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ANCIENT WATER EMBODIED IN TODAY'S ENERGY

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Key Points:
- Water virtually embodied in fossil fuels that is annually "burnt" with them exceeds global evapotranspiration from terrestrial land masses
- The energy that fueled the industrial revolution and is powering modern societies relies on water borrowed from an ancient past
- Water cycle would not be able to sustain current energy needs. "We" are using ancient water that will not be available to future generations

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Abstract The water footprint for fossil fuels typically accounts for water utilized in mining and fuel processing, whereas the water footprint of biofuels assesses the agricultural water used by crops through their lifetime. Fossil fuels have an additional water footprint that is not easily accounted for: ancient water that was used by plants millions of years ago, before they were transformed into fossil fuel. How much water is mankind using from the past to sustain current energy needs? We evaluate the link between ancient water virtually embodied in fossil fuels to current global energy demands by determining the water demand required to replace fossil fuels with biomass produced with water from the present. Using equal energy units of wood, bioethanol, and biodiesel to replace coal, natural gas, and crude oil, respectively, the resulting water demand is 7.39×10^{13} m^3 y^{-1}, approximately the same as the total annual evaporation from all land masses and transpiration from all terrestrial vegetation. Thus, there are strong hydrologic constraints to a reliance on biofuel energy produced with water from the present because the conversion from fossil fuels to biofuels would have a disproportionate and unsustainable impact on the modern water. By using fossil fuels to meet today's energy needs, we are virtually using water from a geological past. The water cycle is insufficient to sustain the production of the fuel presently consumed by human societies. Thus, non-fuel-based renewable energy sources are needed to decrease mankind's reliance on fossil fuel energy without placing an overwhelming pressure on global freshwater resources.

Plain Language Summary We investigate the water footprint of fossil fuels, accounting also for the water that was consumed for the production of the biomass that contributed over geological times to the formation of fossil fuels. We find that the water virtually embodied in fossil fuels that is annually "burnt" with them exceeds the global evapotranspiration from terrestrial land masses. Thus, the water cycle would not be able to sustain the current energy needs of human societies. Thus, the energy that fueled the industrial revolution and is powering modern societies relies on water borrowed from an ancient past, and that will not be available to future generations, similarly to the ongoing depletion (mining) of groundwater in many regions of the world. These results highlight the need to identify non-fuel based forms of renewable energy.

1. Introduction

Energy production—both from renewable sources and fossil fuels—entails water consumption. Water is needed to extract coal and oil [*Wu et al.*, 2009; *Mielke et al.*, 2010], produce biofuel [*Gerbens-Leenes et al.*, 2009; *Rulli et al.*, 2016], operate cooling towers in thermoelectric plants [*Mekonnen et al.*, 2015], clean solar panels from dust deposition [*Ravi et al.*, 2014], and offset evaporative losses in reservoirs for hydropower generation [*Bakken et al.*, 2013]. Most estimates of the water footprint of energy production from fossil fuels focus on the consumption of current water and therefore account for these water losses without considering that the accumulation of fossil fuels during geological times required water consumption for the growth of plant biomass. Fossil fuels "burn" water from an ancient past: the water transpired by plants that contributed to the formation of coal, natural gas, and oil deposits through biological and geological processes. Thus, the water footprint of fossil fuels appears to be much smaller than that of today's biofuels because the water losses of mining and processing are accounted for without also considering those associated with the growth of ancient plant biomass. Therefore, fossil fuels appear to require much less land and water than other energy sources. These (apparently) very water-efficient fuels have powered the industrial revolution and continue to sustain most of the energy needs of industrial societies.

Previous studies have already stressed how the ecological footprint of fossil fuels is much smaller than that of other forms of energy (e.g., draft animal power) used before the industrial revolution [*Hermele*, 2014]. Thus, fossil fuels have provided access to unprecedented amounts of power and replaced a relatively sustainable reliance on present-time land and water with a "mineral" economy that uses resources from a geological past. While some authors have already stressed how modern societies are relying on "ancient sunlight" [*Hartmann*, 2004] (i.e., the light used for photosynthesis by ancient plants that contributed over geological times to fossil fuel formation), the use of ancient water has remained largely unappreciated. Here, we stress how the mineral economy virtually uses water from the past. We determine the magnitude and relative importance of the water amounts that would be required to meet humanity's current energy needs using present-time water resources. By evaluating the extent to which the global water cycle would be able to sustain such needs through biofuel production, we assess whether biofuels offer a way out of the mineral economy and a return to a more direct reliance on today's water resources. In particular, we focus on the hydrologic constraints to such a reversal process, while we refer the reader to other studies [*Gerbens-Leenes et al.*, 2009; *Cassidy et al.*, 2013; *Rulli et al*., 2016] for an analysis of similar constraints associated with land availability.

2. The Water Footprint of Fossil Fuels

We find that, while the production (i.e., extraction and processing) of fossil fuels annually produced around the globe requires 4.64×10^8 m^3 of water per year, the water cost of their biofuel replacements would be several orders of magnitude greater (7.39×10^{13} m^3 y^{-1}) (Figure 1). While the water used in the extraction and processing of fossil fuels is taken from surface water bodies or aquifers (also known as "blue water" [*Falkenmark and Rockstrom*, 2006]), the water used for biofuel production is for the most part soil moisture directly supplied by rain and taken up by plants from the root zone (or "green water" [*Falkenmark and Rockstrom*, 2006]), though in some regions these biofuel crops might use a substantial amount of blue water for irrigation. To appreciate the magnitude of these water uses, we compare them with other human appropriations of freshwater resources as well as with the main water fluxes in the global hydrological cycle (Table 1). Interestingly, we find that the water used for fossil fuel extraction and processing is orders of magnitude smaller than the amount of blue water that is annually used for food production or is sustainably available for human appropriation, based on planetary boundary analyses [*Rockstrom et al.*, 2009]. Despite the ongoing trend of increasing reliance on unconventional fossil fuels such as shale oil, shale gas, and oil sands, which are more water demanding (up to 10 times more, *Mekonnen et al*., 2015; *Rosa et al.*, unpublished data, 2017), the values shown in Table 1 suggest that humanity can afford the water cost of conventional fossil fuel extraction and that, globally, the contribution of this activity to current or future water limitations is relatively small (though the local impact on blue water stocks can be important [*Rosa et al.*, 2016]). Conversely, the water footprint of biofuel substitutes for fossil fuels is an order of magnitude greater than the water used for food production and of the same order of magnitude as the total annual green water flows from continental land masses (Table 1).

Because energy from wood fuel has a much greater water footprint than energy from bioethanol and biodiesel, it could be argued that our analysis provides an overestimate of the water footprint of fossil fuels. However, if we modify the biofuel replacement criteria with coal and crude oil replaced by biodiesel, and natural gas by bioethanol we find a total water footprint of biofuel replacements of 40.17×10^{13} m^3 y^{-1} that is still greater than the water used for food production and is a substantial fraction of annual evapotranspiration from terrestrial ecosystems. The overall result remains the same: The global water cycle cannot sustain the current energy needs of humanity with existing biofuel substitutes. Humanity is indeed virtually using water from the past to fulfill its current energy demand. Most of the energy needs of the industrial era could not be met without tapping ancient water reserves virtually stored in fossil fuels.

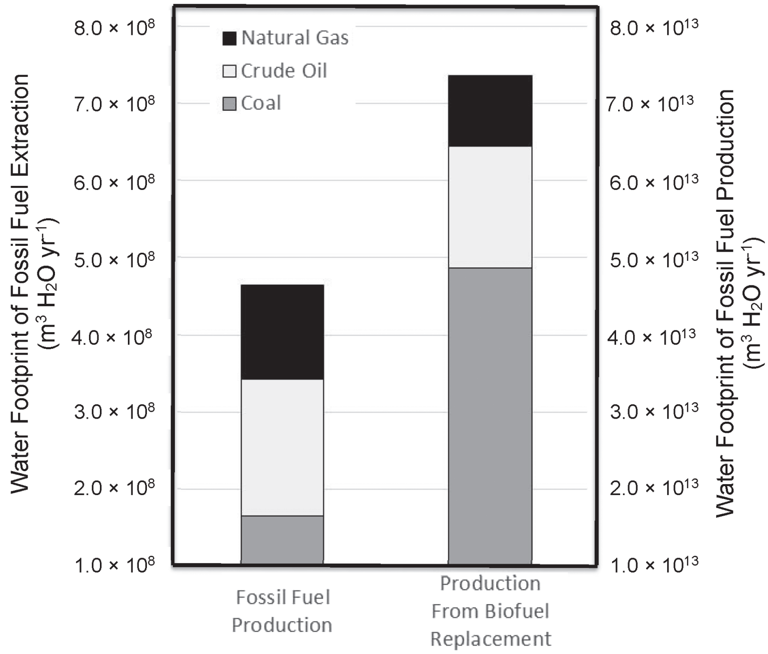

Figure 1. Estimate of the water footprint of current global energy use, accounting for both fossil fuel extraction/processing (left column), and water uses of fossil fuel production (right column) if biofuels (bioethanol, biodiesel, and wood) replace gas, crude oil, and coal.

Table 1. Global Water Flows and Demands in m^3 y^{-1}

	Annual Flow (m^3 y^{-1})	Year
Water cost of present energy demand (this study)	73.9×10^{12}	2014
Water cycle [e.g., *Chow*, 1988]	120×10^{12}	
– Green water (i.e., global evapotranspiration from land)	72×10^{12}	
– Blue water	48×10^{12}	
Freshwater used for food production [*Mekonnen and Hoekstra*, 2011; *Carr et al.*, 2013]	11.8×10^{12} 6.75×10^{12}	2010 1995–2005
Planetary boundaries of blue water [*Rockstrom et al.*, 2009]	4.0×10^{12}	
Virtual water trade (food only) [*Carr et al.*, 2013]	2.8×10^{12}	2010
Groundwater withdrawals [*Margat and Custodio*, 2004]	$0.6\text{-}0.7 \times 10^{12}$	
Freshwater used for biofuel production [*Rulli et al.*, 2016]	0.20×10^{12}	2013
Groundwater depletion [*Konikow*, 2011]	0.14×10^{12}	2001–2008
Water cost of fossil fuel extraction and processing (this study)	4.64×10^{8}	2013

The "Year" column denotes the period considered in each study.

3. Using Water From the Past

Calculating the water footprint of energy resources involves accounting for water use over their lifecycle. Key to this calculation is defining the system boundaries of the analysis. For example, biofuel production considers the agricultural green and blue water used to cultivate the crop, while fossil fuel production considers the water utilized in mining and fuel processing. Constraining the definition of the system boundary for fossil fuels to current water use fails to capture the water used by ancient plants, which were converted to fuel through geologic processes over the course of several million years. While the use of water resources over this time frame may not seem relevant because the timescale is mismatched with the energy needs of society, it points out the important distinction that needs to be made between renewable and nonrenewable resources for footprint accounting. To put the ancient water required to produce fossil fuels in a modern context, we calculate the water required to replace fossil fuels with their closest biofuel equivalent.

Specifically, we replace equal energy units of coal with wood, natural gas with bioethanol, and crude oil with biodiesel.

We find that the global water cycle would not be able to sustain the energy needs of the industrial era. By using fossil energy, human societies are virtually using ancient water similar to the way some regions of the world are relying on groundwater depletion [e.g., *Wada et al.*, 2010; *Konikow*, 2011]. In both cases, water either from a recent past or from geological times is mined unsustainably. Interestingly, the reliance on fossil fuels is associated with a use of water resources that is orders of magnitude greater than groundwater depletion (Table 1). There are, however, some important differences: while groundwater depletion entails an over pumping of "real" water (i.e., physically present), the use of fossil energy "burns" virtual (i.e., embodied) water. This is the water that was consumed in the course of the formation of fossil fuels and is not physically present in them. Moreover, while groundwater mining depletes blue water resources, the use of fossil fuels corresponds for the most part to a use of ancient green water. Regardless of these differences, in both cases the extracted water (real or embodied) will not be available to future generations.

"Ancient water" is only virtually and not also "physically" present in fossil fuels. In this sense, there is a difference with the notion of "ancient carbon" immobilized in coal, gas, and oil deposits. While the burning of fossil fuels releases "ancient carbon" into the mobile portion of the carbon cycle, there is no direct impact on the water cycle because ancient water is not physically released into the atmosphere. Likewise, this analysis could be applied to the nitrogen footprint to quantitatively evaluate the extent to which we are also relying on ancient nitrogen virtually (and in this case partly also physically) embodied in fossil fuels.

The use of renewable resources such as fossil fuels clearly deprives future generations of the option to rely on them. Thus, from the perspective of intergenerational justice, some natural capital is permanently lost, which includes not only the fossil fuel itself, but also the embodied "ancient" water. This water loss is important because the hydrologic cycle does not allow for a replacement of fossil fuels with biomass for crops or forestry products (biofuels). This study shows that not only are coal, gas, and oil burned, but also the "ancient water" embodied in them; thus, it will not be possible to replace those fossil fuels with fuels from present-time plant biomass because of constraints imposed by the water cycle. The notion of "ancient water" allows us to measure from a hydrologic standpoint to what extent fossil fuels can be replaced by biofuels.

Thus, the use of fossil fuels generates new questions of intergenerational justice, which become even more relevant now that we realize that the water cycle would not allow for a replacement of fossil energy with biomass produced with present-time water. These results suggest that a more sustainable system of energy production should not rely on fuels but on non-fuel based renewable sources such as wind, solar energy, and perhaps also nuclear and geothermal power. While biofuels could not fully replace fossil fuels, given the water constraints, some combination of biofuels and other renewables may be able to meet current industry and societal energy needs.

4. Methods

We evaluate the water cost of the replacement of fossil fuels with other energy sources produced with present-time water. To that end, we assume the replacement to be done entirely with biofuels, i.e., fuels derived from plant biomass harvested from forests, plantations, croplands, wetlands, or marginal lands. The use of algae, one of the new generation biofuels, is not accounted for in this study because it is still a small although growing practice. The use of algae as a transportation energy source, however, is also associated with blue water costs, which have been estimated in the 8–193 $m^3\ GJ^{-1}$ range [*Gerbens-Leenes et al.*, 2014]. In recent years, new energy policies have increased the use of a variety of crops to produce first generation biofuels such as bioethanol and biodiesel used in motor vehicles as an alternative to gasoline and diesel, respectively. Likewise, wood biomass can replace oil or coal in thermoelectric plants.

Using global energy production data from the *International Energy Agency* [2016], we estimate the amount of energy that would be needed to replace fossil fuels. For this calculation, production values in 2014 are utilized. Global fossil fuel production data from the most recent Key World Energy Statistics Report [*IEA*, 2016] detail total production in million tons of oil equivalent (Mtoe) that are here converted into TJ units of energy using International Energy Agency conversion ratios (1 Mtoe $= 4.187 \times 10^4$ TJ) [*IEA*, 2016]. Thus in

2014, the global annual fossil fuel energy production was 4.69×10^8 TJ in 2013, including 1.23×10^8 TJ as natural gas, 1.80×10^8 TJ as crude oil, and 1.66×10^8 TJ as coal. Fossil fuel energy was replaced with an equal amount (in TJ) of biofuel energy. The biofuels selected have similar properties (in terms of their possible use in the energy sector) to the representative fossil fuels, thus bioethanol replaced natural gas, biodiesel was used in place of crude oil, and wood supplanted coal. The water footprint of biofuel energy was estimated using literature values: 74,000 m^3 TJ^{-1} for bioethanol, 90,000 m^3 TJ^{-1} for biodiesel, and 293,500 m^3 TJ^{-1} for wood [*Mekonnen et al.*, 2015]. The water footprint for fossil fuel production (i.e., extraction and processing) was included in the comparison to provide juxtaposition, and the values included in the calculation were conservatively selected as the minima in a range of global estimates from *Mekonnen et al.* [2015].

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