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Development of water demand coefficients for power generation from renewable energy technologies

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ABSTRACT

Renewable energy technology-based power generation is considered to be environmentally friendly and to have a low life cycle greenhouse gas emissions footprint. However, the life cycle water footprint of renewable energy technology-based power generation needs to be assessed. The objective of this study is to develop life cycle water footprints for renewable energy technology-based power generation pathways. Water demand is evaluated through consumption and withdrawals coefficients developed in this study. Sixty renewable energy technology-based power generation pathways were developed for a comprehensive comparative assessment of water footprints. The pathways were based on the use of biomass, nuclear, solar, wind, hydroelectricity, and geothermal as the source of energy. During the complete life cycle, power generation from bio-oil extracted from wood chips, a biomass source, was found to have the highest water demand footprint and wind power the lowest. During the complete life cycle, the water demand coefficients for biomass-based power generation pathways range from 260 to 1289 l of water per kilowatt hour and for nuclear energy pathways from 0.48 to 179 l of water per kilowatt hour. The water demand for power generation from solar energy-based pathways ranges from 0.02 to 4.39 l of water per kilowatt hour, for geothermal pathways from 0.04 to 1.94 l of water per kilowatt hour, and for wind from 0.005 to 0.104 l of water per kilowatt hour. A sensitivity analysis was conducted with varying conversion efficiencies to evaluate the impact of power plant performance on water demand. Cooling systems used in power generation plants were also studied and include once-through, recirculating, dry, and hybrid cooling. When only the power generation stage is considered, hydroelectricity and nuclear power generation with once-through cooling systems showed the highest water consumption (68 l of water per kilowatt hour) and water withdrawals coefficients (178 l of water per kilowatt hour), respectively.

1. Introduction

Natural resource use needs to be balanced with electricity demand in such a way that an acceptable level of sustainability is maintained. Most of the focus to this point has been on the mitigation of greenhouse gas (GHG) emissions, and water use in electricity production has received little attention. As part of maintaining a sustainable balance, the quantity and quality of water, a precious natural resource, have to be managed. Cooling systems, as one of the unit operations for thermoelectric power generation, consume large amounts of water through evaporation and are of great concern in terms of water use efficiency [1]. A sustainable energy pathway would reduce the environmental footprint, and water is one of the targeted natural resources to be conserved [2]. Renewable energy technologies (RETs) are proposed as a critical aspect of the water, energy, and food nexus [3]. There is evidence around the world showing how water availability has played a key role in decisions related to power generation. For example, following the 2006–2007 drought in the U.S. and in France in 2003, some coal and nuclear power plants were shut down or are now operating at reduced capacity [4]. The use of renewable energy through improved technologies is expected to have a major role in the future of sustainable energy [5]. The contribution to electricity generation from renewable energy is expected to increase in the U.S. from 13% of the total energy in 2013 to 18% by 2040 [6].

Electricity generation consumes considerable amounts of water during the generation of power during cooling, steam cycle, make-up, cleaning, and fuel life cycle activities. Shale gas is one of the promising fuels for electricity generation and its fuel life cycle stage has environmental concerns due to the huge amounts of water required for hydraulic fracturing [7]. In 2005, thermoelectric power plants withdrew 41% of the total fresh water required in the U.S. with a consumption rate of 3%, and the water use for some renewable energy sources may exceed that of conventional

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Nomenclature

°C	celsius degree
CDS	cadmium sulfide
CDTe	cadmium telluride
C-Si	crystalline silicon
DOE	U.S. Department of Energy
EGS	enhanced geothermal system
EG-silicon	electronic silicon
g CO_2-eq/kWh	gram of CO_2 equivalent per kW h of power generated
GHG	greenhouse gas emissions
GW	gigawatt, equals 10^9 W
HHV	higher heating value
LCA	life cycle assessment
L/kW h	litres of water per kW h of power generated
MG-silicon	metallurgical grade silicon
MJ/kg	mega-joule per kilogram
MW	megawatt, equals 10^6 W
M1	factor of merit in L/kW h for ranking water consumption of a renewable pathway during the upstream stage
M2	factor of merit in L/kW h for ranking water withdrawals of a renewable pathway during the upstream stage
M3	factor of merit in L/kW h for ranking water consumption of a renewable energy pathway using steam cycle during the power generation stage
M^3	cubic metre, a unit of volume in the metric system, equal to a volume of a cube with one metre edges
M4	factor of merit in L/kW h for ranking water withdrawals of a renewable energy pathway using steam cycle during the power generation stage
M5	factor of merit in L/kW h for ranking water consumption of a renewable energy pathway that does not use the steam cycle during the power generation stage
M6	factor of merit in L/kW h for ranking water withdrawals of a renewable energy pathway not using the steam cycle during the power generation stage
p-n	positive-negative junction
PV	photovoltaic
RET	renewable energy technology
U.S.	the United States
WCC	water consumption coefficient in L/kW h during the power generation stage
WCUP	water consumption coefficient in L/kW h during the upstream stage
WR	returned water coefficient in L/kW h during the upstream stage
WRC	recycled water coefficient in L/kW h during the upstream stage
WWC	water withdrawals coefficient in L/kW h during the power generation stage
WWCR	recycled water coefficient in L/kW h during the power generation stage
WWR	returned water coefficient in L/kW h during the power generation stage
WWUP	water withdrawals coefficient in L/kW h during the upstream stage
η	conversion efficiency of power generation from the renewable technology
η_{max}	maximum conversion efficiency
η_{min}	minimum conversion efficiency
η_{ml}	most likely conversion efficiency

technologies [8]. Thermoelectric power plants in Canada, including nuclear, withdrew about 27.8 million m^3 of water in 2005, or 66% of the total water withdrawals, and in the same year hydroelectric power used more than 100 times that amount [9]. Renewable energy has been proposed as a clean, alternative solution to conventional resources from a GHG mitigation point of view. The complete life cycle analysis of nine power generation technologies showed that renewable energy can significantly mitigate GHG emissions [10]. Power generation based on the complete life cycle of nuclear energy has average GHG emissions intensity, in the same range as biomass, hydroelectricity, and wind; this intensity is 7% and 3% of the corresponding values for natural gas and coal-fired power plants, respectively [11]. Direct combustion of biomass to generate power can mitigate up to 1257 g CO_2-eq/kW h compared to the GHG intensity of coal-fired power generation [12], and, based on this same reference, solar thermal power generation can mitigate up to 647 g CO_2-eq/kW h [13].

The use of water for renewable energy has been studied earlier with a focus on the power generation stage and not on life cycle water consumption. Moreover, most of these studies do not assess the effects of conversion efficiencies on water demand coefficients. Water demand coefficients for evaporation from biomass and nuclear power plant cooling systems were estimated and compared with the corresponding conventional thermal power plants without considering the impact of conversion efficiency on estimated water use [14]. Meldrum et al. [15] harmonized water demand coefficients based on earlier studies such as those by Fthenakis and Kim [16] and Wilson et al. [17] for a wide range of power generation technologies over the complete life cycle with a fixed value of conversion efficiency; uncertainty in the variation of water demand coefficients with different levels of power plants performance was not discussed. Fthenakis and Kim [16] reviewed water use for conventional and renewable energy-based power generation and highlighted the necessity of developing complete life cycle analysis with transparent and balanced approach criteria. Although of the fact that all RETs can mitigate GHG emissions, but this is not the case for water conservation as some of these technologies such as hydroelectricity and biomass have negative impact on water use [17]. Water consumption coefficients for the complete life cycle of power generation from different biomass pathways [18] and different renewable energy technologies [19] were developed at a specific conversion efficiency, but the associated water withdrawals coefficients were not included. Water demand coefficients for thermoelectric and hydroelectric power plants were used to estimate the water intensity for hydrogen production with a focus on the cooling system unit operations, yet other stages of the complete life cycle were not included [20]. Comprehensive sustainability indicators were developed for a comparative assessment of power generation technologies, and water demand indicators were represented through fresh water consumption without considering water withdrawals coefficients [21]. Water demand coefficients include both the water consumption coefficient and the water withdrawals coefficient for each pathway are one of the well-established indicators for water use by power generation plants. Water consumption is the amount of water consumed by the unit operations of the process and not returned back to the source, while water withdrawals include water returned to the source apart from consumption. Water consumption and water withdrawals coefficients were developed in earlier studies for gas-fired [22] and for coal-based power generation [23] to cover the