Science of the Total Environment 569–570 (2016) 1282–1288

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Future electricity: The challenge of reducing both carbon and water footprint

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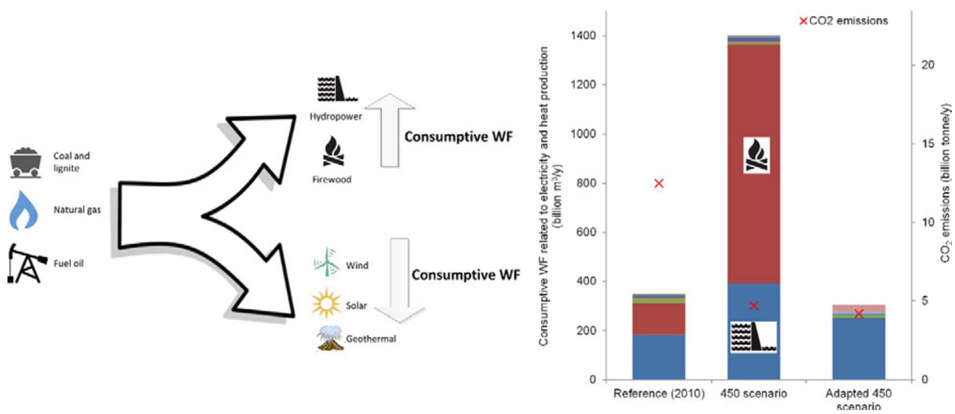
HIGHLIGHTS

- We assessed the consumptive WF in the year 2035 related to the five energy scenarios.
- We considering water use in fuel, construction and operational phase.
- Counter-intuitively, the 'greenest' IEA scenario has the largest WF.
- Transition to renewable energy will decline in both carbon and water footprints.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 25 June 2016
Accepted 26 June 2016
Available online 4 July 2016

Editor: D. Barcelo

Keywords:
Water footprint
Carbon footprint
Electricity and heat
Scenarios

ABSTRACT

We estimate the consumptive water footprint (WF) of electricity and heat in 2035 for the four energy scenarios of the International Energy Agency (IEA) and a fifth scenario with a larger percentage of solar energy. Counter-intuitively, the 'greenest' IEA scenario (with the smallest carbon footprint) shows the largest WF increase over time: an increase by a factor four over the period 2010–2035. In 2010, electricity from solar, wind, and geothermal contributed 1.8% to the total. The increase of this contribution to 19.6% in IEA's '450 scenario' contributes significantly to the decrease of the WF of the global electricity and heat sector, but is offset by the simultaneous increase of the use of firewood and hydropower. Only substantial growth in the fractions of energy sources with small WFs – solar, wind, and geothermal energy – can contribute to a lowering of the WF of the electricity and heat sector in the coming decades. The fifth energy scenario – adapted from the IEA 450 scenario but based on a quick transition to solar, wind and geothermal energy and a minimum in bio-energy – is the only scenario that shows a strong decline in both carbon footprint (−66%) and consumptive WF (−12%) in 2035 compared to the reference year 2010.

1. Introduction

Water consumption estimates for global electricity and heat production found in the literature vary greatly (Mekonnen et al., 2015; Spang et al., 2014; Hejazi et al., 2014; Davies et al., 2013). The estimated

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http://dx.doi.org/10.1016/j.scitotenv.2016.06.204

current water consumption for electricity and heat production ranges from as low as 12.9 km^3/y as estimated by Spang et al. (2014) to as high as 217 km^3/y as estimated by Mekonnen et al. (2015). The main reason for the big difference is that while the latter have assessed the water consumption along the full supply chain and included the water consumption related to hydropower generation and firewood production, the former have looked at only cooling water requirements in power plants. Davies et al. (2013) and Hejazi et al. (2014) estimate global water consumption in electricity production in 2005 to be around 76 km^3/y; they included the water consumption related to hydroelectricity but didn't show the full supply chain and also have not included the water consumption related to firewood used in electricity generation. For a complete picture of water use, it is best to consider the full supply chain (Feng et al., 2014). In the current study we will consider the full water footprint (WF) of electricity and heat generation, i.e. both the direct and indirect water use of the final product, whereby water use refers to both consumptive water use (green and blue WF) and degenerative water use (the grey WF) (Hoekstra et al., 2011). The green WF measures consumption of rain water (most relevant in agriculture and forestry); the blue WF measures consumptive use of surface and groundwater (the net water abstraction from ground- or surface water, i.e. the gross water abstraction minus the volume of water that returns to the catchment from which it was withdrawn); the grey WF is an indicator of water pollution. The WF of electricity and heat is determined by three main factors: the total electricity and heat production (TJ_e/y), the energy mix (the relative contribution of different energy sources), and the specific WF per unit of electricity and heat produced (m^3/TJ_e) per energy source. Over the period 2000–2012, the global consumptive WF of electricity and heat grew by a factor 1.8, mainly due to the increase in total electricity and heat production and the increased use of firewood (Mekonnen et al., 2015). It is expected that the electricity and heat production will rise further, putting additional pressure on scarce freshwater resources.

All available energy scenarios foresee a growth of electricity production in the coming decades. The International Energy Agency (IEA) expects that global demand for electricity will grow faster than the demand for any other form of final energy, although the rate of growth differs among scenarios and depends on government policies related to carbon dioxide (CO_2) emissions, energy efficiency and energy security (IEA, 2012). In IEA's 'current policies scenario', world electricity demand will grow from 91 to162 EJ/y over the period 2010–2035; the CO_2 emission rises from 12.5 to 20.1 billion tonne/y over the same period. In the 'new policies scenario', world electricity demand will grow to 147 EJ/y, with a CO_2 emission of 15.0 billion tonne/y in 2035; in the '450 scenario' electricity demand increases towards 127 EJ/y, with a CO_2 emission of 4.7 billion tonne/y in 2035. The 'efficient world scenario' sees a growth in electricity demand towards 124 EJ/y, with a CO_2 emission of 11.4 billion tonne/y in 2035. So, only the latter two scenarios show a decrease in carbon footprint compared to the reference year. Without changes in the average WF per unit of electricity, the growth in energy demand in the four IEA scenarios will imply corresponding increases of the sector's WF. The average WF per unit of electricity, however, may decrease or increase, depending on changes in the energy mix and in the types of technologies used, e.g. the type of cooling technology in power plants. There are a few existing scenario studies on future water demands related to power generation, but none of them considers all sorts of water use along the full supply chain. The World Energy Council (WEC) has estimated the future water demand in energy production, including the water used in the primary energy production and electricity for its two energy scenarios, per region and per energy source (WEC, 2010). But WEC focused on water use in the operational stage, leaving the water use in the supply chain out of scope. Greenpeace et al. (2012) estimated the water demand for thermal power generation for the fuel supply chain and the operational stage per world region but without specification per energy source. Also, they didn't look at water consumption related to hydropower generation. The IEA has estimated the future water consumption for the whole energy production system, including power generation (IEA, 2012), but also exclude water consumption related to hydropower generation. All three studies have neglected the water consumption related to firewood. Other existing scenario studies on future water demands related to the electricity sector focus on operational water use, leaving water consumption in the supply chain out of scope. For example, Byers et al. (2014) studied cooling water demands related to future electricity generation in the UK to 2050 and showed that freshwater consumption in 2050 will increase under pathways with high levels of carbon capture and storage, but decrease under a pathway with increasing reliance on renewables. Sovacool and Sovacool (2009) studied electricity-water trade-offs in the U.S. till 2025 and showed the operational water use to rise. The Pacific Northwest National Laboratory in the U.S, and the University of Alberta, Canada. together performed a series of studies on future global water demand for electricity generation, with a focus on water use in the operational stage again. Their results are published in Hejazi et al. (2014), who project future water consumption for electricity generation for six scenarios, Kyle et al. (2013), who study the influence of climate change mitigation technology on global water demands for electricity generation, Davies et al. (2013), who analyse the global electric sector water demands to 2095, and Dooley et al. (2013) who show the decrease of water consumption per unit of electricity generated due to more efficient water use for cooling. By focusing on water use in operations and excluding water use in the supply chain, all studies offer a partial view on future water demands.

In their 2014-report, the IPCC (IPCC, 2014) states that the increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use and biodiversity. Examples of actions with co-benefits include improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging climate-altering air pollutants. However, tools to understand and manage these interactions remain limited (IPCC, 2014). An important question in this respect is whether these actions have an impact on WFs. It can be expected that improved energy efficiencies will decrease WFs. A shift to renewable energy sources like wind energy, energy from photovoltaic (PV) cells and geothermal energy will also reduce WFs, because they have a relatively small WF per unit of electricity produced. However, a shift to the use of biomass or hydropower, two other renewables, will increase the total WF, because they have relatively large WFs (Mekonnen et al., 2015). Improvements in cooling technology in power plants may contribute to the reduction of operational water consumption in electricity from fossil fuels, biomass and nuclear energy. According to Dooley et al. (2013), 80% of global electricity production in 2050 will be from facilities that have not been built yet. They estimate that, between 2010 and 2030, water consumption per unit of electricity will decrease by about 25% due to the introduction of new, more water efficient technology.

Another issue is the energy return on energy invested (the EROI factor), an important factor determining the WF per unit of *net* energy produced. As shown in Mekonnen et al. (2015), for fuels with relatively small EROI values, like unconventional oil or shale gas (with EROI values of 3 to 4, compared to EROI values of 10 to 11 for conventional oil or natural gas), WFs per unit of net energy are substantially larger than WFs per unit of gross energy output (e.g. 25% larger in the case of oil sand). This means that shifting towards more energy-intensive fuels like shale gas and shale oil will result in a substantial increase of the WF per unit of net energy produced.

The aim of the current paper is to estimate the consumptive WF in the year 2035 related to the four energy scenarios of the International Energy Agency (the Current Policies Scenario, the New Policies Scenario, the 450 Scenario, and the Efficient World Scenario) and an additional scenario based on one of the IEA scenarios but with a relatively large share of wind and solar energy. The term 'consumptive WF' is used in this paper to refer to the sum of the green and blue WF, but in practice it will refer to blue WF, except for the case of electricity or heat from biomass, because biomass is the only form of energy with a green WF. The novelty of the study is that, for the first time the water requirement of energy scenarios is assessed by considering water use over the full supply chain (fuel, construction and operational phase). In addition, the study integrates the water consumption in firewood production and hydropower generation, which are generally overlooked in most studies, but major water users.

2. Material and methods

There are different methods to assess the water consumed in energy production and consumption. Water Footprint Assessment (WFA) is an approach that quantifies and maps green, blue and grey water footprints, assesses the sustainability, and formulate response strategies (Hoekstra et al., 2011). Life cycle assessment (LCA) evaluates the various environmental impacts of a product or service throughout its entire life cycle (Feng et al., 2014). Environmentally-extended input-output analysis is a method used to trace the flow of embedded energy or natural resources between sectors and across international supply chains (Feng et al., 2014; Kitzes, 2013). In the current paper we have used the WFA method developed by the Water Footprint Network because it has a number of strengths that make this approach more suitable to the current work compared to the other two methods. Green water is included in WFA but not in LCA, while making green water consumption explicit is very valuable, particularly in biomass production, where green water consumption generally forms a major component of total water use. Furthermore, while WFA focuses on assessing water resources appropriation, LCA focuses on environmental impacts of water use rather than on quantifying overall water use itself (Boulay et al., 2013). The purpose of the current study is to quantify freshwater use implications of different energy scenarios, not to quantify environmental impacts of water use. Input-output analysis is a less suitable tool for the purpose of the current study, since we don't focus on tracing of carbon or water footprint through economies.

2.1. Scenarios for future generation of electricity and heat

The WF of electricity and heat is determined by three factors: the total electricity and heat production (TJ_e/y), the energy mix (the relative contribution of different energy sources), and the specific WF per unit of electricity and heat produced (m^3/TJ_e) per energy source. Total electricity and heat production is a function of the size of the population and per capita electricity and heat consumption. Various organizations have developed alternative scenarios for the future development of electricity and heat generation. Generally, scenarios are formulated per world region and specify the energy mix. In this study we explore the WF implications of the four scenarios from the International Energy Agency (IEA, 2012). We used these scenarios, and not for example those from Shell (2013), WEC (2013), Greenpeace and EREC (2010) or Greenpeace et al. (2012), because IEA provides four different storylines (see Supporting Information), whereas Shell, WEC, and Greenpeace et al. each give only two storylines and Greenpeace-EREC three, which limits the scope of exploration. The IEA scenarios are geographically explicit and provide sufficient details on the energy mix necessary for the estimation of the related WF. To assess the effect of an increased share of PV, concentrated solar power (CSP), wind and geothermal in the energy mix in 2035, we developed a fifth scenario based on IEA's 450 scenario and the advanced energy [r]evolution scenario of Greenpeace and EREC (2010). In the adapted 450 scenario, we keep the 2035 electricity and heat production levels for each region unchanged compared to the 450 scenario and keep the relative contributions of the fossil fuels to the total the same, but replaced the nuclear, solar PV, CSP, wind, and geothermal values by the absolute values of the advanced energy [r]evolution scenario of Greenpeace and EREC (2010). It is assumed that electricity from hydropower does not continue to grow after 2020 as in the 450 scenario, and that the bioenergy comes fully from organic waste, assuming a negligible contribution from firewood. As a result, the total electricity supply from solar, wind, and geothermal accounts for 53% in 2035. Table S1 in the Supporting information shows global energy and heat generation and the energy mix per scenario.

2.2. Assessing the consumptive WF of electricity and heat production per scenario

The consumptive WF (sum of green and blue WF) of electricity production ($WF_{e,total}$, m^3/y) is estimated as:

$$WF_{e,total} = \sum_{s} (E \times EM[s] \times WF_e[s])$$

where E is the electricity production (TJ_e/y), $EM[s]$ the relative contribution of energy source s in the energy mix (%), and $WF_e[s]$ the WF per unit of electricity produced from energy source s (m^3/TJ_e). WF_e is the sum of the water footprint related to the three major stages of the supply chain: fuel supply, construction and operation. For heat production we followed the same approach. Except for firewood, the consumptive WF is always fully blue WF. For firewood, which requires rainwater in its production, almost all of the consumptive WF refers to green WF.

Data on WFs per unit of electricity per energy source, for each stage in the supply chain, were collected from difference sources and are reported in the Supplementary Information. The specific WF per unit of electricity and heat produced differs across energy sources. The largest WFs are generally found for electricity from firewood and hydropower, the smallest for electricity from wind, solar and geothermal energy and from organic waste. The WFs of electricity from fossil fuels and nuclear energy are in between these two extremes. Given a certain energy source, WFs still vary, depending on both energy efficiencies (like the energy efficiency in power plants) and water use efficiencies (e.g. in cooling of power plants). The WF per TJ of oil and gas was adjusted based on the relative future contribution of unconventional fuels (oil and gas) as specified in the IEA scenarios (IEA, 2012). We took the weighted average WF of the conventional and unconventional fuels per scenario.

The fuel input and electricity production per energy source and per region for the three IEA scenarios were obtained from IEA (2012). The energy conversion efficiency was implicitly included in the input data. For IEA's efficient world scenario, the fuel input and electricity production per energy source are provided only at a global level. We derived the heat production per energy source based on the relative contribution of the energy sources in power generation input. We have considered the following energy sources: coal, natural gas, oil, nuclear,

Table 1
Consumptive WF of global electricity and heat production in operations and along the supply chain (billion m^3/y), per energy source, for the reference case (2010) and per scenario (2035).

Scenario	Year	Hydro-power	Fire-wood	Coal & lignite	Nuclear	Natural gas	Oil	Geo-thermal	Solar	Wind	Total
Reference	2010	185	128	20	8.0	6.1	2.16	0.09	0.02	0.00	348
Current policies scenario	2035	337	559	35	11	11	1.45	0.27	0.57	0.01	956
New policies scenario	2035	359	698	25	12	9.9	1.21	0.39	1.05	0.01	1107
450 scenario	2035	392	973	10	17	6.7	0.77	0.55	2.65	0.02	1403
Efficient world scenario	2035	406	473	19	12	8.1	0.95	0.30	0.58	0.01	919
Adapted 450 scenario	2035	252	0.71	8.7	1.3	5.7	0.49	5.5	30	0.03	305

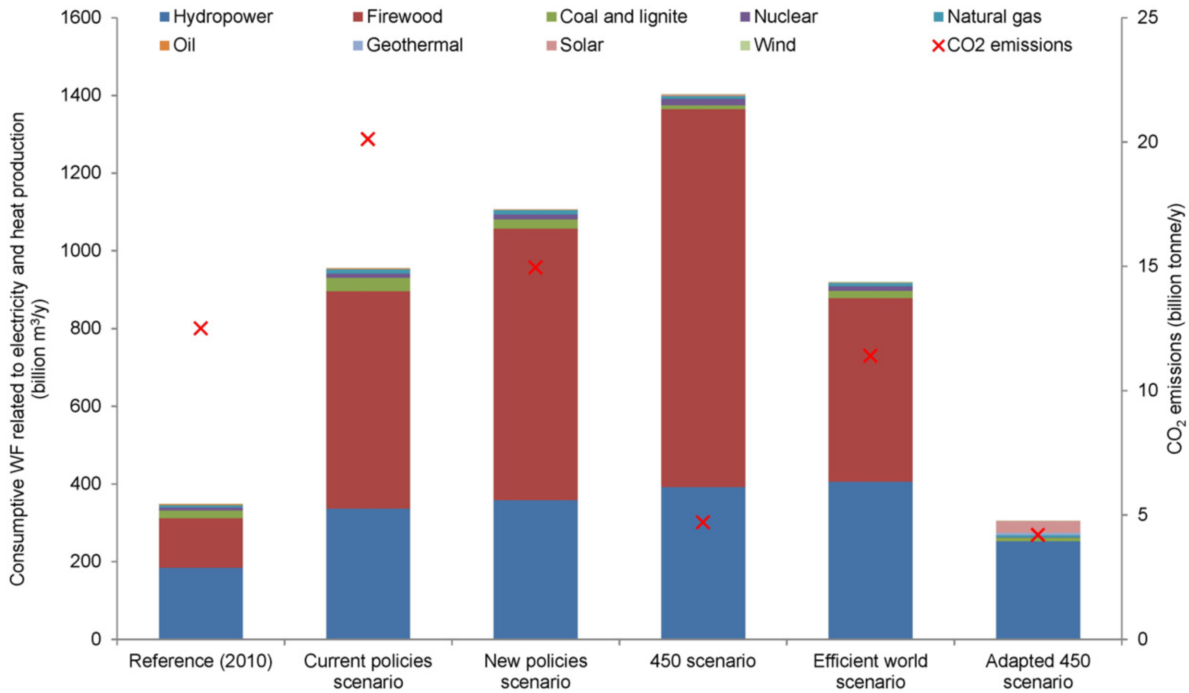

Fig. 1. Contribution of different energy sources to the total consumptive WF of electricity and heat production, and CO_2 emission in the reference case (2010) and per scenario (2035). The consumptive WF per scenario per energy sources was derived by multiplying the electricity and heat production by the respective WF per unit of electricity and heat produced from the energy sources as described in the Material and methods section. The projected CO_2 emission levels per scenario were taken from IEA (2012).

firewood, hydropower, photovoltaic (PV) cells, concentrated solar power (CSP), wind and geothermal. The data from IEA (2012) provide firewood and organic waste as one group under the heading 'bioenergy'. We split the 'bioenergy' into firewood and organic waste, based on their fraction in the bioenergy for the current situation as obtained from Enerdata (2014). We assumed a WF of zero for organic waste.

3. Results

3.1. Consumptive WF in five global electricity and heat production scenarios

The consumptive WF per energy source per scenario is shown in Table 1. The total WF in 2035 is smallest in the adapted 450 scenario because of its large share of solar, wind, and geothermal energy, which have a relatively small WF per unit of electricity generated. Among the four IEA scenarios, the total WF is smallest for the efficient world scenario, followed by the current policies, the new policies and the 450 scenario. Counter-intuitively, the 'greenest' IEA energy scenario, with the smallest carbon footprint, thus has the largest WF (Fig. 1). The differences in the WF across the scenarios are due to differences in the volume of final electricity and heat output, but more importantly to differences in the applied energy mix. Although, the 450 scenario has 22% lower final electricity and heat output compared to the current policies scenario, the WF in the 450 scenario is 1.5 times larger than the WF in the current policies scenario because of the relatively large shares of hydropower (18% in the 450 compared to 12% in the current policies) and

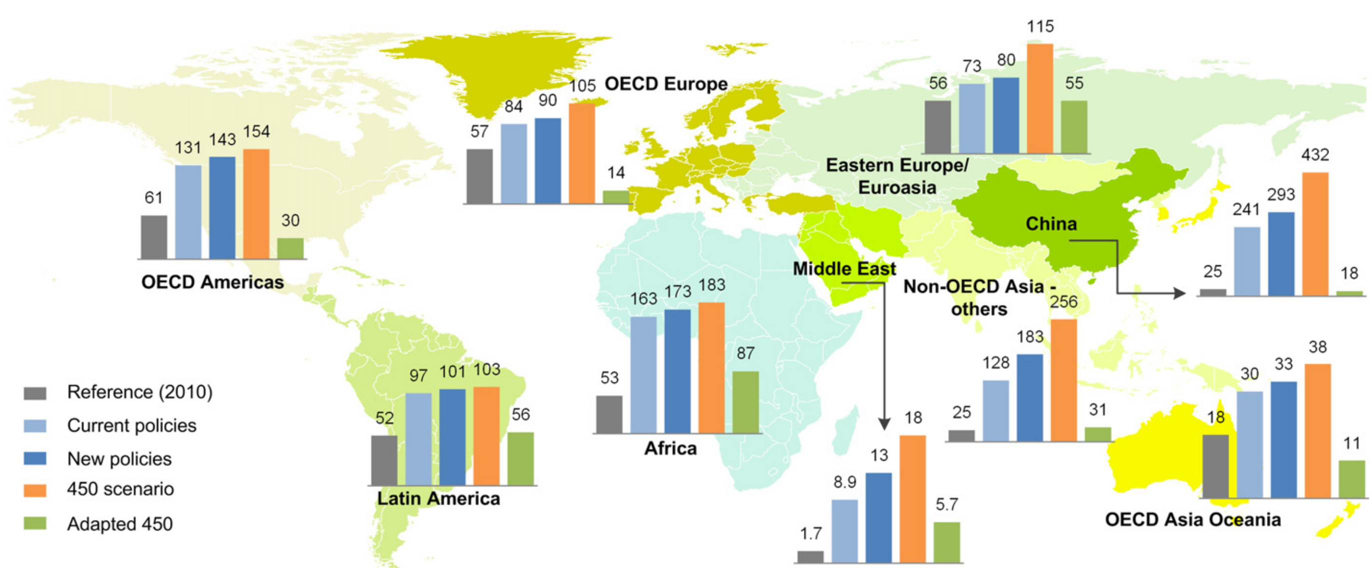

Fig. 2. Consumptive WF of electricity and heat production in operations and along the supply chain (the bar charts are in billion m^3/y), per region, for the reference case (2010) and per scenario (2035).

Table 2
Consumptive WF of electricity and heat for the fuel, construction and operation stages per scenario, in 2035 (billion m^3/y).

Scenario	Supply chain WF			Operational WF		Total WF
	Fuel		Construction			
	Firewood	Other fuels		Hydro	Other energy sources	
Current policies scenario	557	3.72	0.39	337	57	956
New policies scenario	696	3.07	0.55	359	49	1107
450 scenario	970	2.26	1.00	392	37	1403
Efficient world scenario	472	2.46	0.36	406	39	919
Adapted 450 scenario	0.00	0.84	8.00	252	44	305

biomass (7.1% in the 450 compared to 3.2% in the current policies), which both have relatively large WFs per unit of energy output.

Firewood contributes most to the total WF in all scenarios except for the adapted 450 scenario, followed by hydropower. In the adapted 450 scenario, hydropower has the largest share (83%) in the total WF. The contribution of other renewables to the total WF is very small in the IEA scenarios (0.1–0.3%) but relatively large (12%) for the adapted 450 scenario that strongly relies on those other renewables. The WF related to firewood is almost fully green water while for the other energy sources it is fully blue water.

Fig. 2 shows the consumptive WF of electricity and heat production per region per scenario (excluding IEA's efficient world scenario due to lack of full regional specification in that scenario). China takes the largest share of the total WF in all the scenarios except the adapted 450, mainly due to the large WF related to firewood.

Table 2 gives the consumptive WF of electricity and heat production per production stage per for each of the four IEA scenarios and the adapted 450 scenario. The fuel supply stage takes the largest share of the total WF in the four IEA scenarios, but the operational WF takes the largest share in the adapted 450 scenario. The operational WF is dominated by hydropower, which contributes 86% (under the current policies scenario) to 91% (under the 450 scenario) to the total operational WF of electricity and heat generation in 2035.

The average WF per unit of gross and net energy produced in 2035 is smallest for the adapted 450 scenario, followed by IEA's current policies scenario, and largest for the 450 scenario (Fig. 3). In the latter case, this is again caused by the large share of hydropower and biomass. The fact that total electricity and heat generation in the 450 scenario is much lower than in the current policies scenario cannot compensate for the effect of the increase in the WF per unit of energy. The WF per unit of *net* energy is larger than the WF per *gross* energy by about 4–5% for the four IEA scenarios and 1% for the adapted 450 scenario.

4. Discussion

The study shows the likely increase of the consumptive WF of the electricity and heat sector to 2035 if strong investments are not made into solar, wind and geothermal energy. We base our results on data from literature on water consumption per unit of energy for different energy sources, combined with estimates of future electricity and heat production per energy source. We used median values on WFs per unit of energy per energy source from Meldrum et al. (2013). In Mekonnen et al. (2015) we show the large ranges in the values of WFs for the different energy sources. By taking the median values, we did not take efficiency improvements for energy generation or water consumption into account, and in this way probably overestimate future WFs. Extrapolating current WFs forward excludes efforts to decrease the WFs per unit electricity generated, as shown for example by Dooley et al. (2013) and by Davies et al. (2013) Cooling systems for power plants move into the direction of wet cooling towers and dry cooling, away from once-through cooling systems (Davies et al., 2013). The latter have relatively large water withdrawal, but a smaller blue WF than the wet cooling systems. Dry cooling has the smallest WF per unit of electricity, but high relative costs (Davies et al., 2013). Technological advances in combination with larger use could decrease the costs of dry cooling and improve its application. However, the

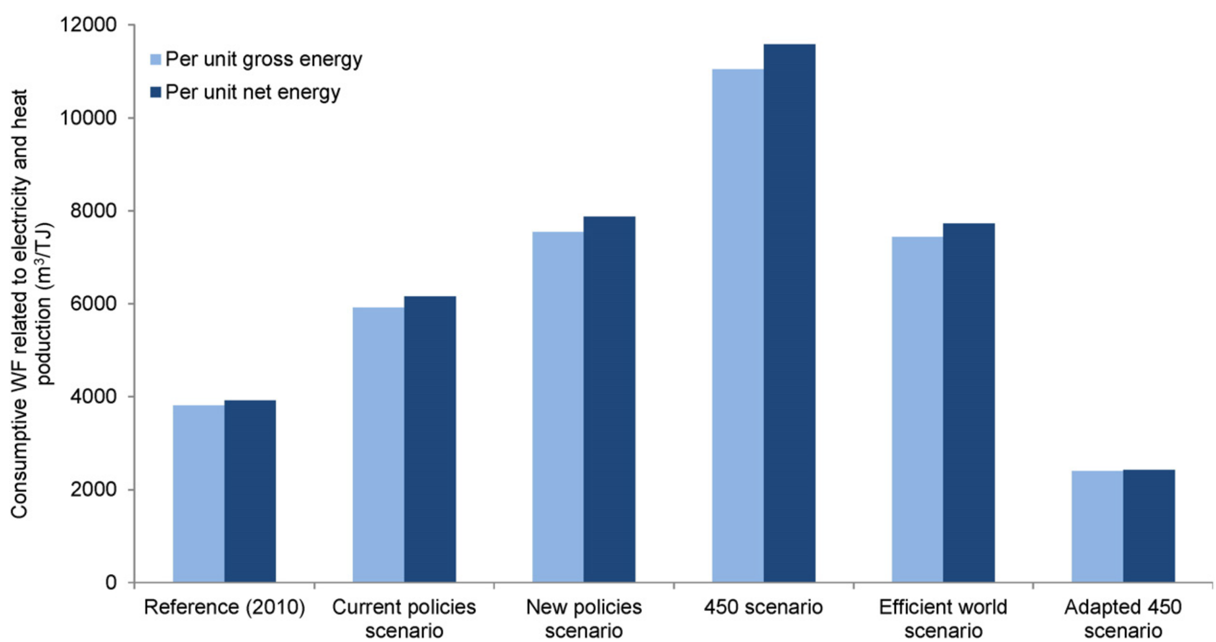

Fig. 3. Average consumptive WF per unit of gross and net electricity and heat produced (m^3/TJ_e), for the reference case (2010) and per scenario (2035).

overall global WF reduction that could be achieved with different cooling systems arrangements or efficiency gain will not be very significant, given the fact that the operational water footprint related to cooling water requirement is relatively small (6% of the total WF in the case of the current policies scenario and even less in the other scenarios). If we assume that there will be a 25% reduction in the consumptive WF at the operational stage as suggested by Dooley et al. (2013), the reduction in the total WF will be around 1.3% in the current policies scenario, 1.0% in the new policies scenario, 0.6% in the 450 scenario, 0.9% in the efficient world scenario and 3.2% in the adapted 450 scenario. If we assume a 10% improvement in the energy conversion efficiency for all fuels (coal and lignite, gas, oil, nuclear, and firewood), the largest decrease in the total WF of electricity-heat in 2035 is attained under the 450 scenario, with a 6.9% reduction in the WF, followed by the new policies scenario (6.3%), the current policies scenario (5.9%), and the efficient world scenario (5.2%).

The IEA scenarios are not explicit about the ratios of firewood and organic waste in the total biomass figures. By absence of any information, we assumed the ratios to remain constant compared to the current situation (2010), but since the WF of firewood is much larger than that of organic waste (which has even been assumed to be zero in this study), the outcomes are sensitive to this assumption. We have allocated only part of the evapotranspiration of forests used for firewood supply to firewood, by accounting only the forest area that would be needed if all firewood would come from production forest exploited at maximum sustainable exploitation rate (see Supplementary information). Suppose that in a specific case, the actual exploitation is only half of the maximum sustainable exploitation rate, because the forest is also used for other purposes, we assume that only half of the forest is used for firewood production, which implies we only count half of the total evapotranspiration from the forest. Future studies could improve the way forest evapotranspiration is allocated to the multiple purposes of a forest certainly for the purpose of getting the order of magnitude right.

The WF of hydropower related to reservoir evaporation should be distributed to the various purposes of the reservoir according to the relative value of the different purposes. Due to the absence of a global dataset on the purposes of all different reservoirs and the respective values of those purposes, we followed a simple rule in allocating the evaporation from reservoirs either fully or partially to hydropower depending on whether hydroelectric generation is the primary secondary or tertiary purpose of a reservoir (see details in the Supplementary information). While reservoir areas fluctuate throughout the year, in estimating the evaporation from the reservoir, we have used reservoir areas that refer to the water surface at full capacity, which may lead to an overestimation of the WF of hydropower. A final remark is to be made on the definition of the water footprint of an artificial reservoir. The blue water footprint is defined as total evaporation from the reservoir, while one could argue to consider the difference between the evaporation from the reservoir and the evapotranspiration from the area before the reservoir was built. The latter, however, measures *additional* evaporation, an indicator of downstream hydrological impact, while the water footprint aims to measure *total* water consumption that is not available for competing uses (Mekonnen and Hoekstra, 2012).

The scenarios regarding future energy demands and energy mixes are all based on assumptions regarding future developments. Energy demand is strongly correlated to economic activity and sensitive to energy prices, which means that projections are sensitive to the underlying assumptions about the rate of economic growth and market developments. Population growth is an important driver of energy use as well, directly through its impact on the size and composition of energy demand and indirectly through its effect on economic growth and development (IEA, 2012). Changes in these factors are uncertain, making the results of the study indicative and sensitive to policy decisions.

The IEA scenarios may not all be realistic from a water resources point of view. When water becomes scarcer in 2035, feedback mechanisms may occur that will favour energy sources and technologies with smaller WFs or that will even reduce the growth rate in total electricity use. Such feedback mechanisms are not included in the scenarios presented.

Mining of fuels such as coal, lignite and uranium, or materials for construction, generally pollute water, causing a grey WF. The release of chemicals and thermal loads from power plants also increases the grey WF. Due to lack of good data on water pollution of mining and chemical loads from power plants we did not include the grey WF, underestimating the total WF of electricity and heat.

5. Conclusions

Energy scenarios are mainly developed based on forecasts of future energy demand and on expectations regarding the swiftness with which humanity will shift away from fossil fuels to renewable energy. Water constraints hardly play a role in the discussion about future energy scenarios. Surprisingly, the 'greenest' electricity scenario of the IEA, i.e. the scenario with a relatively small growth in electricity demand and with the largest fraction of renewables in 2035, has the largest WF. While the total electricity and heat production in 2035 will have grown by 1.4 times compared to 2010, the total consumptive WF in the 450 scenario will grow almost 4 fold. This is due to the large contribution of hydropower and firewood to the total. The other renewable energy sources – solar, wind, and geothermal – have a very small contribution to the total WF in all IEA scenarios. Only substantial growth in the fractions of these energy sources – as in the adapted 450 scenario – can contribute to a lowering of the rapid projected growth of the WF of the electricity and heat sector in the coming decades. In 2010, electricity from solar, wind, and geothermal contributed 1.8% to the total. The increase of this contribution to 19.6% in the 450 scenario contributes significantly to the decrease of the WF of the global electricity and heat sector, but is offset in this scenario by the simultaneous increase of the use of firewood and hydropower. With the adapted 450 scenario we show that reducing both carbon and water footprint is possible. The total WF of electricity and heat production in 2035 under this adapted scenario is much smaller than in the four IEA scenarios: 32% of the WF under the current policies scenario and 22% of the WF under the 450 scenario. The WF in 2035 under the adapted 450 scenario will even be 12% smaller than the WF in the reference year 2010.

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 Enel Foundation. The work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.06.204.

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