). However, it is recognized that the directive does not consider all pollutants. Pollutants not included are hormones, medicines, nanoparticles (e.g. TiO_2), cosmetics, and food additives. The quality of Dutch surface water has improved since 1970 when considering the concentrations of dangerous pollutants from the directive of 1975. However, this has not resulted in lower requirements for purification, because of the introduction of other pollutants and more stringent water quality standards. This is due in part to better chemical analysis techniques to identify small concentrations of pollutants. The Dutch Ministry of Infrastructure and the Environment is making a new list of acceptable levels of pollutants in surface water for municipal use (RIVM, 2011).

At present, the Dutch policy standards for drinking water are included in the Drinking Water Law (Drinkwaterwet – Dutch Government, 2009). The protection of Dutch groundwater quality is regulated in the Water Directive, preventing groundwater pollution by setting standards for activities in areas where groundwater is withdrawn. The Dutch policy includes a complete ban on the use of chloride for purification (RIVM, 2011). In the Netherlands, per capita water use has decreased thanks to technological improvements, for example the introduction of more efficient toilets, washing machines and showers. These technological improvements, in combination with increased public awareness, were so effective that government campaigns to make the public more aware of their water use stopped (de Moel, Verberk, & van Dijk, 2006).

The Dutch Drinking Water Law (Dutch Government, 2009a) assigns the responsibility for wastewater treatment and disposal to the water boards. In 2006, 98.6% of total wastewater in the Netherlands was treated in a wastewater treatment plant (Directoraat-Generaal Water / Directoraat-Generaal Milieubeheer, 2008).

The freshwater chain

Figure 1 shows a freshwater chain that consists of six components: water withdrawal; water purification; water distribution; water use; collection of wastewater; and wastewater treatment and disposal. All of these components require energy. This article estimates the energy requirements of all six components for the Dutch water system. The study excludes the energy required to build infrastructure, such as pipes and pumps, as this is generally attributed to energy embodied in industry.

The total energy footprint of a freshwater chain depends on the choices made for each component. For example, surface water is more readily accessible than groundwater, and so less energy is required for its extraction. However, surface water generally contains more contaminants than groundwater, so more energy is required for treatment. The utility's choice of whether to extract surface or groundwater will be a function of the accessibility and purity of each; there is often a trade-off whereby more accessible water sources are also more contaminated. Another factor affecting the energy footprint of water is the desired quality. The desired quality of municipal water may differ between regions, which can affect the choice of purification method, and thus the energy costs. This is also the case with wastewater, as numerous options for treatment exist, each of which will bring water to a different level of purity while requiring a different amount of energy.

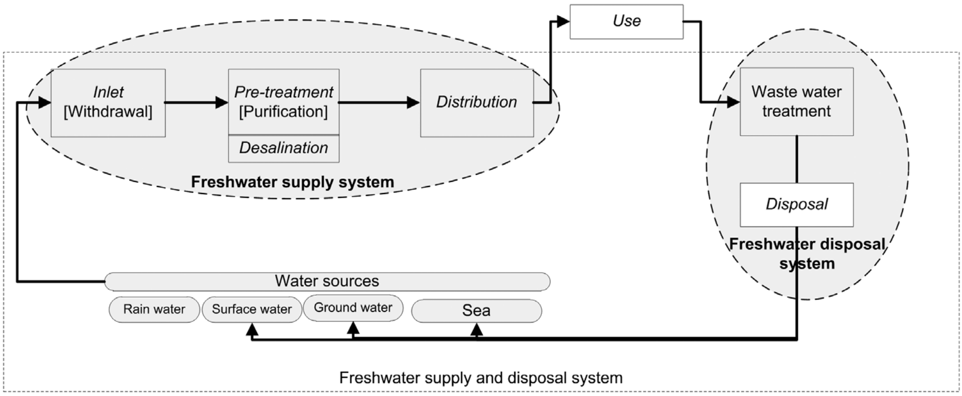

Figure 1. A typical freshwater chain, depicting its components.

Energy

The global energy system uses fossil fuels (coal, natural gas and conventional oil), renewables (e.g. biomass, solar energy, wind energy) and nuclear energy (uranium) for the supply of heat, electricity and transport fuels (IEA, 2015). The Netherlands has large natural gas stocks (Wolters-Noordhoff Atlas Productions, 2007), and not only exports but also uses large quantities of natural gas (IEA, 2015). Based on IEA statistics (2015), gas contributes about one-fifth of the total energy supply in the global energy mix. In the Netherlands the contribution is larger, at about one-third.

Energy is almost always required for the provision of water. Mechanical energy for pumping can be generated by humans and draught animals, renewable technologies, or diesel or electrical pumps. For example, either electrical or diesel energy is required to withdraw ground or surface water. Additionally, electricity is required for municipal water treatment. Examples of municipal water treatment that require electricity are biological activated carbon filtration, softening and ozonation (Barrios et al., 2008). Households also use energy for water. In the Netherlands, natural gas is one of the primary sources used for heating water. Last, when water is treated prior to disposal, energy is required.

The energy needed to produce useful fuels and electricity is termed 'energy required for energy' (ERE) and depends on the energy source and the efficiency of power generation. Values for electricity generated in the Netherlands are about 2.65 (Blok, 2006; Falkena et al., 2003). Different mixes for electricity have different ERE values. For example, the ERE of electricity from coal is 2.60 MJ/MJ, of electricity from natural gas 1.96 MJ/MJ (Meldrum, Nettles-Anderson, Heath, & Macknick, 2013), and for renewable energy, such as electricity from biomass, it is 2.5–5.0 MJ/MJ (Faaij, 2006), meaning that the latter form of electricity is almost twice as energy-intensive as electricity from coal or natural gas. When the energy requirements of water are assessed, these ERE values must be taken into account. This is because total energy use depends partly on the source of that energy. For example, when Dutch tap water is heated mainly by natural gas, and not by electricity, energy losses associated with the conversion of energy in a power plant are avoided.

Method

The study combined information on water use in Dutch households with data on energy for water (energy to supply water, to heat the water for a specific application, to dispose of water, and for wastewater treatment). In all the components of the freshwater chain, energy is needed for different processes. The total energy footprint of the freshwater chain (excluding the energy related to water infrastructure), EF_{water} (in MJ/m^3), consists of six components: $EF_{withdrawal}$, the energy footprint to withdraw the water from a specific source; $EF_{purification}$, the energy footprint to purify a unit of water; $EF_{distribution}$, the energy footprint to distribute the water to the required location; EF_{use}, the energy in the use phase, mainly for water heating; $EF_{collection}$, the energy footprint to collect water and bring it to a wastewater treatment plant; and $EF_{treat+disposal}$, the energy footprint to treat the wastewater to the required quality standard and then to dispose of it). This is shown in Equation (1):

$$EF_{water} = EF_{withdrawal} + EF_{purification} + EF_{distribution} + EF_{use} + EF_{collection} + EF_{treat+disposal} (MJ/m^3) \quad (1)$$

Information on water use in the Netherlands is available from TNS-NIPO (2008). Table 1 gives the average daily per capita household water use in the Netherlands for 1995–2007 for 12 use categories. For the assessment of the energy requirement in the use phase, this study used the data for 2007. Energy in the use phase is related to the heating of water. The study distinguished five categories of warm water use: washing machine; tap water (shower, bath, dishwashing by hand, personal washing, washing by hand); cooking; dishwashing machine; and coffee and tea. Total water use in a Dutch household in 2007 is expressed in m^3 per capita per year for five use categories in which the categories shower, bath, dishwashing by hand, personal washing and washing by hand from Table 1 are added into the category of warm tap water.

Table 2 gives the energy requirements of the processes that supply water for municipal services in the Netherlands from two Dutch sources, as well as energy for wastewater transport and treatment. The table shows that depending on the technology applied, energy requirements for water supply in the Netherlands might differ by a factor of three. When the ERE factor is included, municipal water supply ranges between 4 and 13 MJ/m^3. For sewage water transport and treatment, Frijns et al. (2008) give energy requirements of 1.05 and 3.35 MJ/m^3, respectively. The energy required to supply and dispose of water in the Netherlands lies between 8.4 and 17.4 MJ/m^3.

Table 1. Average water use (litres per capita per day) in the Netherlands, 1995–2007.

	1995	1998	2001	2004	2007
Toilet	42.0	40.2	39.3	35.8	37.1
Shower	38.3	39.7	42.0	43.7	49.8
Washing machine	25.5	23.2	22.8	18.0	15.5
Bath	9.0	6.7	3.7	2.8	2.5
Dishwashing by hand	4.9	3.8	3.6	3.9	3.8
Personal washing	4.2	5.1	5.2	5.1	5.3
Washing by hand	2.1	2.1	1.8	1.5	1.7
Cooking	2.0	1.7	1.6	1.8	1.7
Coffee/tea	1.5	1.1	1.0	1.0	1.2
Dishwasher	0.9	1.9	2.4	3.0	3.0
Drinking water	-	0.5	0.5	0.6	0.6
Other water use	6.7	6.1	6.7	6.4	5.3
Total	**137.1**	**131.9**	**130.7**	**123.8**	**127.5**

Source: TNS-NIPO (2008).

Table 2. Energy requirements of the processes to supply water for municipal services as well as energy for wastewater transport and treatment. All figures in kJ/m^3 except where noted.

Processes	Barrios et al. (2006)	Frijns et al. (2008)
Raw water intake	40.4	2.2
Coagulation		86.4
Lake water reservoir		
Pumping from lake water	80.4	
Rapid sand filtration	49.1	43.2
Pumping to water treatment plant	100.4	
Ozonation	181.9	
Softening (energy for pumping)	574.9	72.0
Biological activated carbon filtration	0.0	28.8
Slow sand filtration	86.9	
Storage and pumping into distribution network	396.0	396.0
UV disinfection		223.2
Membrane filtration		3,600.0
Flotation		180.0
Aeration		288.0
Total electricity (kJ/m^3)	1,510.0	4,919.8
Total energy (kJ/m^3) including a factor for ERE (2.65)	4,001.5	13,037.5
Wastewater transport and treatment process		
Wastewater transport		1,050
Wastewater treatment		3,350
Total		4,400

In the use phase, households often heat the water, for example for showering or washing. To calculate the energy requirement related to freshwater use in a Dutch household, the study combined information on natural gas and electricity use for heating water from Kramer et al. (1998) with information on water use for bathing, showering, dishwashing and washing machines from TNS-NIPO (2008) for the year 1997. In 1997, an average Dutch household used 14.7 GJ to warm tap water (Kramer et al., 1998). The study assessed the household size in 1997 as the average of the household size in 1995 and 2000 of 2.35 and 2.30 persons, respectively (Centraal Bureau voor de Statistiek (CBS), Planbureau voor de Leefomgeving (PBL) en Wageningen Universiteit en Researchcentrum (Wageningen UR), 2015). It calculated energy use to warm tap water (in GJ per capita per year) by dividing household energy use for tap water by the household size in 1997 and by dividing energy use per capita in 1997 by the warm tap water use in 1998 from TNS-NIPO (2008). The study assumed that tap water use in 1998 was the same as in 1997. It also assumed that energy to warm tap water (in MJ/m^3) did not change between 1997 and 2007.

To calculate the energy requirement for water for washing machines, the study derived data on water and electricity use from the Dutch Consumentenbond (2010), an organization that tests household machines. Based on the water and energy use per kg of clothes for three advised machines (Miele W5825, water use 13 L/kg, electricity use 0.13 kWh/kg; Whirlpool Denver 1600, water use 10 L/kg, electricity use 0.10 kWh/kg; Indesit IWC5145, water use 9 L/kg, electricity use 0.17 kWh/kg), the study calculated the electricity needed to heat a unit of water by dividing average energy use per kg of clothes (kWh/kg) by average water use per kg of clothes (m^3/kg), converting kWh to MJ by applying a factor of 3.6 and converting litres to m^3 by applying a factor of a thousand. The energy required to heat a unit of water (in MJ/m^3) was calculated based on an ERE for electricity of 2.65.

For dishwashers, the study used the same approach and based the calculations on four brands: Ikea Lagan DW60, water use 14.83 L/turn, electricity use 1.064 kWh/turn; Bosch SRS4 5M02EU, water use 16.80 L/turn, electricity use 1.460 kWh/turn; Siemens SN65E001EU, water use 12.00 L/turn, electricity use 1.06 kWh/turn; and Whirlpool ADG 9527/2, water use 14.00 L/turn, electricity use 1.054 kWh/turn. The equation for energy for cooking was obtained from Gerbens-Leenes (2000):

$$\text{Energy for cooking} = \text{Vwg} \times \text{sww} \times \text{delta T} \times 1/\text{e} \times 10^{-6}(\text{MJ}) \quad (2)$$

where Vwg is the amount of water to be heated (g), sww is the specific heat of water (4.18 J/g·K) (Verkerk, 2008), delta T is the temperature difference between tap water and boiling water (assumed to be 85 °C), e is the efficiency of warming water using natural gas (0.5) and the factor of 10^{-6} is used to convert from J to MJ.

Results

Table 3 gives the energy requirements for warm tap water, washing and dishwashing machine water, cooking (based on natural gas use) and coffee/tea (based on electricity use), total energy use and total water use per capita per year in 2007. The energy used to heat water (MJ/m^3) for dishwashers is relatively large, while that for washing machines is relatively small, probably because washing machines use mostly cold water for rinsing. The table also shows that energy for water to prepare coffee or tea is the largest per unit of water, at roughly three times the energy requirement of warm tap water. This is caused by the difference in heating temperature and by the use of electricity rather than natural gas, which has a higher ERE. Energy to warm tap water dominates energy for water use; energy to prepare coffee and tea is the smallest. Most of the water is needed for tap water, followed by water for the washing machine. The amount of water used for coffee and tea is relatively small.

The results for the energy footprint of supply and disposal, 8.4–17.4 MJ/m^3, are based on the results for water supply of municipal services, including a factor of 2.65 for ERE. The study used the values of 4 and 13 MJ/m^3 for municipal water supply and of 4.4 MJ/m^3 for wastewater transport and treatment, based on data from Barrios et al. (2008) and Frijns et al. (2008) – see Table 2. When energy requirements for warm tap water, washing and dishwashing machine water, cooking (based on natural gas use) and coffee/tea (based on electricity

Table 3. Energy requirements for warm tap water, washing and dishwashing machine water, cooking (based on natural gas use) and coffee/tea (based on electricity use), plus total energy use and total water use per capita per year, for 2007.

	Energy for heating (MJ/m^3)	Energy for supply and disposal (MJ/m^3)	Total energy (MJ/m^3)	Total energy use (MJ per person per year)	Total water use (m^3 per person per year)
Washing machine	124	8.4–17.4	132–141	747–798	5.66
Warm tap water	302	8.4–17.4	310–319	7144–7352	23.03
Cooking (natural gas)	711	8.4–17.4	719–728	446–452	0.62
Dishwashing machine	769	8.4–17.4	777–786	851–861	1.10
Coffee/tea (electricity)	942	8.4–17.4	950–959	416–420	0.44

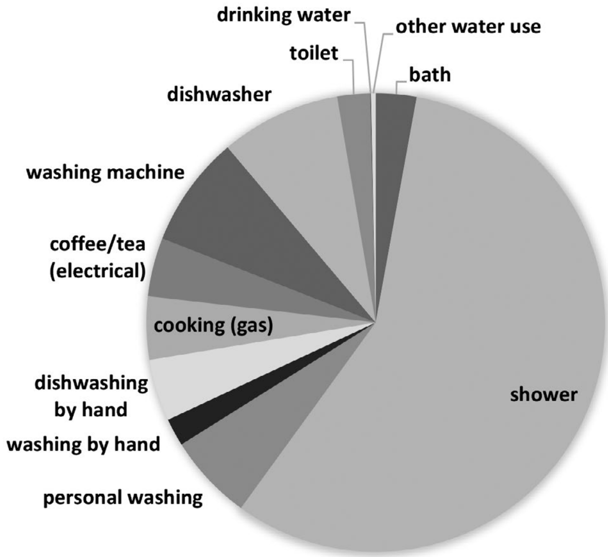

Figure 2. Energy for water in Dutch households.

use) are combined with water use, the energy requirement for municipal water supply and use in the Netherlands lies between 9.6 and 10.2 GJ per capita per year. When the higher value for water supply from Frijns et al. (2008) is taken, 9.3 GJ (92%) is energy used by households to heat water, 0.6 GJ (6%) for water supply, and 0.2 GJ for water treatment (2%). The energy requirement for heating water is dominated by the shower (on average 5.5 GJ per capita per year), the dishwasher (0.8 GJ per capita per year) and the washing machine (0.7 GJ per capita per year). Energy for heating the rest of the water in a Dutch household (washing, dishwashing, cooking, and preparing coffee and tea) is 2.3 GJ per capita per year. Figure 2 shows the relative energy use per household function. The top three energy requirements are for water for the shower (58%), water for the dishwasher (9%) and water for the washing machine (8%).

Discussion

The data for Dutch municipal water supply and disposal used in this study are derived from the detailed studies of Barrios et al. (2008) and Frijns et al. (2008). Energy requirements for water supply, including ERE values, vary between 4 and 13 MJ/m^3; wastewater transport and disposal requires 4.4 MJ/m^3 (including ERE). In the Netherlands, water leakages in the supply system are small, in general less than 3% (Smeets et al., 2009). In countries where leakage rates are high, for example in Bulgaria, where the leakage rate is 50% (European Environment Agency, 2003), energy to supply a unit of water to a household (MJ/m^3) doubles. When energy for water is compared for different countries, losses also need to be taken into account. A recent study of the energy footprints of water production, treatment, end use, reclamation and disposal (Plappally & Lienhard, 2012) gave values between 0.01 kWh/m^3 (Australia) and 1.5 kWh/m^3 (Spain) for conventional water treatment. This is 0.04–5.2 MJ/m^3 without the ERE value and 0.1–14.3 MJ/m^3 including the ERE value. The values for the Netherlands fall within this range. A recent study from South Africa on the life cycle of the water sector (Buckley et al., 2011) gives similar values. For example, for the primary treatment of wastewater, both Frijns et al. and Buckley et al. give energy requirements of 0.11 kWh/m^3.

This study finds that in the Netherlands energy use related to water use in households is dominated by the heating of water. Energy is used to warm water for clothes washers, dishwashers, taps, baths and showers. Energy requirements per m^3 of water depend on the source of the energy for heating, in which natural gas is more efficient than electricity, and on the final temperature of the water. For cooking, water needs to be heated to its boiling temperature (100 °C), requiring more energy (MJ/m^3) than water that needs to be heated for the shower. This study finds energy requirements ranging from 124 MJ/m^3 to heat the water for the washing machine to 942 MJ/m^3 to heat the water for coffee and tea preparation. Estimates for California, in the US, show that the warming of one cubic metre of water ranges between 5.4 kWh (19.4 MJ/m^3, including ERE for gas for the shower) and 25.9 kWh (247 MJ/m^3, including ERE for electricity) for the dishwasher (Plappally & Lienhard, 2012), which is much more than the energy needed to purify water, even when using desalination technologies. However, there is a large difference between the values for heating shower water in the Netherlands and in California. The specific heat of water is 4.18×10^3 J kg^{-1} K^{-1} (Verkerk, 2008). This means that in the Netherlands, where heating of the shower water requires 302 MJ/m^3, when no energy losses occur, the temperature difference between water before heating and after heating is about 72 K, whereas in California the temperature difference is only 5 K. Assuming that shower water does not have temperatures far above the body temperature of 38 °C, possibly the values for the Netherlands are overestimated or the heating of tap water is energy-inefficient. For cooking, the efficiency to heat water using natural gas is about 50% (Gerbens-Leenes, 2000). The results for the heating of tap water suggest that the efficiency is smaller than for cooking. On the other hand, the temperature increase for California is small. Because the impact of the use of warm water for the shower on the total energy use in a household is so large, better estimates of the energy to heat shower water are needed.

This study finds that 92% of the energy use for water in a Dutch household goes to heat the water. This is larger than the results of other studies, probably because this study also took the ERE values into account. Frijns et al. (2008) estimated that the energy use in the water use stage of the Dutch municipal water supply chain is four times the total for the other steps of the chain. This estimate of Frijns et al. is in line with two other studies that give similar results for the US. Sanders and Webber (2012) show that 75% of energy for water in US households is used to heat the water. Plappally and Lienhard (2012) show that in California 72% of the energy is used in households to heat the water. This means that in order to decrease the energy footprint of the water supply chain, the focus should be on the consumption stage, where human behaviour, especially related to showering and bathing, is the most important factor. The energy required for specific technologies in different steps of the water supply chain has received much attention, not only from scientists, but also from the water sector itself. Where technologies of municipal water suppliers in some countries are well documented, as was shown for the Netherlands (Barrios et al., 2008; Frijns et al., 2008), information for many other countries for different types of water sources is lacking or not publicly available. For example, the FAO's database, Aquastat, does not provide information on wastewater treatment for many EU countries for 1993–2002 (FAO, 2015). This means that the results of this case study cannot easily be compared to other countries or to other sectors.

Where utilities in the water sector providing municipal water have a good overview on how much water is supplied to customers and how it is treated, there is limited information on agricultural and industrial water supply. For example, there are large differences in energy footprints for groundwater pumping that depend on groundwater tables and on pumping efficiencies. The pumping efficiency of 25% reported for South Asia (Shah, Scott, Kishore, & Sharma, 2003) is relatively low compared to efficiencies of 70% published by the Hydraulic Institute, Europump, and the US Department of Energy's Office of Industrial Technologies (2000).

It is stressed that the results presented here are based on rough estimates of the freshwater supply chain and should be interpreted not at face value but within the context of all assumptions made. For water, the study used information from a limited number of sources. For energy, it combined information from the literature. The results, therefore, give an indication of energy footprints of water, show differences among types of water used and treated, and estimate per capita energy footprints of water in Dutch households. Although the study has used rough estimates, it gives a first impression of the relative energy footprint of water supply in comparison with total energy supply in a household and can be used to estimate future energy consequences from changes in the water system. When more comprehensive data-sets become available, it will be possible to make more accurate calculations. In order to contribute to the debate on the 'water-energy nexus', this study applies a systems approach giving the factors that determine the energy footprint of the water supply chain, from water withdrawal to disposal. It shows that, basically, there are six steps in the water supply chain that determine the energy footprint of water: water withdrawal, purification, distribution, use, wastewater collection, and wastewater treatment and disposal. In each of these steps, policy choices need to be made that will not only influence the energy footprint per step, but also cause trade-offs in other links. For example, the intake of surface water requires less energy than the intake of groundwater, but often surface water needs more energy for purification. The study shows that human behaviour in the water use stage dominates energy footprints in the whole water supply chain. If less water is used for energy-intensive processes, like showering, then significant gains can be made. In the European Union, labelling requirements show consumers the water and energy efficiency of household machines, such as washing machines (Milieucentraal, 2015). This could contribute to lower water and energy use.

Conclusions

The Netherlands is a country with abundant water that uses groundwater and surface water for freshwater supply. Although most of the year large rivers provide sufficient water, sometimes droughts occur, necessitating storage, and surface water quality is not always sufficient. Water quality is improved by infiltration in dunes; chlorine is not used at all. The Dutch policy in supplying municipal water is one of regional self-sufficiency, so that utilities do not need to transport water over large distances or elevate it to higher levels. The result of this policy is that water utilities obtain water from areas close to municipal demand centres. In the withdrawal, purification and distribution components of the water chain, relatively little energy is required, about 8–17 MJ per cubic metre of water produced. This figure includes wastewater disposal and treatment. In the Netherlands, in 1995–2007, average per capita water use decreased from 137 to 127 litres per day. This reduction was mainly caused by more efficient toilets and washing machines, in combination with public-awareness campaigns that emphasized the importance of water conservation. On the other hand, water use for showers increased from 38 to 50 litres per capita per day. This trend is important from an energy perspective, because showers represent 58% of total energy requirements for Dutch household water use.

In the Netherlands, the energy requirement of municipal water lies between 9.6 and 10.2 GJ per capita per year, dominated by direct household energy use for heating water. The top three energy requirements are energy for shower water (58%), energy for washing machine water (9%) and energy for dishwasher water (8%). When one compares energy for water to total energy requirements per capita per year of 112 GJ (Moll et al., 2005), the contribution of energy for water is about 9% of the total direct and indirect energy requirements of households in the Netherlands. This suggests that there are potential system gains from reducing the energy required to meet water demand.

To reduce the energy required to meet water demand, one should consider not only the energy required for water production, including energy losses due to leakages, but also the energy associated with how water is used. In the Netherlands, water use represents a significantly larger portion of energy consumption than water supply and wastewater treatment. Ninety-two per cent of energy for water is used to heat water. In the US it has been shown that 72–75% of energy for water in US households is needed to heat the water. While these case studies offer insights into energy for water in the Netherlands and the US, similar case studies should be performed in other countries to allow comparison. Case studies from water-scarce countries that require significantly more energy for water extraction would be particularly relevant for comparison, as they would demonstrate whether the relationship between energy for water supply and water use differs between water-scarce and water-abundant countries. The conclusions suggest that the energy associated with water use is much larger than the energy for water supply and wastewater treatment and disposal. Given this, any initiatives aimed to reduce energy consumption related to water should focus on the end use of water in addition to how water is supplied.

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