Environmental Science
Water Research & Technology

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/c5ew00026b



# The consumptive water footprint of electricity and heat: a global assessment†

Mesfin M. Mekonnen,* P. W. Gerbens-Leenes and Arjen Y. Hoekstra

Water is essential for electricity and heat production. This study assesses the consumptive water footprint (WF) of electricity and heat generation per world region in the three main stages of the production chain, *i.e.* fuel supply, construction and operation. We consider electricity from power plants using coal, lignite, natural gas, oil, uranium or biomass as well as electricity from wind, solar and geothermal energy and hydropower. The global consumptive WF of electricity and heat is estimated to be 378 billion $m^3$ per year. Wind energy (0.2–12 $m^3$ $TJ_e^{-1}$), solar energy through PV (6–303 $m^3$ $TJ_e^{-1}$) and geothermal energy (7–759 $m^3$ $TJ_e^{-1}$) have the smallest WFs, while biomass (50 000–500 000 $m^3$ $TJ_e^{-1}$) and hydropower (300–850 000 $m^3$ $TJ_e^{-1}$) have the largest. The WFs of electricity from fossil fuels and nuclear energy range between the extremes. The global weighted-average WF of electricity and heat is 4241 $m^3$ $TJ_e^{-1}$. Europe has the largest WF (22% of the total), followed by China (15%), Latin America (14%), the USA and Canada (12%), and India (9%). Hydropower (49%) and firewood (43%) dominate the global WF. Operations (global average 57%) and fuel supply (43%) contribute the most, while the WF of construction is negligible (0.02%). Electricity production contributes 90% to the total WF, and heat contributes 10%. In 2012, the global WF of electricity and heat was 1.8 times larger than that in 2000. The WF of electricity and heat from firewood increased four times, and the WF of hydropower grew by 23%. The sector's WF can be most effectively reduced by shifting to greater contributions of wind, PV and geothermal energy.

Received 29th January 2015,
Accepted 8th March 2015

DOI: 10.1039/c5ew00026b

rsc.li/es-water

**Water impact**

Energy production requires significant volumes of fresh water and has significant impacts on water resources through thermal and chemical pollution. Energy's dependence on water availability makes it vulnerable to water scarcity. There is a close interlink between energy and water, which requires a nexus approach to ensure a sustainable supply of both. This research addresses the energy and water nexus focusing on global electricity and heat generation and assesses the consumptive water footprint (WF) of electricity and heat for different energy sources, per world region, considering both fossil and renewable sources. The largest WF is produced by hydropower and bioelectricity, a finding that is very relevant to the discussion on shifting from fossil towards renewable and sustainable energy sources.

## 1. Introduction

The availability of fresh water of sufficient quality is an important issue on present policy agenda, whereby the relation to energy security has received increasing attention.[1,2] Fresh water is increasingly considered a global resource, because of the growing importance of international trade in water-intensive commodities.[3] Today, fossil fuels are still the dominant energy source, supplying about 80% of world energy use.[4] The key fossil fuels for electricity are coal, conventional oil and natural gas, while the production of unconventional fossil fuels like shale oil and shale gas increases.[5] For the European electricity supply, nuclear energy is also important, especially in countries like France and Finland. Globally, in 2010, 80% of electricity generation came from thermo-electric power plants, with 13% of global electricity production generated in nuclear power plants.[4] The growing demand for energy, *e.g.* in countries with large economic growth, such as Brazil and China, has stimulated the expansion of renewable energy, *e.g.* hydropower and wind and solar energy. Biomass is another renewable energy source, providing energy carriers like bioethanol or biodiesel, and also electricity when used in power plants. Fossil fuels are generally considered as important drivers of climate change.[6] Although renewables are often regarded as clean energy sources, there has been increasing concern about their environmental sustainability in recent years. Such

*Water Management Group, Twente Water Centre, University of Twente, The Netherlands. E-mail: m.m.mekonnen@utwente.nl; Fax: +31 53 4895377; Tel: +31 53 4892080*

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c5ew00026b

concerns include, for example, the large amount of water used for growing biomass.[7]

Water is needed for energy production and energy is needed for water supply. In 2012, the International Energy Agency (IEA) recognized the importance of the relationship between water and energy. In its annual report, the *World Energy Outlook*, IEA projects a rise of 85% in water use for energy production over the next twenty years, related to the expected shift towards more water-intensive power generation and the expanding use of biofuels.[8] This concern of the IEA came almost thirty years after the first warning on the importance of water use in energy supply by Harte and El-Gasseir[9] in *Science*. In 1994, Gleick, at the Pacific Institute in California, published the growing water crisis and its relationship to energy supply. The data provided by Gleick[10] are still cited, often through a string of citations, but one may doubt whether they are still valid, since practices of water use have changed over the past decades.[5]

Especially in the United States, energy–water interdependencies are recognized.[11] The topic became an issue on the policy agenda when the US congress asked for a national Energy–Water Roadmap in the Energy Policy Act of 2005, initiating research into the direction of reducing water demand in energy production conducted by the national laboratories of the Department of Energy.[11] A study focused on the US assessed the volume of consumptive water use to produce a unit of electricity.[12] Other examples with a focus on the US include studies on future electricity–water trade-offs,[13] studies on water demand of energy and its implications on sustainable energy policy development,[14] a review of water use in the US electric power sector[15] and an overview of life cycle water use for electricity generation.[16] Especially, the last study provides a good overview of recent data of water use for electricity generation, including water needed for fuels. However, there is still a lack of a comprehensive global overview of the WF of electricity, addressing the different energy mixes used per country and including both operational and supply-chain water use.

Water is essential for energy production. Water is used, for example, in extraction, processing and transportation of fuels, and to grow biomass for bioenergy. When coal is mined, water is needed for coal preparation (coal washing), dust suppression and machine cooling. At the same time, water is produced from the mines. This water is often polluted and needs to be treated before discharge or recycling.[5] For oil, when the pressure in an oil reservoir decreases, water can be injected into the wells to drive the oil out.[5] For uranium, consumption of water occurs when the uranium ore is mined and converted to uranium fluoride, but it occurs most significantly in the process of enrichment.[5]

Electricity from renewables includes electricity generated from geothermal energy (geo-electricity), hydropower (hydroelectricity), solar energy (captured through either concentrated solar power (CSP) or photovoltaic (PV systems), wind energy (wind electricity) and burning biomass (bio-electricity). In the New Policies Scenario of the IEA,[8] it is expected that electricity generation from renewables will nearly triple from 2010 to 2035, reaching 31% of total generation. It is expected that in 2035, hydropower will provide half of renewable-based electricity, wind almost one-quarter and PV 7.5%.

Energy and water are very much interlinked that achieving their supply for all countries requires a nexus approach. Conventional policy making in silos needs to give way to this nexus approach, reducing trade-offs and building synergies across sectors. In this research, we address the energy and water nexus. We focus on the global generation of electricity and heat. Electricity is the fastest growing form of energy use, almost doubling in the next two decades,[17] particularly in China. In 2009, China generated 17% of its electricity through hydropower[8] which contributed to one third of global electricity growth.[17]

A generally accepted indicator of water use is the water footprint (WF) that measures the volume of fresh water used to produce a product over the full supply chain, showing water consumption by source and polluted volumes by the type of pollution.[18] The blue WF measures the consumptive use of surface and ground water; the green WF measures consumption of rain water (most relevant in agriculture and forestry); the grey WF is an indicator of water pollution. WFs can be assessed for different entities, for example, products, consumers, businesses, nations or humanity as a whole. In the case of electricity and heat, the green WF will generally be negligible, with an exception for electricity or heat from biomass, which needs to be grown and thus requires rain water for production. The term 'consumptive WF' will be used in this paper to refer to the sum of the green and blue WFs, but in practice, except for the case of electricity or heat from biomass, it refers to the blue WF. Examples of earlier studies on the WF of energy are the assessment of the WF of hydroelectricity,[19] the WF of biofuels and bio-electricity[7,20] and the WF related to cooling in power plants.[12] Today, energy companies become increasingly aware of their corporate responsibility and the importance of water in their business.

Current water consumption is not sustainable within the context of the global availability of fresh water and the earth's assimilation capacity.[21] Humanity's blue WF, *i.e.* the consumption of surface and ground water, exceeds the maximum sustainable blue WF during at least parts of the year in half of the world's river basins,[22] while in two-thirds of the world's river basins, water pollution related to nitrogen and phosphorus emissions into water exceeds the assimilation capacity.[23] With the growth of electricity demand by over 70% between 2010 and 2035, over half in China (38%) and India (13%) alone,[8] it can be expected that the WF for cooling will rise accordingly with increased pressure on water resources. Another issue is that river water temperatures increase due to global warming, decreasing the capacity of power plants due to cooling problems.[24]

The aim of the current paper is to assess the WF of electricity and heat per world region, expressed in $m^3$ per unit of gross energy, as well as per year. The study will investigate the most important types of power plants (using coal, lignite, natural gas, shale gas, conventional and unconventional oil, uranium and biomass) and heat generation and give an overview of WFs of electricity from renewables as well (wind, solar, geothermal and hydropower). We include combined heat and power generation. The main research questions are as follows:

- What is the consumptive (blue plus green) WF of electricity and heat generation for different energy sources and technologies in the three main stages of the production chain, *i.e.* fuel supply, construction and operation, per unit of gross energy produced and per unit of net energy produced?
- What is the consumptive WF of electricity and heat generation per energy source per world region?

The next section, section 2, provides the methods and data applied in the study. The results of the study are presented in section 3. In section 4, we discuss the limitations of the results following from the scope of the study and from the various assumptions taken. We also put the WF of the electricity and heat sector into the context of global water scarcity. Finally, section 5 concludes with a summary of the main findings of the study.

## 2. Method

### 2.1 Range of WFs of electricity for different energy sources and technologies

The WF of electricity ($WF_e$, $m^3\ TJ_e^{-1}$) refers to the water volumes consumed and polluted in the different stages of the supply chain of electricity. In this study, we distinguish between the three major stages in the production of electricity: fuel supply, construction and operation. The first stage is relevant only for fuel-based electricity (when electricity is based on coal, lignite, oil, gas, uranium or biomass). In the other cases (hydro, solar, wind and geo-electricity), we only consider two production stages: construction and operation. The fact that production of electricity costs energy as well implies that there is a difference between the WF of the gross energy produced in electricity and heat generation and the WF of the net energy produced.

We made an inventory of the processes per stage and indicated the range of values per stage per energy source. The data for water consumption in the literature are often expressed in different units. For coal, lignite and oil, WFs are generally expressed in terms of water volume per unit of mass ($m^3$ per tonne); for natural gas and firewood, in terms of water volume per unit of volume ($m^3\ m^{-3}$). For coal, lignite, oil, natural gas, nuclear energy (uranium) and firewood, WFs can also be provided in terms of water volume per unit of embedded heat energy ($m^3\ TJ_h^{-1}$) as well as water volume per unit of electricity obtained ($m^3\ TJ_e^{-1}$).

The annual amount of fuel $F$ used to produce electricity and/or heat (expressed in mass or volume per year) can be expressed in terms of fuel energy equivalent (FEE, $GJ_h$ per year) by multiplying $F$ by the higher heating value (HHV) of the fuel:

$$\mathrm{FEE} = F \times \mathrm{HHV} \quad (1)$$

The HHV of coal varies for the top-ten largest producing countries between 18.5 and 27.3 $GJ_h$ per tonne (ref. 4) and that of lignite varies between 8 and 15 $GJ_h$ per tonne.[25] Conventional oil has an HHV of 42 $GJ_h$ per tonne and unconventional oil has an HHV of 38 $GJ_h$ per tonne.[5] The HHV of natural gas is 0.034 $GJ_h\ m^{-3}$.[26] The HHV of wood pellets is 11 $GJ_h\ m^{-3}$.[27]

The electricity produced ($E$, $GJ_e$ per year) from a given fuel energy equivalent (FEE, $GJ_h$ per year) is calculated as:

$$E = \frac{\mathrm{FEE}}{\mathrm{ERE}} \quad (2)$$

where ERE is the energy required for energy ($GJ_h/GJ_e$), which is the inverse of the efficiency of the power plant. The ERE values for different energy sources are provided in Table 1.

The WF of a fuel ($WF_f$, in $m^3$ per tonne for coal, lignite and oil, and in $m^3\ m^{-3}$ for natural gas and firewood) translates into WF per unit of embedded heat energy ($WF_{h,f}$, $m^3\ TJ^{-1}$) based on the higher heating value of the fuel (HHV):

$$WF_{h,f} = \frac{WF_f}{\mathrm{HHV}} \quad (3)$$

For all fuels (coal, lignite, oil, natural gas, uranium, and biomass), we converted WF per unit of embedded heat energy ($WF_{h,f}$, $m^3\ TJ_h^{-1}$) to WF per unit of electricity ($WF_{e,gross}$, $m^3\ TJ_e^{-1}$) based on the efficiency of converting heat into electricity, using the formula:

$$WF_{e,gross} = WF_{h,f} \times \mathrm{ERE} \quad (4)$$

In this stage, we speak about the WF per unit of gross energy (in the form of electricity) produced. However, energy is needed for mining of fossil fuels and uranium, and for the construction of installations for renewables, such as CSP and PV installations, wind turbines and hydropower plants. We used the ratio of the energy needed to make energy available, the EROI or energy return on (energy) invested[31] to calculate the WF per unit of net energy ($WF_{e,net}$, $m^3\ TJ_e^{-1}$) by:

**Table 1** Energy required for energy (ERE) values per energy source

| Energy source | ERE for electricity ($MJ_h/MJ_e$) | References |
|---|---|---|
| Coal | 2.6 | Meldrum *et al.*[16] |
| Lignite | 2.92 | Meldrum *et al.*[16] |
| Oil | 2.58 | IEA[28] |
| Natural gas | 1.96 | Meldrum *et al.*[16] |
| Uranium | 3.03 | Murray[29] |
| Biomass | 2.5–5.0 | Faaij[30] |

$$WF_{e,net} = WF_{e,gross} \times \frac{EROI}{(EROI - 1)} \quad (5)$$

The data for WFs in the different stages of production per energy source have been derived from different sources. The blue WF refers to water consumption, *i.e.* net water abstraction. We scanned the usefulness of the different sources in this respect and used the more recent publications, which clearly report water consumption, to establish ranges for the WF per stage of electricity production per type of energy source.

### 2.2 Method to estimate the water footprint of electricity and heat per energy source per country

As explained in section 2.1, we distinguish the three main stages in the generation of electricity and heat: fuel supply, construction and operation. From the perspective of the operational process of generating electricity and heat, the first two stages together can be regarded as the supply chain. The WF of electricity and heat production (WF, in $m^3$ per year) is the sum of the supply-chain WF and the operational WF:

$$WF = WF_{supply\ chain} + WF_{operation} \quad (6)$$

For all fossil fuels, nuclear energy and biomass, the WF of electricity production ($WF_{e,total}$, $m^3$ per year) is calculated as:

$$WF_{e,total}[f] = WF_{h,f}[f] \times FEE[f] + (WF_{e,c}[f] + WF_{e,o}[f]) \times E[f] \quad (7)$$

where $WF_{h,f}[f]$ is the WF of fuel f per unit of thermal energy ($m^3\ TJ_h^{-1}$), FEE[f] is the annual consumption of fuel f to produce electricity ($TJ_h$ per year), $WF_{e,c}[f]$ is the WF related to the construction of the power plant expressed per unit of electricity produced over the lifetime of the plant ($m^3\ TJ_e^{-1}$), $WF_{e,o}[f]$ is the operational WF per unit of electricity produced from fuel f ($m^3\ TJ_e^{-1}$), and $E[f]$ is the annual production of electricity from fuel f ($TJ_e$ per year). For heat production, we followed the same approach. For combined heat and power (CHP) systems, the fuel input provides both heat and electricity. We have estimated the amount of fuel allocated to heat and electricity in CHP plants based on the relative contribution of heat and electricity in the total energy production in CHP plants. In the case of district heating systems, we assumed the WF of the operational stage to be 10% of that in the case of CHP systems, because district heating systems do not require cooling like CHP systems.

Non-biomass renewable energy sources (hydropower, CSP, PV, wind and geothermal) are not fuel-based, so the WF related to electricity production ($WF_{e,total}$, $m^3$ per year) consists of two components only:

$$WF_{e,total}[r] = (WF_c[r] + WF_o[r]) \times E[r] \quad (8)$$

The fuel input and electricity and heat production per energy source and per country for the period 2000–2012 were obtained from Enerdata.[26] We have considered the following energy sources/technologies: coal, natural gas, oil, nuclear, firewood, hydropower, PV, CSP, wind and geothermal. We have not considered biomass sources other than wood (organic waste, crops). We also excluded electricity from pumping stations, a specific type of hydropower source to store energy for a short period.

The WF of firewood (expressed in $m^3\ m^{-3}$) was calculated by following the approach of Van Oel and Hoekstra.[32] The evapotranspiration from forests at the global level was estimated by combining data from FAO.[33,34] The wood yield per country was taken from the data obtained by Van Oel and Hoekstra.[32] We used the regional average for countries with missing yield data. Per country, we used a weighted-average WF of firewood based on the proportion of domestic production of wood and imported wood chips. The data for domestic wood production and importation of wood chips per country were obtained from FAO.[35] In order to derive the WF per unit of heat content of wood ($m^3\ TJ_h^{-1}$), we used an HHV value of wood pellets of 11 $GJ_h\ m^{-3}$.[27]

The operational WF of hydroelectricity was estimated by dividing the evaporation from the hydropower reservoirs by the electricity generated. To estimate the evaporation per reservoir, we combined two data sources: the long-term average annual actual evapotranspiration at a resolution of 5 × 5 arcminute[33] and the reservoir areas from the Global Lakes and Wetlands Database (GLWD).[36] In many cases, reservoirs are multi-purpose, used not only for hydroelectric generation purposes, but also for flood control and/or water supply purposes, for example, in agriculture. Therefore, the evaporation per reservoir has been fully or partially allocated to hydroelectric generation depending on the purpose of the reservoir. For reservoirs with hydroelectric generation as the primary purpose, we fully allocated the evaporation to hydroelectric generation; for reservoirs where hydroelectric generation is the secondary purpose, we allocated 50% of the evaporation to hydroelectric generation, and for reservoirs where hydroelectric generation is the tertiary purpose, we allocated 33% of the evaporation to hydroelectric generation. Per country, the evaporation allocated to hydroelectric generation is divided by the total national hydroelectric generation.[26] For countries where data for reservoir areas and thus evaporation were missing, we took the regional average of the WF per TJ. Because of the absence of good reservoir data, for all countries in Western Europe, we took the weighted average of the data for the WF per TJ of Northern and Southern Europe. The WFs estimated in this way may be underestimated for two reasons: first, the spatial resolution of the database for actual evapotranspiration from FAO[33] may not fully capture the smaller reservoirs, so the estimate may refer to evapotranspiration from the land surface instead of open water, and second, the GLWD data miss the smaller reservoirs so the aggregated evaporation per country may not fully capture the total evaporation from all the reservoirs in a country.

For coal, lignite, natural gas, nuclear, PV, CSP, wind and geothermal energy, the WFs at the different stages of electricity production were obtained from Meldrum *et al.*[16] For hydropower, the WF related to power plant construction was obtained from Inhaber.[37] For biomass and oil, we assumed the WF related to power plant construction and operation to be the same as that for coal and lignite. For oil, the WF related to fuel supply was obtained from Williams and Simmons.[5] For our calculations, we took the median number and averaged the values per technology.

It should be noted that we quantified the WF of electricity and heat production per country, but the WF presented for a country is not necessarily fully located in that country. For imported fuels and materials, WFs are located in the countries where the fuels and materials are mined. For example, France imports uranium from Canada and Niger, the Netherlands imports coal from Colombia, the USA, Russia, and South Africa, and Germany imports natural gas from Russia, Norway and the Netherlands. In general, the WF related to electricity and heat generation in a specific plant or country will generally stretch across the globe.

# 3. Results

### 3.1 Consumptive WF of electricity and heat generation per energy source per country

In the assessment of the WF of electricity and heat production per country, we combined data for the energy mix per country and global-average estimates for the WFs of the different energy sources as shown in Table 2 (values in bracket). Only for firewood and hydropower, we used country-specific estimates or regional estimates in the absence of country-specific data (as discussed in section 2.2).

Globally, coal and lignite are the main sources of energy, contributing about 41% to the total electricity and heat produced during 2008–2012 (Table 3). The other major energy sources are natural gas (26%), hydropower (14%) and nuclear energy (11%). The contribution of the different energy sources differs per country. China depends largely on coal and lignite for its electricity and heat production. Coal and lignite account for 80% and hydropower accounts for 14% of the total electricity and heat production in China. The picture is different in the case of Latin America and the Caribbean where hydropower and natural gas account for 55% and 23% of the total electricity and heat production of the region, respectively. In Europe and in Asia (excluding China and India), natural gas is the preferred source of energy, contributing about 39 and 40% to the total electricity and heat production of the regions, respectively.

Fig. 1 gives the average consumptive WF per unit of electricity and heat production ($m^3\ TJ_e^{-1}$) for all countries in the world for the period 2008–2012. The average WF per unit of energy for the different countries depends mainly on the fuel mix in their electricity and heat production. In addition, for fuels, the energy conversion efficiency plays a role, and for firewood and hydropower, the specific WF per country is important. As shown in Fig. 2, the WF per unit of electricity and heat produced differs quite significantly among the different energy sources. Firewood has the largest WF per unit of electricity and heat produced (156 000 $m^3\ TJ_e^{-1}$), followed by hydropower (15 100 $m^3\ TJ_e^{-1}$), while wind has the smallest WF (1.3 $m^3\ TJ_e^{-1}$). The global production-weighted WF per unit of electricity and heat produced was 4241 $m^3\ TJ_e^{-1}$. The figure also shows the ranges of values (minimum and maximum) per energy source, which accounts for the uncertainty involved in the estimates. In most parts of Africa, Latin America and the Caribbean, where hydropower accounts for the larger contribution to electricity production, the WF is above the global average. Besides, since these regions are located in

Table 2 The consumptive WF per unit of electricity output for different energy sources per stage of production[a]

| | Fuel supply | | | Construction | Operation | Total |
|---|---|---|---|---|---|---|
| Energy source | $WF_f$ ($m^3$ per tonne) | $WF_{h,f}$ ($m^3\ TJ_h^{-1}$) | $WF_{e,f}$ ($m^3\ TJ_e^{-1}$) | $WF_{e,c}$ ($m^3\ TJ_e^{-1}$) | $WF_{e,o}$ ($m^3\ TJ_e^{-1}$) | $WF_e$ ($m^3\ TJ_e^{-1}$) |
| Coal | 0.18–4.2 | 6.6–228 (15) | 17–665 | 0.32–26 (1) | 61–1410 (485) | 79–2100 |
| Lignite | 0.10–0.72 | 12–48 (15) | 31–139 | 0.32–26 (1) | 61–1410 (485) | 93–1580 |
| Conventional oil | 0.33–8.9 | 7.8–212 (20) | 20–546 | 0.32–26 (1) | 194–615 (485) | 214–1190 |
| Unconventional oil (oil sand) | 3.3–10 | 87–270 | 224–697 | 0.32–26 | 194–615 | 419–1340 |
| Unconventional oil (oil shale) | 1.8–17 | 47–459 | 121–1180 | 0.32–26 | 194–615 | 316–1830 |
| Natural gas | — | 0.6–18 (2.2) | 1.2–35 | 0.32–1.1 (1) | 74–1200 (267) | 76–1240 |
| Shale gas | — | 3.5–34 | 6.9–67 | 0.32–1.1 | 74–1200 | 81–1270 |
| Nuclear | — | 5.7–169 (20.2) | 17–512 | 0.3 | 0–936 (609) | 18–1450 |
| | ($m^3\ m^{-3}$) | | | | | |
| Firewood | 210–1100 | 19 000–100 000 | 48 000–500 000 | 0.32–26 (1) | 61–1410 | 48 000–500 000 |
| Hydropower | — | — | — | 0.30 | 300–850 000 (950–138 000) | 300–850 000 |
| Concentrated solar power | — | — | — | 84–179 (169) | 34–2000 (559) | 118–2180 |
| Photovoltaics | — | — | — | 5.3–221 (86) | 1.1–82 (19) | 6.4–303 |
| Wind | — | — | — | 0.10–9.5 (1) | 0.1–2.1 (0.2) | 0.2–12 |
| Geothermal | — | — | — | 2.0 | 5.3–757 (335) | 7.3–759 |

[a] The numbers have been rounded off. The values between brackets represent the median values and are used in the assessment of the WF of electricity and heat production per country. In the assessment of the WF of electricity and heat from firewood and hydropower, we used country-specific estimates, or regional estimates in the absence of country-specific data as discussed in section 2.2. For hydropower, the lowest value shown between brackets is for China; the largest value is for Africa. Sources: ref. 5, 7, 10, 16, 19, 20, 29, 32, 37–59. The complete list of data sources for the WF per energy source is provided in the ESI.

**Table 3** Electricity and heat production per energy source per region (PJ$_e$ per year) for the period 2008–2012[a]

| Country | Coal and lignite | Natural gas | Hydropower | Nuclear | Oil | Wind | Firewood | Geothermal | Solar | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Europe | 6650 | 10 180 | 2579 | 4294 | 866 | 567 | 493 | 125 | 112 | 25 866 |
| Eastern Europe | 3772 | 6942 | 749 | 1239 | 457 | 17 | 89 | 8.9 | 4.3 | 13 277 |
| Western Europe | 1390 | 1203 | 544 | 2276 | 93 | 219 | 144 | 34 | 56 | 5958 |
| Northern Europe | 775 | 876 | 844 | 548 | 64 | 109 | 216 | 51 | 0.1 | 3483 |
| Southern Europe | 713 | 1159 | 442 | 232 | 251 | 221 | 45 | 31 | 52 | 3146 |
| China | 14 612 | 286 | 2508 | 285 | 135 | 181 | 101 | 152 | 0.00 | 18 259 |
| USA and Canada | 7280 | 4280 | 2338 | 3306 | 208 | 380 | 195 | 74 | 7.5 | 18 067 |
| Other Asian countries | 4094 | 5965 | 1236 | 1392 | 2077 | 33 | 104 | 147 | 2.2 | 15 051 |
| Latin America and Caribbean | 252 | 1129 | 2652 | 111 | 605 | 18 | 39 | 36 | 0.16 | 4842 |
| India | 2406 | 381 | 414 | 92 | 51 | 74 | 84 | 0.00 | 0.00 | 3501 |
| Africa | 921 | 766 | 386 | 48 | 274 | 7.7 | 5.3 | 5.1 | 0.09 | 2412 |
| Oceania | 660 | 193 | 140 | 0.0 | 24 | 23 | 7.1 | 30 | 0.02 | 1077 |
| Global total | 36 874 | 23 180 | 12 251 | 9528 | 4239 | 1284 | 1028 | 570 | 122 | 89 076 |

[a] Data source: Enerdata.[26] The data shown for solar are the sum of PV and CSP.

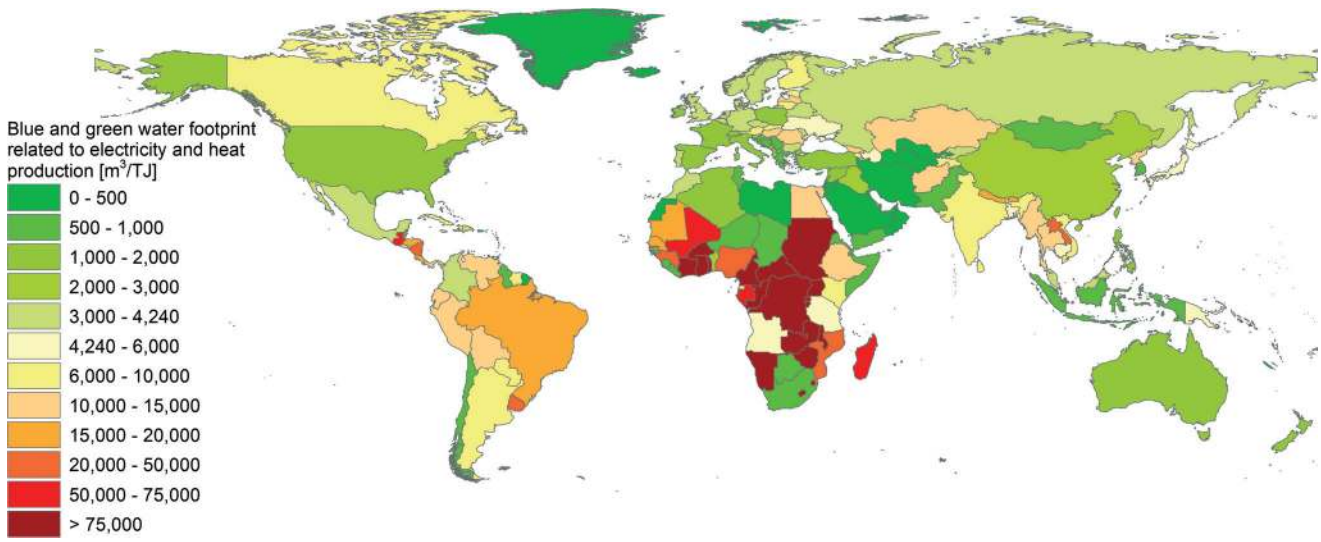


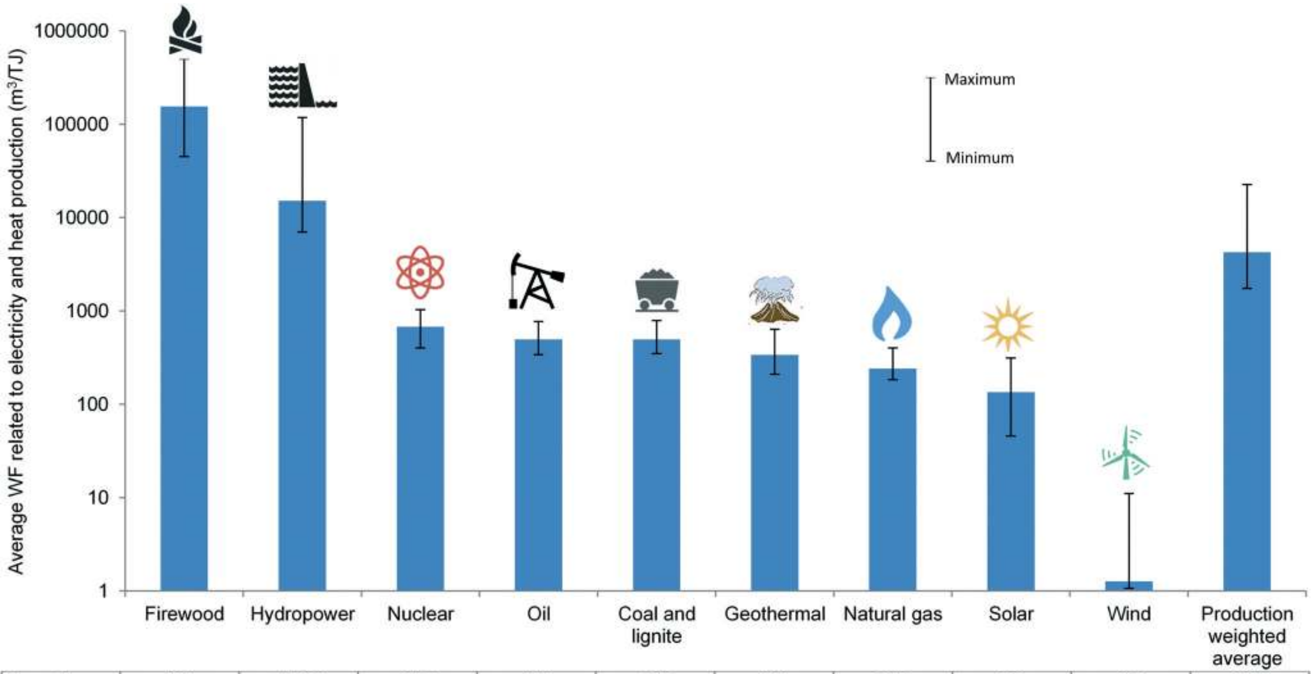

**Fig. 1** The average consumptive WF related to electricity and heat production, per unit of energy (m$^3$ TJ$_e$$^{-1}$), per country for the period 2008–2012. Countries with some shades of green have a WF below the global average (4241 m$^3$ TJ$_e$$^{-1}$) while countries shaded yellow or red have a WF above the global average.

equatorial and arid regions, the WF of hydropower (expressed in m$^3$ TJ$_e$$^{-1}$) is relatively large. In a number of African countries (Burundi, Central African Rep., DR Congo, Lesotho, Malawi, Namibia, Swaziland, and Zambia), hydropower accounts for about 90% to 100% of their electricity production and their WF is among the largest in the world (125 000–138 000 m$^3$ TJ$_e$$^{-1}$). Among the regions, Africa has the largest WF, with a weighted average of 22 800 m$^3$ TJ$_e$$^{-1}$, followed by Latin America with 11 200 m$^3$ TJ$_e$$^{-1}$. The weighted-average WF of the electricity and heat sector in India is 9400 m$^3$ TJ$_e$$^{-1}$, in Europe 3240 m$^3$ TJ$_e$$^{-1}$, in China 2990 m$^3$ TJ$_e$$^{-1}$, in the USA and Canada 2520 m$^3$ TJ$_e$$^{-1}$ (on average), and in Oceania 1900 m$^3$ TJ$_e$$^{-1}$. Countries in the Middle East depend mainly on natural gas and oil for their electricity production and have a WF between 200–500 m$^3$ TJ$_e$$^{-1}$.

Table 4 gives the consumptive WF of electricity and heat per production stage per region over the period 2008–2012. The global consumptive WF of electricity and heat production (supply chain plus operational) was 378 billion m$^3$ per year for the period 2008–2012. Europe contributed about 22% to the global consumptive WF, followed by China (15%), Latin America and the Caribbean (14%), the USA and Canada (12%), and India (9%). For a large number of countries, the operational WF takes the largest share (*e.g.* as much as 85% in Latin America and the Caribbean), followed by the fuel supply stage. At the global level, the operational WF contributed about 57%, while the fuel supply stage contributed about 43%. The contribution of power plant construction to the total consumptive WF was quite small (0.02%). About 90% of the WF was due to the production of electricity and the remaining 10% was due to the production of heat.

Table 5 shows the consumptive (operational plus supply chain) WF of electricity and heat per energy source (million m$^3$ per year) for a number of regions over the period 2008–2012. In all regions, the relative contribution of hydropower and firewood to the total consumptive WF was very large.




| | Firewood | Hydropower | Nuclear | Oil | Coal and lignite | Geothermal | Natural gas | Solar | Wind | Production weighted average |
|---|---|---|---|---|---|---|---|---|---|---|
| Operation | 400 | 15100 | 610 | 440 | 440 | 340 | 240 | 50 | 0.2 | 2410 |
| Construction | 0.4 | 0.3 | 0.3 | 1.1 | 1.1 | 2.1 | 1.1 | 90 | 1.1 | 1.0 |
| Fuel supply | 156000 | 0 | 68 | 55 | 54 | 0 | 6 | 0 | 0 | 1830 |

**Fig. 2** Average consumptive WF per unit of electricity and heat produced ($m^3$ $TJ_e^{-1}$) for the period 2008–2012. Note that the scale is logarithmic. The ranges shown reflect minimum and maximum values per energy source. The values in the table represent the WF ($m^3$ $TJ^{-1}$) for the three main stages of the electricity and heat production chain.

**Table 4** Consumptive WF of electricity and heat per production stage per region (million $m^3$ per year) for the period 2008–2012

| | Electricity | | | Heat | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|
| | Supply chain WF | | | Supply chain WF | | | | | |
| Region | Fuel | Power plant construction | Operational WF | Fuel | Power plant construction | Operational WF | Electricity | Heat | Total |
| China | 36 956 | 14 | 8419 | 8945 | 3.4 | 193 | 45 390 | 9141 | 54 531 |
| Latin America and Caribbean | 7264 | 3.0 | 45 944 | 1034 | 0.0 | 0.03 | 53 211 | 1034 | 54 245 |
| Europe | 19 394 | 23 | 48 585 | 14 035 | 9.5 | 1713 | 68 001 | 15 757 | 83 758 |
| Western Europe | 9598 | 8.1 | 3857 | 3375 | 0.81 | 208 | 13 463 | 3584 | 17 047 |
| Eastern Europe | 2865 | 5.2 | 39 257 | 4321 | 7.7 | 1272 | 42 128 | 5600 | 47 728 |
| Northern Europe | 4264 | 2.0 | 3963 | 5703 | 0.66 | 154 | 8229 | 5858 | 14 087 |
| Southern Europe | 2666 | 7.3 | 1507 | 636 | 0.30 | 79 | 4181 | 715 | 4896 |
| India | 24 364 | 3.3 | 4596 | 3926 | 0.00 | 0.00 | 28 963 | 3926 | 32 889 |
| USA and Canada | 19 513 | 15 | 21 669 | 4121 | 0.55 | 170 | 41 197 | 4292 | 45 489 |
| Other Asian countries | 17 387 | 13 | 27 830 | 4255 | 0.89 | 289 | 45 231 | 4545 | 49 776 |
| Africa | 1007 | 2.2 | 53 879 | 159 | 0.0 | 0.0 | 54 888 | 159 | 55 047 |
| Oceania | 551 | 1.0 | 1405 | 86 | 0.02 | 3.62 | 1957 | 90 | 2047 |
| Global total | 126 435 | 74 | 212 328 | 36 562 | 14 | 2368 | 338 838 | 38 945 | 377 782 |

However, the contribution of the different energy sources to the total consumptive WF differed per region. In India and China, firewood was dominant, contributing about 85 and 83% to their total electricity and heat production related WF, respectively. In Europe, the contribution of firewood to the total WF was about 39%; in the USA and Canada, this was 51%. In Europe, nuclear power contributed about 3% to the total consumptive WF related to electricity and heat production, and in the USA and Canada, it was 5%.

The electricity from hydropower contributes about 49% to the total WF of the global electricity and heat sector. Firewood contributes 43%. Although coal and lignite provide 41% of global electricity and heat (Table 5), they contribute 4.8% to the global electricity and heat related WF. The contribution of geothermal, solar and wind energy to the total WF was very small (0.06%).

Over the last few years, the global production of electricity and heat has increased.[26] As a result of this increase, the

**Table 5** Consumptive WF of electricity and heat production (operations plus supply chain) per energy source and per region (million $m^3$ per year) for the period 2008–2012

| Country | Hydropower | Firewood[a] | Coal & lignite | Nuclear | Natural gas | Oil | Geothermal | Solar | Wind | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 2393 | 45 197 | 6597 | 193 | 65 | 35 | 51 | 0.0 | 0.23 | 54 531 |
| Latin America and Caribbean | 45 130 | 8253 | 136 | 75 | 310 | 330 | 12 | 0.02 | 0.02 | 54 245 |
| Europe | 42 397 | 32 836 | 3191 | 2908 | 2058 | 310 | 42 | 15 | 0.72 | 83 758 |
| Western Europe | 1603 | 12 774 | 759 | 1541 | 306 | 46 | 11 | 5.8 | 0.28 | 17 047 |
| Eastern Europe | 37 033 | 6894 | 1624 | 839 | 1224 | 110 | 3.0 | 0.45 | 0.02 | 47 728 |
| Northern Europe | 3113 | 9951 | 394 | 371 | 217 | 23 | 17 | 0.01 | 0.14 | 14 087 |
| Southern Europe | 648 | 3217 | 413 | 157 | 312 | 130 | 11 | 8.6 | 0.28 | 4896 |
| India | 3207 | 28 114 | 1372 | 62 | 104 | 30 | 0.0 | 0.0 | 0.09 | 32 889 |
| USA and Canada | 14 936 | 23 092 | 3913 | 2239 | 1171 | 112 | 25 | 1.30 | 0.48 | 45 489 |
| Other Asian countries | 22 609 | 21 233 | 2189 | 943 | 1623 | 1130 | 50 | 0.23 | 0.04 | 49 776 |
| Africa | 53 062 | 1091 | 501 | 32 | 211 | 148 | 1.7 | 0.01 | 0.01 | 55 047 |
| Oceania | 1012 | 584 | 375 | 0.0 | 53 | 13 | 10 | 0.0 | 0.03 | 2047 |
| Global total | 184 746 | 160 398 | 18 272 | 6453 | 5595 | 2107 | 192 | 16 | 2 | 377 782 |

[a] In all cases other than firewood, the WF is 100% blue.



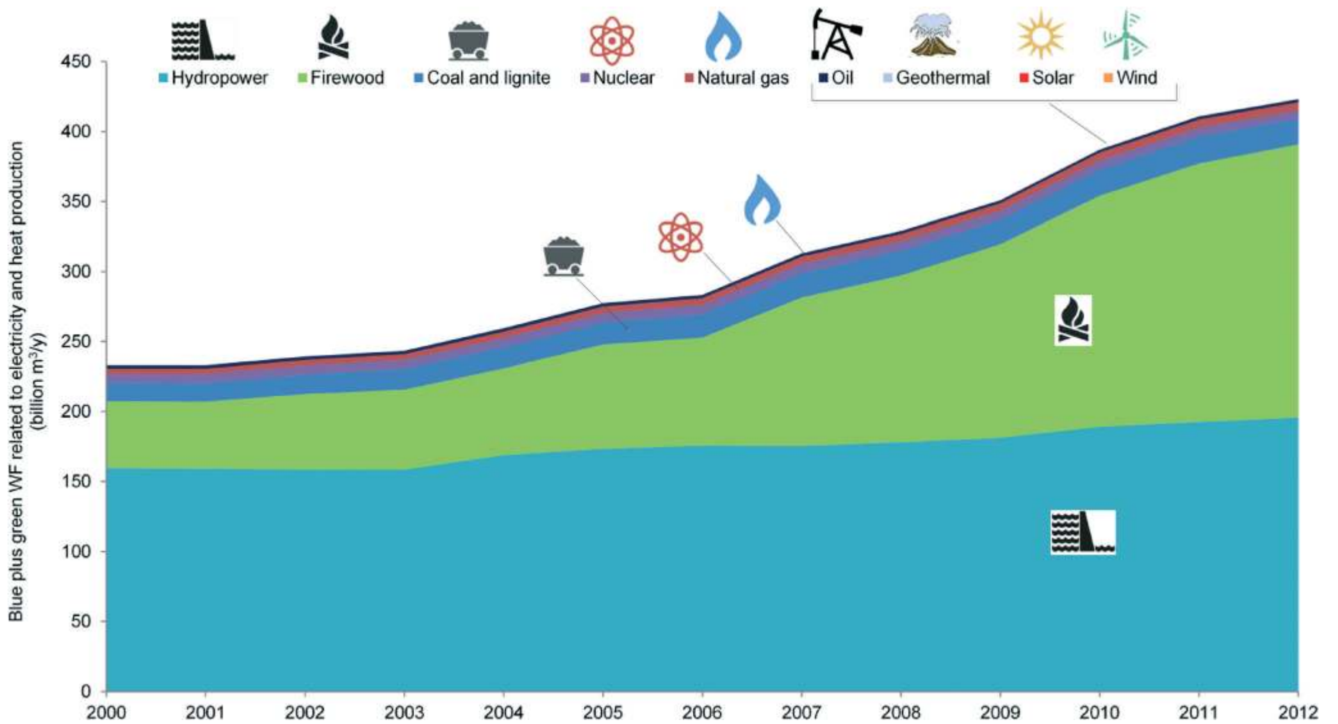



**Fig. 3** Increase in the consumptive WF related to global electricity and heat production (operations plus supply chain) over the period 2000–2012, per energy source.

consumptive WF related to electricity and heat production has shown significant growth. The consumptive WF in 2012 was 1.8 times larger than that in 2000 (Fig. 3). The WF of electricity–heat has shown growth for all energy sources, except for nuclear energy and oil. The largest growth in the period 2000–2012 was for solar and wind energy, which have grown about 33- and 16-fold, respectively. Their contribution to the total consumptive WF of the sector remains very small though. The WF of hydroelectricity has grown by about 23%, while that of firewood has grown by a factor of four over the period 2000–2012. The contribution of hydropower to the total WF has dropped from 68% to 46%, while that of firewood has grown from 21% to 46%. The contribution of coal and lignite to the total consumptive WF has dropped by about 25%.

# 4. Discussion

The study provides ranges for WFs of electricity and heat produced from fossil fuels, uranium and renewables per unit of gross energy as well as per unit of net energy. Next, it gives an overview of the global present-day WFs on the national, regional and global scale. We based our results on data from the literature on water consumption per unit of energy for different energy sources, combined with information on electricity and heat production per energy source per country. To calculate WF per country, we made several assumptions. Moreover, collected data are based on information from different sources, each of which adds a degree of uncertainty. Estimates for the WF of hydropower, for example, are sensitive to climatic data and data concerning the size of the storage reservoir surface. We therefore emphasise that the figures presented in this study are rough estimates. Below, we address the most important limitations of the study.

Limitations regarding the scope of the study:

• We included heat generation in power plants, but excluded the use of firewood in households, due to a lack of data regarding local heat generation at the household level. In some countries, *e.g.* in developing countries, household energy use contributes largely to the total heat produced. This means that we underestimate the WF of heat generation for countries with large home use of firewood.

• We included the use of firewood to generate electricity and heat in power plants, but excluded the use of crops and organic waste. Burning harvested crops is an exception, so this exclusion cannot significantly affect the outcome of the global assessment, but organic waste becomes a significant part of the fuel in some power plants. We assumed that the WF of organic waste is zero. This leads to an underestimation of the WF of the electricity and heat sector because by applying organic waste to produce energy, it gets a value and is no longer negligible. The WF related to the generation of the products that resulted in the waste should no longer be fully allocated to the primary product, but also partly to the valuable 'waste' by-product. We also excluded the use of other municipal and household waste to generate electricity and/or heat, again assuming a zero WF for this sort of fuel.

• When fuels such as coal, lignite and uranium, or materials for construction, such as copper, are mined, this generally comes along with water pollution, causing a grey WF. Power plants also release different chemicals and thermal loads to fresh water. Due to the absence of good data for water pollution due to mining and chemical loads from the power plants, we did not include the grey WF, underestimating the total WF of electricity and heat.

• The study excluded electricity generated from pumping hydropower stations. Pumping stations store electricity which is overproduced, *e.g.* from nuclear power stations during the night, or from wind turbines when there is a lot of wind, as potential energy that can be released in the form of hydropower when electricity is needed again. Hydropower from pumping stations supposedly has a smaller WF than conventional hydropower, because it is stored during part of the day, however, data for this field are lacking. Globally, electricity produced by pumping stations is about 2% of the total electricity production from hydropower, but in some countries the share is much larger.[26] In Germany, for example, the share is 24% of the total hydropower.

Limitations regarding the assumptions:

• For the assessment of the present-day WFs on the national scale, we used median WF values for the different energy sources from the study by Meldrum *et al.*[16] That study, however, may be biased towards data for USA, which means that the estimates for other countries may actually deviate in cases where electricity generation technology substantially differs from the USA average.

• The global assessment of the WF of electricity and heat is based on WF per unit of gross energy output. As shown in Table 6, this underestimates WFs because due to energy inputs in the supply chain, the net energy yield is less than the gross energy production.

**Table 6** The consumptive WF per unit of gross energy and per unit of net energy for different energy sources for the fuel supply and the total production chain of electricity[b] ($m^3$ $TJ_e^{-1}$)

| Energy source | EROI[a] | Fuel supply | | Total | |
|---|---|---|---|---|---|
| | | $WF_{e,gross}$ ($m^3$ $TJ_e^{-1}$) | $WF_{e,net}$ ($m^3$ $TJ_e^{-1}$) | $WF_{e,gross}$ ($m^3$ $TJ_e^{-1}$) | $WF_{e,net}$ ($m^3$ $TJ_e^{-1}$) |
| Coal | 80 | 17–665 | 17–674 | 79–2100 | 79–2110 |
| Lignite | 80 | 31–139 | 32–141 | 93–1580 | 93–1580 |
| Conventional oil | 11 | 20–546 | 22–601 | 214–1190 | 216–1240 |
| Unconventional oil (oil sand) | 3 | 224–697 | 337–1050 | 419–1340 | 531–1690 |
| Unconventional oil (oil shale) | 4 | 121–1180 | 162–1580 | 316–1830 | 356–2220 |
| Natural gas | 10 | 1.2–35 | 1.4–39 | 76–1240 | 76–1240 |
| Shale gas | 4 | 6.9–67 | 9–90 | 81–1270 | 84–1290 |
| Nuclear | 10 | 17–512 | 19–569 | 18–1450 | 20–1506 |
| Firewood | 17 | 48 000–500 000 | 52 000–535 000 | 48 000–500 000 | 52 000–535 000 |
| Hydropower | 100 | — | — | 300–850 000 | 303–860 000 |
| Concentrated solar power | 1.6 | — | — | 118–2180 | 315–5810 |
| Photovoltaics | 6.8 | — | — | 6.4–303 | 7.5–355 |
| Wind | 18 | — | — | 0.2–12 | 0.2–12 |
| Geothermal | 2–17 | — | — | 7.3–759 | 7.8–1520 |

[a] Energy return on (energy) invested. The EROI values for coal, lignite, oil, gas, nuclear and biomass are defined as the energy produced in the form of fuel divided by the energy inputs into fuel production ($MJ_h/MJ_h$). In the case of fuels, we thus neglect the energy inputs in power plant construction and operations. The EROI values for hydropower, CSP, PV, wind and geothermal refer to the energy produced in the form of electricity divided by the energy inputs into construction and operation ($MJ_e/MJ_h$). [b] Data sources: for biomass from Nonhebel,[62] for geothermal from Herendeen and Plant,[63] and for all other energy sources from Murphy and Hall.[31]

• There are three different cooling types for power plants – wet and dry cooling towers and once-through cooling systems – that have different consumptive WFs; the largest is for wet cooling towers, the value for once-through cooling systems is 40% less, and much smaller values are given for dry cooling towers.[5] The ratios of different cooling types applied per country differ, but data for these were lacking. For our global assessment, we therefore used the median value for cooling from the study by Meldrum *et al.*[16]

• We assumed that power plants use fresh water for cooling. When power plants are located close to the sea, however, salt water (without a WF) can be used for cooling. For those countries that have many power plants located close to the sea, we overestimated the WF.

• In the case of combined heat and power (CHP) plants, the WF of the fuel was allocated to electricity and heat based on relative production volumes of the two (in terms of energy), not on the basis of the relative economic values of the two, due to the absence of information regarding the latter type of data. In cases where the economic value of electricity per unit of energy exceeds the value of heat, underestimation of the WF of electricity and overestimation of the WF of heat can be expected.

• The WFs related to evaporation from water reservoirs used for hydroelectric generation have been fully or partially allocated to hydroelectricity based on whether hydroelectric generation is the reservoir's primary, secondary or tertiary purpose – using a simple rule (section 2.2). It would be fair to distribute the WF related to reservoir evaporation to the various purposes of the reservoir according to the relative value of the different purposes, but this was not possible due to the absence of a global dataset on the purposes of all different reservoirs and the respective value of those purposes. The WF of hydroelectricity per country was estimated based on available data for reservoir areas from Lehner and Döll,[36] evaporation data from FAO,[33] and total hydroelectric generation from Enerdata.[26] Both reservoir areas and evaporation data may have been underestimated, the former due to incompleteness of the reservoir database and the latter due to the limited spatial resolution of the evaporation database, as a result of which the evaporation data may reflect land evapotranspiration rather than open water evaporation for grid cells in which land dominates open water. These factors may lead to an underestimation of the WF of hydroelectricity per country. On the other hand, the data for reservoir areas refer to the water surface at full capacity, while reservoir areas actually fluctuate throughout the year,[19] which may lead to an overestimation of the WF of hydroelectricity. A further note regarding the WFs of hydroelectricity is that the outcomes are very sensitive to the ratio of area flooded per unit of installed capacity. In this study, we have assumed all hydropower to be reservoir-based, even though 4% of the global installed capacity is of the run-of-the-river type. The latter type does not have a reservoir-related blue WF. Furthermore, for countries where the reservoir area data were missing altogether, we estimated the WF of total hydroelectric generation based on regional averages of the WF per unit of hydroelectricity. Given the above disclaimers, the presented data for WFs related to hydroelectricity per country and region should thus be taken with caution. However, the general finding that the WFs of hydroelectricity are larger than the WFs of other forms of electricity remains valid.

We assessed the WF of electricity and heat generation based on the consumptive WF per unit of gross energy produced. However, if the energy inputs in the electricity and heat production and the fuel supply chain are accounted for, the WF could increase significantly. As shown in Table 6, a large EROI indicates a large energy return on energy invested. Large returns are shown for coal and hydropower. Unconventional oil and gas, CSP and in some cases geothermal energy have relatively small returns on energy investments. The differences in WF per unit of net energy and WF per unit of gross energy are the largest for energy sources with relatively large energy inputs in the production process relative to the energy output (small EROI values). When accounting for the energy inputs in fuel supply, the WFs of unconventional oil and shale gas increase by about one third (compared to when we do not account for these inputs). The WF of geothermal energy can be doubled, while that of CSP can be tripled.

In order to identify areas in risk of water shortage for electricity production, we compared, per country, the fuel production (in TJ per year) and the operational WF of electricity and heat generation to the annual average monthly blue water scarcity. Monthly blue water scarcity was estimated, per month and per country, by dividing the total monthly blue water footprint within the country[60] by the total monthly (internal + external) water availability in the country. The latter was calculated as the total monthly (internal + external) water resources of the country minus the environmental flow requirements.[22] Monthly internal and external water resources per country were estimated based on annual values from AQUASTAT[61] and data for the variability of run-off within the year.

Table 7 shows the fraction of fuels produced in countries with blue water scarcity above 100% and also the fraction of the operational WF of electricity and heat production for countries with blue water scarcity above 100%. About 46% of fuelwood produced globally, 42% of natural gas, and 30% of crude oil were produced in countries with blue water scarcity above 100%. Natural gas and oil contribute about 31% and 25% to the total fuel supply, respectively. For both coal and uranium, the fraction that was produced in countries with blue water scarcity above 100% was 14%. Overall, about 28% of the global fuel was produced in countries with water scarcity above 100%. About 22% of the global operational WF related to electricity and heat production was obtained in countries with blue water scarcity above 100%. The fraction of the operational WF for places with blue water scarcity above 100% differs per energy source. The largest fraction is found for solar energy (60%) and oil (44%). However, the contributions of solar energy and oil to the total operational WF are very small. Hydropower contributes about 86% to the

Table 7 Percentage of fuels produced and operational water footprint (WF) of electricity and heat generated in countries with blue water scarcity (WS) above 100%

| Energy source | Contribution to total fuel supply | Contribution to total operational WF | Percentage of fuel produced in countries with blue WS >100% | Percentage of the operational WF in countries with blue WS >100% |
|---|---|---|---|---|
| Coal | 38% | 8% | 14% | 12% |
| Natural gas | 31% | 3% | 42% | 23% |
| Oil | 25% | 1% | 30% | 44% |
| Nuclear | 2% | 3% | 14% | 4.2% |
| Geothermal | | 0.1% | | 5.4% |
| Solar | | 0.0% | | 60% |
| Wind | | 0.0% | | 19% |
| Hydropower | | 86% | | 23% |
| Firewood | 5% | 0.2% | 46% | 15% |
| Total | 100% | 100% | 28% | 22% |



total operational WF and 23% of its operational WF occurs in countries with blue water scarcity above 100%. Coal and gas together contribute about 11% to the total operation WF. About 12% of the coal and 23% of the gas operational WF occurs in countries with blue water scarcity above 100%. Future scenarios for global fuel supply and electricity production should be evaluated in terms of risks of water shortage.

## 5. Conclusions

The consumptive WF of electricity, expressed as the total volume of water consumed over the supply chain, per unit of gross electricity produced, primarily depends on the energy source. The renewables wind energy (0.2 to 12 $m^3$ $TJ_e^{-1}$), solar energy from PV (6 to 303 $m^3$ $TJ_e^{-1}$) and geothermal energy (7 to 759 $m^3$ $TJ_e^{-1}$) have the smallest WFs. The renewables biomass and hydropower have the largest WFs, between 50 000 and 500 000 $m^3$ $TJ_e^{-1}$ for biomass and between 300 and 850 000 $m^3$ $TJ_e^{-1}$ for hydropower. The WFs of electricity from fossil fuels and nuclear energy show similar ranges for the different sorts of energy. For coal, we find a range of 80 to 2100 $m^3$ $TJ_e^{-1}$, for lignite 90 to 1600 $m^3$ $TJ_e^{-1}$, for conventional oil 200 to 1200 $m^3$ $TJ_e^{-1}$, for unconventional oil 300 to 1800 $m^3$ $TJ_e^{-1}$, for natural gas 75 to 1200 $m^3$ $TJ_e^{-1}$, for shale gas 80 to 1300 $m^3$ $TJ_e^{-1}$, and for nuclear energy 20 to 1450 $m^3$ $TJ_e^{-1}$. The WF of solar energy from CSP is in the same order of magnitude as the WF of electricity from fossil fuels and nuclear energy, because of the need for cooling.

In the case of electricity from fossil fuels and nuclear energy, the largest contribution to the blue WF is generally from the operational stage, in which water is lost through cooling. There are large differences in the blue WFs for different cooling technologies. The largest blue WFs are found for wet cooling towers, smaller blue WFs are found for once-through cooling systems using fresh water and again smaller WFs are found for dry cooling towers and once-through cooling systems using saline water.[5] Once-through cooling systems can have a very large grey WF related to thermal pollution.

For all sources of electricity, the energy return on energy invested (the EROI factor) is an important factor in determining the WF of the net energy produced. In the case of fuels, there is also the conversion efficiency (from fuels to electricity) of the power plants, *i.e.* the energy required for energy (the ERE factor). Improving energy efficiency in power plants (reducing the ERE factor) and reducing energy inputs in the supply chain as a whole (increasing the EROI factors) will contribute to the reduction of the WF per unit of net energy produced in the form of electricity and heat. For fuels with relatively small EROI values, like unconventional coal or shale gas (with EROI values of 3 to 4, compared to an EROI value of 80 for coal or lignite), this means that WF per unit of net energy provided are substantially larger than WF per unit of gross energy output (*e.g.* 25% larger in the case of coal sand). In the case of renewables, particularly, CSP has a low EROI value (1.6), which results in an increase of the WF from 120–2200 $m^3$ per TJ of gross energy to 300–5800 $m^3$ per TJ of net energy.

The total global electricity and heat production was 89 076 $PJ_e$ per year (2008–2012). Coal and lignite contribute 41% to this total, natural gas 26%, hydropower 14% and nuclear energy 11%. The contributions of oil, firewood, wind, geothermal and solar energy are relatively small. The contribution of the different energy sources differs among countries, thus, resulting in differences in WF per unit of electricity. The global weighted-average WF of electricity and heat is 4241 $m^3$ $TJ_e^{-1}$. When countries have a relatively large contribution of hydropower or firewood in the energy mix for electricity and heat, the WF is relatively large. WFs larger than the global average are found in countries like Brazil, Argentina, India, Canada, Japan and many African countries. WFs below the global average are found in countries like the USA, China, European countries (except for Austria, Finland, Hungary, Romania, Slovakia, Ukraine and the Baltic States), Australia, Russia, Mexico, Indonesia, Colombia and South Africa. The annual global consumptive WF of electricity and heat was 378 billion $m^3$ per year for the period 2008–2012. Europe has the largest WF (22% of the total), followed by China (15%), Latin America (14%), the USA and Canada (12%), and India (9%). Other countries contribute to the other 28%. The WF of China of 55 billion $m^3$ per year is dominated by firewood (83%), followed by coal and lignite (12%). In India, the

WF of 33 billion $m^3$ per year is dominated by firewood (85%), followed by hydropower (10%). In Europe and in the USA and Canada, the contribution of wood to the total WF is 39 and 51%, respectively; the contribution of coal is 4 and 9%; the contribution of nuclear power is 3 and 5%.

The global WF of electricity and heat of 378 billion $m^3$ per year is dominated by hydropower with a contribution of 49%, followed by firewood (43%). The dominant fuels for electricity and heat supply, coal and lignite, contribute only 5%, followed by nuclear energy (1.7%), natural gas (1%) and oil (0.6%). The contribution of the other renewables, wind, geothermal and solar energy, is negligible. The global blue WF related to electricity and heat production (excluding the WF of electricity from biomass) of 217 billion $m^3$ per year is significant compared to the global blue WF of the agricultural, industrial and domestic sectors of 1025 billion $m^3$ per year,[60] which illustrates the significant role the power sector plays in putting pressure on the global freshwater system.

In general, the operational stage contributes the most to the total WF of electricity and heat; the global average is 57%. In Latin America and the Caribbean, this is even higher (85%). The fuel supply stage contributes 43%, while the WF of the construction stage is negligible (0.02%). Electricity production contributes 90% to the total WF, and heat production contributes the other 10%.

Over the period 2000–2012, the total energy production increased, resulting in increasing WFs. The global consumptive WF of electricity and heat in 2012 was 1.8 times larger than that in 2000. The WF of electricity and heat from firewood increased four times, while the WF of hydropower grew by 23%.

Our findings indicate that the consumptive WF of the electricity and heat sector can most effectively be reduced by moving towards greater contributions of wind energy, energy from photovoltaic cells and geothermal energy. Even greater benefits can be obtained with these forms of energy if greater energy returns on energy invested can be achieved through technological improvements. The consumptive WF of fossil-fuel based electricity can best be reduced by moving towards greater efficiencies in the power plants, by avoiding the use of oil from bituminous sands as well as shale oil and gas, and by moving towards dry cooling towers. Burning biomass in power plants leads to a major increase in the WF of electricity and heat; burning biomass grown for this purpose (firewood or crops) is not recommendable, but organic waste may be an option to be further studied. Hydroelectricity has a major contribution to the overall WF of the electricity sector and needs to be further evaluated on a case-by-case basis.

## Acknowledgements

This research was financed by and carried out in collaboration with the Enel Foundation. We would like to thank Renata Mele and Christian Zulberti of the Enel Foundation.

## References

1 UN Water, *The United Nations World Water Development Report 2014: Water and Energy*, UNESCO, Paris, France, 2014.
2 World Economic Forum, *Water security: The water-food-energy-climate nexus*, Island Press, Washington, D.C., USA, 2011.
3 A. Y. Hoekstra, *The Water Footprint of Modern Consumer Society*, Routledge, London, UK, 2013.
4 IEA, *Key world energy statistics*, International Energy Agency, Paris, 2013.
5 E. D. Williams and J. E. Simmons, *Water in the energy industry: An introduction*, BP International, London, UK, 2013.
6 IPCC, *Renewable energy sources and climate change mitigation, Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, USA, 2012.
7 W. Gerbens-Leenes, A. Y. Hoekstra and T. H. van der Meer, *Proc. Natl. Acad. Sci. U. S. A.*, 2009, **106**, 10219–10223.
8 IEA, *World energy outlook 2012*, International Energy Agency, Paris, 2012.
9 J. Harte and M. El-Gasseir, *Science*, 1978, **199**, 623–634.
10 P. H. Gleick, *Annu. Rev. Energy Environ.*, 1994, **19**, 267–299.
11 R. Pate, M. Hightower, C. Cameron and W. Einfeld, *Overview of energy-water interdependencies and the emerging energy demands on water resources*, Report SAND 2007-1349C, Sandia National Laboratories, Albuquerque, New Mexico, USA, 2007.
12 W. Wilson, T. Leipzig and B. Griffiths-Sattenspiel, *Burning our rivers: the water footprint of electricity*, River Network, Portland, Oregon, USA, 2012.
13 B. K. Sovacool and K. E. Sovacool, *Energy Policy*, 2009, **37**, 2763–2773.
14 S. Hadian and K. Madani, *Sustainability*, 2013, **5**, 4674–4687.
15 R. S. Dodder, *Curr. Opin. Chem. Eng.*, 2014, **5**, 7–14.
16 J. Meldrum, S. Nettles-Anderson, G. Heath and J. Macknick, *Environ. Res. Lett.*, 2013, **8**, 015031.
17 US-EIA, *Annual energy outlook 2012*, U.S. Energy Information Administration, Washington, D.C., USA, 2012.
18 A. Y. Hoekstra, A. K. Chapagain, M. M. Aldaya and M. M. Mekonnen, *The water footprint assessment manual: Setting the global standard*, Earthscan, London, UK, 2011.
19 M. M. Mekonnen and A. Y. Hoekstra, *Hydrol. Earth Syst. Sci.*, 2012, **16**, 179–187.
20 P. W. Gerbens-Leenes, A. Y. Hoekstra and T. van der Meer, *Ecol. Econ.*, 2009, **68**, 1052–1060.
21 A. Y. Hoekstra and T. O. Wiedmann, *Science*, 2014, **344**, 1114–1117.
22 A. Y. Hoekstra, M. M. Mekonnen, A. K. Chapagain, R. E. Mathews and B. D. Richter, *PLoS One*, 2012, 7, e32688.
23 C. Liu, C. Kroeze, A. Y. Hoekstra and W. Gerbens-Leenes, *Ecol. Indic.*, 2012, **18**, 42–49.
24 M. T. H. Van Vliet, J. R. Yearsley, F. Ludwig, S. Vogele, D. P. Lettenmaier and P. Kabat, *Nat. Clim. Change*, 2012, **2**, 676–681.

25 Lexikon Energiewelten, www.energiewelten.de/elexikon/lexikon/index3.htm Accessed 4 October, 2014.
26 Enerdata, Global Energy & $CO_2$ Data, www.enerdata.net, Accessed 26 June, 2014.
27 Biomass Energy Centre, Typical caloric values of fuels, www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL Accessed 14 October, 2014.
28 IEA, *Energy balances of OECD countries, 1995–1996*, OECD/IEA, International Energy Agency, Paris, 1999.
29 R. L. Murray, *Nuclear energy: An introduction to the concepts, systems, and applications of nuclear processes*, Butterworth-Heinemann, Burlington, USA, 6th edn, 2009.
30 A. Faaij, *Mitigation and Adaptation Strategies for Global Change*, 2006, vol. 11, pp. 335–367.
31 D. J. Murphy and C. A. S. Hall, *Ann. N. Y. Acad. Sci.*, 2010, **1185**, 102–118.
32 P. R. Van Oel and A. Y. Hoekstra, *Water Resour. Manage.*, 2012, **26**, 733–749.
33 FAO, *Food and Agricultural Organization*, Rome, Italy, 21 June 2009 edn, 2009.
34 FAO, 1 July 2001 edn, 2001.
35 FAO, 2014.
36 B. Lehner and P. Döll, *J. Hydrol.*, 2004, **296**, 1–22.
37 H. Inhaber, *Energy Sources*, 2004, **26**, 309–322.
38 S. Arnøy, M.Sc., Norwegian University of Life Sciences, 2012.
39 T. H. Bakken, Å. Killingtveit, K. Engeland, K. Alfredsen and A. Harby, *Hydrol. Earth Syst. Sci.*, 2013, **17**, 3983–4000.
40 BLM, *Final environmental impact statement for the West Antelope II coal lease application*, Report WYW163340, Department of the Interior, Bureau of Land Management (BLM), Casper Field Office, Casper, Wyoming, USA, 2008.
41 T. A. Demeke, M. Marence and A. E. Mynett, presented in part at the Proceedings from Africa, Addis Ababa, Ethiopia, 16–18 April, 2013.
42 DOE, *Energy technology characterizations handbook: Environmental pollution and control factors*, US Department of Energy (DOE), Washington D.C., USA, 1983.
43 R. Evans, P. Roe and J. Joy, presented in part at the Minerals Council of Australia's Sustainable Development Conference, Brisbane, Australia, November, 2003.
44 V. Fthenakis and H. C. Kim, *Renewable Sustainable Energy Rev.*, 2010, **14**, 2039–2048.
45 I. Herath, M. Deurer, D. Horne, R. Singh and B. Clothier, *J. Cleaner Prod.*, 2011, **19**, 1582–1589.
46 J. Macknick, R. Newmark, G. Heath and K. C. Hallett, *Environ. Res. Lett.*, 2012, **7**, 045802.
47 M. M. Mekonnen and A. Y. Hoekstra, *Hydrol. Earth Syst. Sci.*, 2011, **15**, 1577–1600.
48 G. M. Mudd, *Mine Water Environ.*, 2008, **27**, 136–144.
49 NETL, *NETL life cycle inventory data – Unit process: Underground mine, Illinois no. 6 bituminous coal operation*, Department of Energy, National Energy Technology Laboratory (NETL), Pittsburgh, Pennsylvania, USA, 2009.
50 NETL, *Role of alternative energy sources: Geothermal technology assessment*, Report DOE/NETL-2012/1531, Department of Energy, National Energy Technology Laboratory (NETL), Pittsburgh, Pennsylvania, USA, 2012.
51 M. J. Pasqualetti and S. Kelley, *The water costs of electricity in Arizona*, Arizona Department of Water Resources, Phoenix, USA, 2008.
52 E. Schneider, B. Carlsen, E. Tavrides, C. van der Hoeven and U. Phathanapirom, *Energ. Econ.*, 2013, **40**, 898–910.
53 E. S. Spang, W. R. Moomaw, K. S. Gallagher, P. H. Kirshen and D. H. Marks, *Environ. Res. Lett.*, 2014, 9.
54 J. D. Stempien, H. Meteyer and M. S. Kazimi, *Water use in the nuclear fuel cycle*, Report MIT-NES-TR-017, MIT Center for Advanced Nuclear Energy Systems, Massachusetts, USA, 2013.
55 M. A. Tefferi, *M.Sc. Master Thesis*, Norwegian University of Science and Technology, 2012.
56 P. Torcellini, N. Long and R. Judkoff, *Consumptive water use for U.S. power production*, Report TP-550-33905, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2003.
57 M. Wu, M. Mintz, M. Wang and S. Arora, *Consumptive water use in the production of bioethanol and petroleum gasoline*, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Chicago, USA, 2008.
58 M. Wu, M. Mintz, M. Wang and S. Arora, *Environ. Manage.*, 2009, **44**, 981–997.
59 M. B. Yesuf, *M.Sc. Master Thesis*, Norwegian University of Science and Technology, 2012.
60 A. Y. Hoekstra and M. M. Mekonnen, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**, 3232–3237.
61 FAO, *Food and Agriculture Organization*, 2012.
62 S. Nonhebel, in *Economics of Sustainable Energy in Agriculture*, ed. E. C. van Ierland and A. O. Lansink, Kluwer Academic Publishers, The Netherlands, 2002, vol. 24, ch. 6, pp. 75–85.
63 R. A. Herendeen and R. L. Plant, *Energy*, 1981, **6**, 73–82.

## Supplementary Information

*Table S1. Literature on the WF of electricity from different energy sources.*

| Energy source | Data sources regarding WF of energy |
|---|---|
| Coal | DOE[1]; Gleick[2]; Evans et al.[3]; Inhaber[4]; BLM[5]; NETL[6]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Williams and Simmons[10]; Spang et al.[11] |
| Lignite | DOE[1]; Gleick[2]; Evans et al.[3]; BLM[5]; NETL[6]; Meldrum et al.[9]; Williams and Simmons[10]; |
| Conventional oil | Gleick[2]; Inhaber[4]; Williams and Simmons[10]; Spang et al.[11]; WU et al.[12, 13] |
| Unconventional oil (oil sand) | Gleick[2]; Williams and Simmons[10]; Spang et al.[11]; WU et al.[12, 13]; |
| Unconventional oil (oil shale) | Gleick[2]; Williams and Simmons[10]; WU et al.[12]; |
| Natural gas | Gleick[2]; Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Williams and Simmons[10]; Spang et al.[11] |
| Shale gas | Gleick[2]; Meldrum et al.[9]; Williams and Simmons[10]; Spang et al.[11] |
| Nuclear | Gleick[2]; Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Williams and Simmons[10]; Spang et al.[11]; Mudd[14]; Murray[15]; Schneider et al.[16]; Stempien et al.[17]; |
| Biomass (crops) | Fthenakis and Kim[7]; Gerbens-Leenes et al.[18]; Mekonnen and Hoekstra[19] |
| Biomass (firewood) | Fthenakis and Kim[7]; Meldrum et al.[9]; Van Oel and Hoekstra[20] |
| Hydropower | Gleick[2]; Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Torcellini et al.[21]; Pasqualetti and Kelly[22]; Gerbens-Leenes et al.[23]; Herath et al.[24]; Arnøy[25]; Yesuf[26]; Tefferi[27]; Mekonnen and Hoekstra[28]; Bakken et al.[29]; Demeke et al.[30] |
| Concentrated solar power | Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Spang et al.[11] |
| Photovoltaics | Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Spang et al.[11] |
| Wind | Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Spang et al.[11] |
| Geothermal | Inhaber[4]; Fthenakis and Kim[7]; Macknick et al.[8]; Meldrum et al.[9]; Spang et al.[11]; NETL[31] |

References

1. DOE, *Energy technology characterizations handbook: Environmental pollution and control factors*, US Department of Energy (DOE), Washington D.C., USA, 1983.
2. P. H. Gleick, *Annual Review of Energy and the Environment*, 1994, 19, 267-299.
3. R. Evans, P. Roe and J. Joy, presented in part at the Minerals Council of Australia's Sustainable Development Conference, Brisbane, Australia, November, 2003.
4. H. Inhaber, *Energy Sources*, 2004, 26, 309-322.
5. BLM, *Final environmental impact statement for the West Antelope II coal lease application*, Report WYW163340, Department of the Interior, Bureau of Land Management (BLM), Casper Field Office, Casper, Wyoming, USA, 2008.
6. NETL, *NETL life cycle inventory data – Unit process: Underground mine, Illinois no. 6 bituminous coal operation*, Department of Energy, National Energy Technology Laboratory (NETL), Pittsburgh, Pennsylvania, USA, 2009.
7. V. Fthenakis and H. C. Kim, *Renewable and Sustainable Energy Reviews*, 2010, 14, 2039-2048.
8. J. Macknick, R. Newmark, G. Heath and K. C. Hallett, *Environmental Research Letters*, 2012, 7, 045802.
9. J. Meldrum, S. Nettles-Anderson, G. Heath and J. Macknick, *Environmental Research Letters*, 2013, 8, 015031.
10. E. D. Williams and J. E. Simmons, *Water in the energy industry: An introduction*, BP International, London, UK, 2013.

11. E. S. Spang, W. R. Moomaw, K. S. Gallagher, P. H. Kirshen and D. H. Marks, *Environmental Research Letters*, 2014, 9.
12. M. Wu, M. Mintz, M. Wang and S. Arora, *Consumptive water use in the production of bioethanol and petroleum gasoline*, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Chicago, USA, 2008.
13. M. Wu, M. Mintz, M. Wang and S. Arora, *Environmental Management*, 2009, 44, 981-997.
14. G. M. Mudd, *Mine Water Environ*, 2008, 27, 136-144.
15. R. L. Murray, *Nuclear energy: An introduction to the concepts, systems, and applications of nuclear processes*, Butterworth-Heinemann, Burlington, USA, 6th edn., 2009.
16. E. Schneider, B. Carlsen, E. Tavrides, C. van der Hoeven and U. Phathanapirom, *Energy Economics*, 2013, 40, 898-910.
17. J. D. Stempien, H. Meteyer and M. S. Kazimi, *Water use in the nuclear fuel cycle*, Report MIT-NES-TR-017, MIT Center for Advanced Nuclear Energy Systems, Massachusetts, USA, 2013.
18. W. Gerbens-Leenes, A. Y. Hoekstra and T. H. van der Meer, *Proceedings of the National Academy of Sciences of the United States of America*, 2009, 106, 10219-10223.
19. M. M. Mekonnen and A. Y. Hoekstra, *Hydrology and Earth System Sciences*, 2011, 15, 1577-1600.
20. P. R. Van Oel and A. Y. Hoekstra, *Water Resources Management*, 2012, 26, 733-749.
21. P. Torcellini, N. Long and R. Judkoff, *Consumptive water use for U.S. power production*, Report TP-550-33905, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2003.
22. M. J. Pasqualetti and S. Kelley, *The water costs of electricity in Arizona* Arizona Department of Water Resources, Phoenix, USA, 2008.
23. P. W. Gerbens-Leenes, A. Y. Hoekstra and T. van der Meer, *Ecological Economics*, 2009, 68, 1052-1060.
24. I. Herath, M. Deurer, D. Horne, R. Singh and B. Clothier, *Journal of Cleaner Production*, 2011, 19, 1582-1589.
25. S. Arnøy, M.Sc., Norwegian University of Life Sciences, 2012.
26. M. B. Yesuf, M.Sc. Master Thesis, Norwegian University of Science and Technology, 2012.
27. M. A. Tefferi, M.Sc. Master thesis, Norwegian University of Science and Technology, 2012.
28. M. M. Mekonnen and A. Y. Hoekstra, *Hydrol. Earth Syst. Sci.*, 2012, 16, 179-187.
29. T. H. Bakken, Å. Killingtveit, K. Engeland, K. Alfredsen and A. Harby, *Hydrol. Earth Syst. Sci.*, 2013, 17, 3983-4000.
30. T. A. Demeke, M. Marence and A. E. Mynett, presented in part at the Proceedings from Africa, Addis Ababa, Ethiopia, 16-18 April, 2013.
31. NETL, *Role of alternative energy sources: Geothermal technology assessment*, Report DOE/NETL-2012/1531, Department of Energy, National Energy Technology Laboratory (NETL), Pittsburgh, Pennsylvania, USA, 2012.