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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 complete life cycle of fuel extraction and power generation stage. Since renewable technologies are still at various stages of development and demonstration, there needs to be a life cycle approach to understand the full impacts of the technologies. In addition, there is good potential for conversion efficiency improvement in the power generation technologies, and the potential can be better understood by assessing their impacts. There is little research that comparatively assesses life cycle water consumption coefficients for different renewable energy pathways. Tan and Zhi [24] highlighted the lack of studies on the water-energy nexus for solar, wind, and geothermal technologies and recommended future research be conducted in this field. This study is an effort to fill that gap and its novelty is that it includes sixty pathways of power generation based on the complete life cycle of renewable energy technologies and identifies the uncertainty in water demand coefficients from variations in the conversion efficiency of the power plants. This study is different from earlier similar studies by the authors [22,23] in that it investigates the sustainability of renewable energy technologies and compares them with fossil fuel-based power generation with a different view of water use along with the already well-considered view of GHG emissions.

The main objectives of this paper are to:

- Develop water demand coefficients for renewable energy technologies over the complete life cycle of power generation from biomass, nuclear, solar, wind, hydroelectricity, and geothermal,
- Comparatively assess the upstream and power generation stages of the water demand coefficients for various renewable energy technologies,
- Comparatively assess the water demand of sixty different pathways in the conversion of renewable energy to power; and
- Assess the impact of conversion efficiency on water use for renewable energy pathways through a comprehensive uncertainty analysis.

2. Scope and system boundary

Pathways were structured specific to renewable energy sources (see Fig. 1). The main unit operations considered for water demand coefficients during the entire life cycle are fuel extraction (if any), conversion technology for power generation, and the cooling system (if any). For the base case, the specific conversion efficiency of power plants was assumed and impacts of variations were studied later in the sensitivity analysis. This base case conversion efficiency was taken as the most likely value in a model executed through Monte Carlo simulations [25–28]. The most likely value is bound by minimum and maximum efficiencies to study the uncertainty of the assumed values [22].

Two sets of water demand coefficients were developed and further harmonized at certain conversion efficiencies. The first set of developed coefficients covers the complete life cycle of the pathway and the second set is limited to unit operations for power generation. The conversion efficiency was varied in the sensitivity analysis to study the effect of power plant performance on the water demand coefficient levels.

The water consumption coefficient (WCUP) and the water withdrawals coefficient (WWUP) in the upstream stage are correlated to the conversion efficiency (η) through the factors of merit M1 and M2, respectively, as follows (as taken from a previous study conducted by the authors [23]):

$$\mathrm{WCUP} = \mathrm{M1} * (1/\eta) \tag{1}$$

$$\mathrm{WWUP} = \mathrm{M2} * (1/\eta) \tag{2}$$

Factors of merit are constant coefficients in L/kW h assigned to differentiate between the water demand coefficients of pathways from the same set. The lower the factor of merit, the better the performance of a pathway with respect to the water demand coefficient.

There are two types of correlations between water demand coefficients and conversion efficiencies (η) identified in this paper for the power generation stage. The first type includes all renewable energy technologies that use a steam cycle to generate electricity (thermoelectric), as shown in Fig. 2. These technologies cover all biomass, nuclear, solar-thermal, and geothermal pathways and are governed by the factors of merit M3 for the water consumption coefficient (WCC) and M4 for the water withdrawals coefficient (WWC) (based on an earlier study [23]), as follows:

$$\mathrm{WCC} = \mathrm{M3} * ((1/\eta) - 1) \tag{3}$$

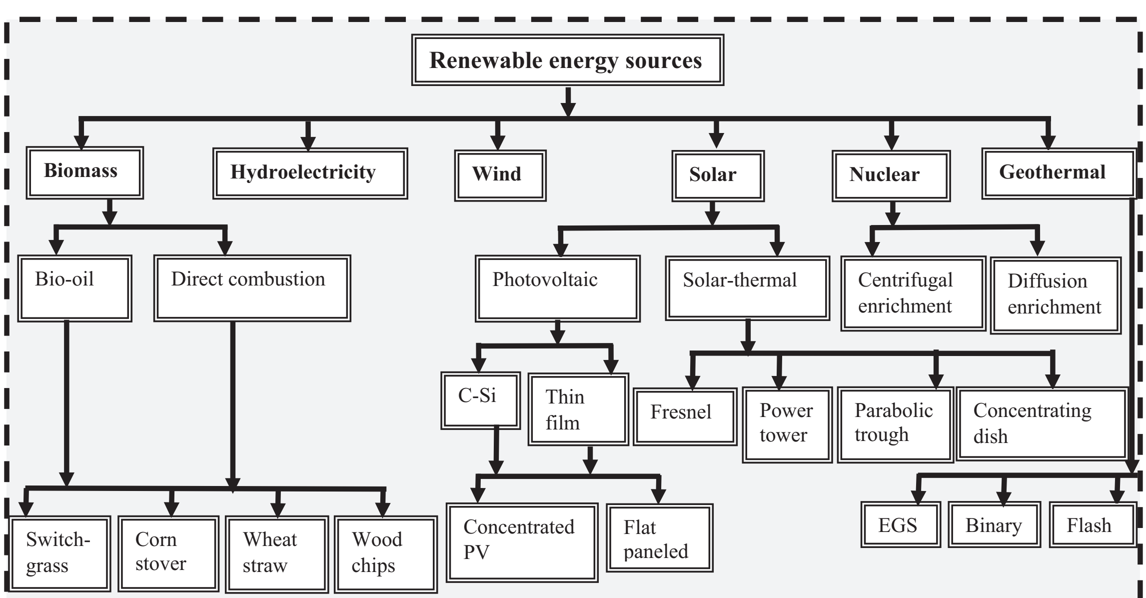

Fig. 1. Renewable energy pathways C-Si is the photovoltaic panel made of Crystalline Silicon.EGS is the enhanced geothermal system. Hydroelectricity, wind, solar photovoltaic, and solar concentrating dish are the pathways with no cooling systems. Biomass and nuclear are the pathways with principle fuels.

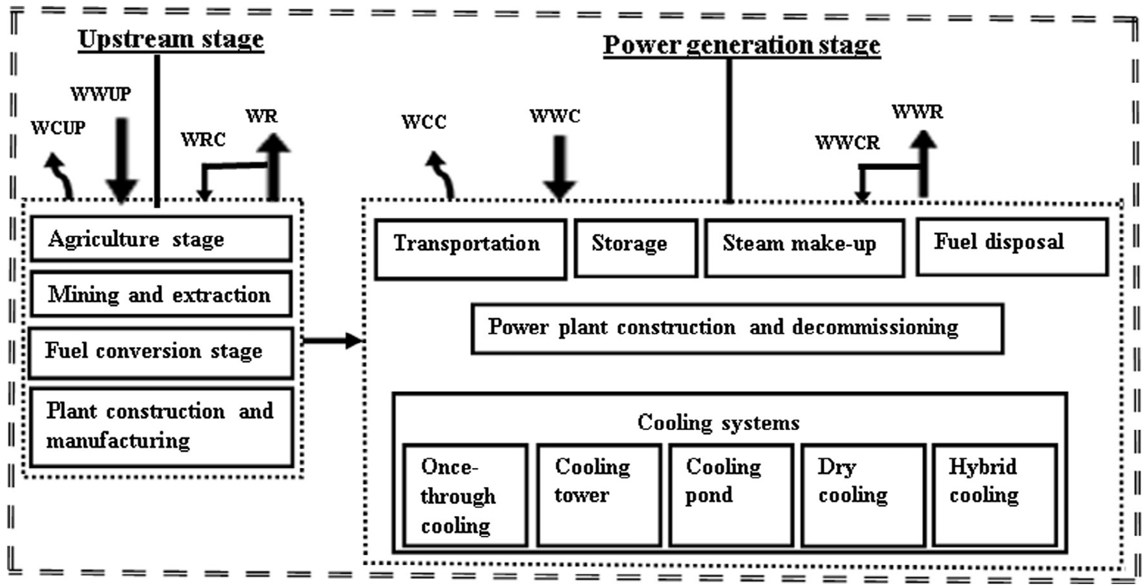

Fig. 2. Life cycle water footprints of thermoelectric renewable energy pathways WCUP and WCC are the coefficients for water consumption at the upstream and power generation stage, respectively. WWUP and WWC are the coefficients for water withdrawals at the upstream and power generation stage, respectively. WR and WWR are the coefficients for returned water at the upstream and power generation stage, respectively.WRC and WWCR are the coefficients for recycled water at the upstream and power generation stage, respectively.

$$\mathrm{WWC} = \mathrm{M4} * ((1/\eta) - 1) \tag{4}$$

The second set of factors of merit, M5 and M6, is assigned to the rest of the technologies (wind, hydroelectricity, and solar-photovoltaic as shown in Fig. 3) to correlate the conversion efficiency (η) to the water consumption coefficient (WCC) and water withdrawals coefficient (WWC), respectively, as follows:

$$\mathrm{WCC} = \mathrm{M5} * (1/\eta) \tag{5}$$

$$\mathrm{WWC} = \mathrm{M6} * (1/\eta) \tag{6}$$

The six factors of merit (M1-M6) were determined from the base case values of water demand coefficients and the associated conversion efficiency.

2.1. Pathway descriptions

Six types of power generation from renewable energy sources were selected: biomass, nuclear, solar, wind, hydroelectricity, and geothermal. Biomass and nuclear are the principle renewable sources although some other sources such as municipal solid waste, wastewater treatment sludge, and short rotation forestry are not considered in this study. Cooling systems (once-through, cooling tower, cooling pond, and dry cooling) were considered for the biomass, solar-thermal, nuclear, and geothermal power generation pathways [29,30]. Hybrid cooling was considered for the solar-thermal pathways (power tower and parabolic trough) as well as the geothermal energy-based pathways using binary technology [15].

2.1.1. Biomass pathways

Biomass pathways were subdivided by fuel into direct or bio-oil combustion of one of four feedstocks (switchgrass, corn stover, wheat straw, and wood chips) [18,31]. Direct combustion burns biomass feedstock in a boiler to produce steam, and power is generated in a Rankine cycle. The power generation unit operations in this case are similar to those for coal-fired power generation. In the

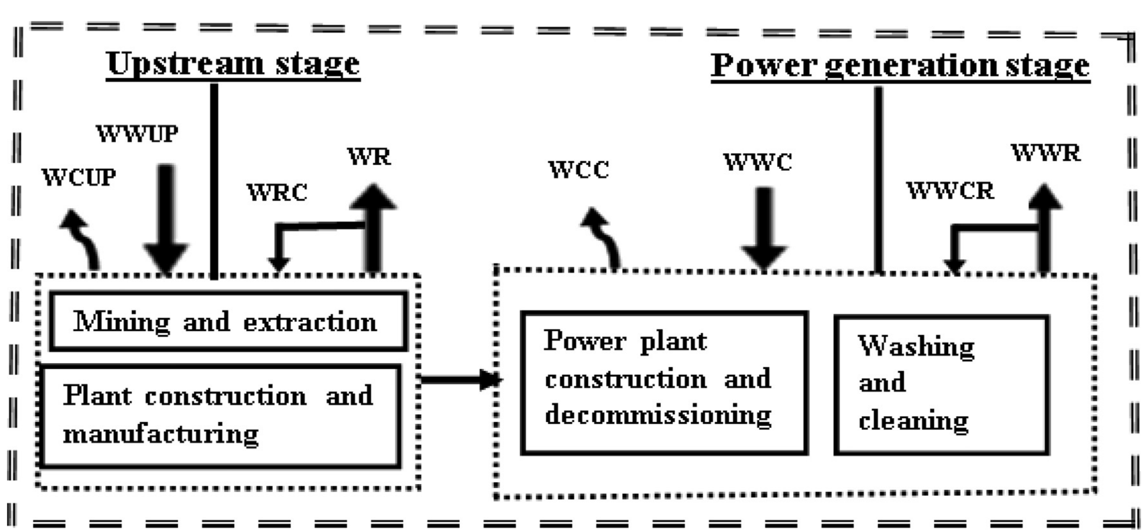

Fig. 3. Life cycle water footprints of photovoltaic, wind, and hydroelectricity pathways.

other combustion method, bio-oil is produced through pyrolysis and combusted as fuel to generate power. The agricultural stage for both biomass technologies (direct combustion and bio-oil combustion) and the conversion stage for bio-oil pathways were added to the upstream unit operations (see Fig. 2). Further details can be found in earlier studies [18,31].

Other pathways of biomass-based power generation such as gasification [32] and co-firing [33] are not considered in this paper, and the technologies (direct combustion and bio-oil combustion) are considered as target cases.

2.1.2. Nuclear pathways

Nuclear energy is one of the most cost-effective energy sources and considered in the current study as one of the renewable energy technologies [34]. Nuclear fuel pathways consider fuel enrichment by diffusion or centrifugally [10,15]. Laser enrichment is a technology used to enrich uranium but is not available commercially, and most nuclear power plants use uranium U-235 that has been enriched from 0.7% content raw uranium (the remaining 99.3% is U-238) to a range of 3–5% [35,36]. Nuclear power generation in Korea is expanding because it costs less than other fossil fuel-based power and nuclear plants can be located in remote coastal areas for safety and easy access of cooling water [37].

The upstream stage of nuclear power generation includes extraction, grinding, conversion, enrichment, and plant construction. The power generation stage includes cooling systems, steam make-up, fuel disposal, and power plant construction and decommissioning (see Fig. 2).

2.1.3. Solar pathways

Solar energy power generation technologies include solar-thermal and photovoltaic. Solar-thermal technologies include power tower, parabolic trough, Fresnel lens, and dish systems [38,39]. Photovoltaic systems can be made by thin film or crystalline silicon (C-Si) and the modes of operation are flat paneled or concentrated photovoltaic (PV).

Solar-thermal technology generates power through concentrating sun rays to heat a medium fluid that rotates a turbine and a generator. The shape of solar collectors varies depending on the technology. The power tower has heliostats to reflect the incoming sun rays into a tower carrying the central receiver. The concentrated sun rays heat the fluid in the central receiver and the kinetic energy of this fluid is converted to mechanical and electric energy through the turbine and the generator. Parabolic trough technology focuses the sun's rays on a linear receiver (pipe) to heat the fluid and generate power. In Fresnel lens technology, curved mirrors reflect the sun's rays onto a linear receiver to generate power. A parabolic dish concentrates the sun's rays on a focal point (a receiver and a Sterling engine) to generate power [40,41]. A more detailed description of solar thermal technologies can be found in a comprehensive review by Zhang et al. [42].

A thin film photovoltaic module has two semiconductors, cadmium telluride (CDTe or $CuInSe_2$) and cadmium sulfide (CDS), which make up a p-n junction. CDTe and CDS are deposited in thin layers onto a transparent glass panel [43]. A crystalline silicon (C-Si) module is manufactured by purifying silica sand into metallurgical grade silicon (MG-silicon) and then to electronic silicon (EG-silicon). The silicon is melted and cast in molds into polycrystalline blocks to produce multi-silicon wafers. Etching, doping, screen printing, coating, and testing are the main steps involved in finalizing the product. An aluminium frame is added to support the manufactured photovoltaic panel. Some laminated panels do not need this frame [44]. The performance of PV panels has improved and the production costs have been drastically reduced so that they can compete with other power generation pathways. Solar is third after hydroelectricity and wind of the total installed capacity of renewable energy in the world [45].

The operation of solar-thermal technologies needs water for cooling, and the water demand for materials extraction, manufacturing, and construction of the systems is included in the upstream stage (see Fig. 2).

Photovoltaic power generation requires minimal water during operation, for panel washing, and no cooling system is needed (see Fig. 3).

2.1.4. Wind and hydroelectricity pathways

Wind is created by the difference in ambient temperature initiated from the sun's heat. Wind turbines are mounted on a tower to convert the kinetic energy of wind into mechanical and then electric energy through a generator [46]. Wind energy is one of the fastest-growing power generation technologies in the world [47,48] and can be installed on dry land or offshore on wet surfaces such as sea or fresh water [49]. The total wind power capacity in the world by the end of 2015 was 433 GW, with more than half (248 GW) installed in three countries, China (30%), the U.S. (17%), and Germany (10%) [50]. Power generation operations from wind energy do not require cooling systems (see Fig. 3), and minimal water is required (for cleaning the turbines and for construction during the upstream stage).

Hydroelectricity originates from moving water, which converts kinetic energy to mechanical energy through a turbine and then to electric energy through a generator. Some hydropower plants are located in the running stream of water (run-of-river), and for high power production scales, dams are constructed to increase the height (head) of the falling water. Reservoirs are constructed with dams to store water for other uses and to help control the amount of running water through the penstock to the turbine [51]. In 2014, more than 16% of the total power generated in the world was from hydroelectricity [50,52]. Interconnections and hybrid systems are used to balance supply and demand sides of electricity. Skagerrak 4 is an interconnection project that has been operating since 2015 to balance hydroelectricity generation in Norway with wind and thermal power generation in Denmark, and Longyangxia is a hybrid project in China to mix 1280 MW from hydroelectricity and 850 MW from solar PV [50]. Hydroelectricity operations consume significant amounts of water through evaporation from the reservoir. Water demand during the upstream stage is for hydropower plant construction (see Fig. 3).

2.1.5. Geothermal pathways

Geothermal pathways include binary, flash, and enhanced geothermal system (EGS) technologies. Binary technology operates at a low temperature (85–175 °C) and uses geothermal liquid to heat through the exchanger an intermediate working fluid (such as isobutene) at a boiling point that is lower still. The kinetic energy of the heated working fluid is converted to mechanical energy to rotate the turbine, which is coupled to the electric generator, for power generation [53,54]. Geothermal flash is the most common geothermal power generation technology; in this system, a mixture of water and steam produced from the reservoir is flashed in a separate tank at low pressure. The steam is separated and used to generate electricity; the water not flashed is returned to the geothermal reservoir through an injection well [53–56]. In EGS technology, water as a working fluid is circulated in a closed loop through the injection well to rocks and pumped out through a production well. Circulated water is heated to the steam phase to run the turbine and generate power [57]. The total installed capacity of geothermal power generation in the world in 2015 was 12635 MW with the largest share from the U.S. (27%), followed by the Philippines (15%), Mexico (8%), and New Zealand (8%) [58]. 79% of the installed capacity in the U.S. is from the Geysers and Imperial Valley in California State. Chena Hot Springs in Alaska operates through binary technology with 74 °C the lowest temperature, and a hybrid power plant is located in Nevada, at Stillwater, with mixed sources of geothermal, solar PV, and solar thermal power generation. The cooling system is the most critical unit operation determining the level of water demand during the power generation stage of geothermal pathways (see Fig. 2).

3. Assumptions and input data

Water demand coefficients for the various unit operations were developed and integrated to estimate the overall life cycle water footprint. The estimates were further harmonized at the most likely conversion efficiencies assumed in the base case. Table 1 shows the most likely, minimum, and maximum efficiencies considered in this study.

Coefficients for the power generation stage from biomass pathways were derived from an earlier work by the authors [23]. The complete life cycle water demand coefficients for agricultural biomass feedstocks (switchgrass, corn stover, and wheat straw) were estimated after taking into account fuel production stage data taken from an earlier study [18]. Forest biomass-based power was estimated based on Canadian pine tree characteristics [59–61]. Table 2 shows the input data used to develop water demand coefficients for biomass pathways. Input data for nuclear pathways are shown in Table 3; solar-thermal and geothermal pathways are shown in Tables 4 and 5 gives input data for photovoltaic, wind, and hydroelectricity pathways.

4. Results and discussion

Table 6 shows the developed generic water demand coefficients for 60 different renewable energy pathways based on the most likely conversion efficiencies (see Table 1) and after combining the input data from Tables 2–5. The four steps of the life cycle assessment (LCA) methodology [74] are followed in this study. Water as an inventory is analysed and the quantitative impacts are assessed and represented by water withdrawals and water consumption coefficients. The results of the water demand coefficients are assigned to the pathways for comparative assessment and an uncertainty analysis is conducted based on the variations of the conversion efficiency. Based on the complete life cycle of renewable energy pathways, biomass-based power generation has the most negative impact on water demand. This is because the complete life cycle includes the high water requirement in the agriculture stage. Power generation from the combustion of bio-oil produced from wood chip feedstock has the highest water demand coefficients; power generation from wind energy has the lowest.

When power generation is considered alone, the hydroelectricity pathway has the highest water consumption coefficient due to the large amount of water that evaporates in the reservoir. Due to the nature of once-through cooling systems, the associated water withdrawals are generally large, and nuclear-based power generation with this cooling system technology has the highest water withdrawal coefficient. Despite the lower conversion efficiency of nuclear power plants, the steam cycle has a major part in this high water withdrawal coefficient. The cooling system also affects the water demand for power generation. In terms of the complete life

Table 1
Assumed conversion efficiencies of renewable energy technologies.

Items	Minimum conversion efficiency (η_{min}) (%)	Most likely conversion efficiency (η_{ml}) (%)	Maximum conversion efficiency (η_{max}) (%)	Comments/Source
Biomass power plant	20	33	40	According to the DOE, small capacity plants have low efficiency (20%) and with new techniques would reach over 40% [62]. η_{ml} is assumed based on a study by Singh et al. [18]. Direct combustion and bio-oil pathways were assumed to have the same range of conversion efficiency
Nuclear power plant	30	33	36	Based on the comprehensive review conducted by Warner and Heath [63] for nuclear power plants, which showed that boiler water reactors have lower efficiency than pressurized water reactors. η_{ml} is assumed as the average value
Solar-thermal power tower	7	20	25	η_{min} is based on historical data [64], η_{ml} on the review by Meldrum et al. [15], and η_{max} on the expected improvement of the technology after 2025 [39]
Solar-thermal parabolic trough	10	15	25	
Solar-thermal Fresnel lens	10	11	25	Based on under-construction plants and expected technology improvement after 2025 [39]
Solar-thermal concentrating dish	15	22	25	
Solar photovoltaic system	4	13	22	η_{min} and η_{max} are taken from a study assessing sustainability indicators [65], and the average value is considered for η_{ml}.
Wind power plant	24	39	54	
Hydroelectricity power plant	82	90	98	η_{ml} is considered according to [65,66] and η_{min}, η_{max} were respectively assumed −8% and +8% compared to η_{ml}. η_{max} is extended from 95% [67] to 98% to accommodate for the expected technology improvement [52]
Geothermal with binary technology	1	8	16.3	η_{min} is the actual efficiency of the Chena Hot Springs power plant with an average operation temperature 73 °C [68]. η_{ml} is based on a power plant with an operating temperature of 180 °C [69]. η_{max} is based on the upper end efficiency of a Miravalles Unit 5 power plant in Costa Rica [70]
Geothermal with flash technology	5	11	20	η_{min} and η_{max} are based on the correlations developed by Moon and Zarrouk [68] and η_{ml} on a power plant operating at 180 °C [69]
Geothermal with EGS technology	7	9	12	η_{ml} is based on the average from global efficiency ranges of 7.4–10.4% and η_{max} derived from ten case studies [71]

Table 2
Input data for water demand coefficients of biomass pathways.

Pathway	Upstream stage	Power generation stage[d]							
		Once-through cooling		Cooling tower		Cooling pond		Dry cooling	
	WCUP/WWUP (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)
Wood chips-Direct combustion	622.45[a]	1.36	127.34	2.20	2.53	2.13	2.55	0.22	0.25
Wood chips-Bio-oil	1161.81[b]								
Corn stover-Direct combustion	259.38[c]								
Corn stover-Bio-oil	326.59[c]								
Wheat straw-Direct combustion	318.30[c]								
Wheat straw-Bio-oil	465.80[c]								
Switchgrass-Direct combustion	672.13[c]								
Switchgrass-Bio-oil	823.67[c]								

[a] Estimated water footprint for Canadian pine = 1.141 m^3 of water per kg of wood [59,60] with 20 MJ/kg HHV for wood [61], and conversion efficiency (η_{ml}) 33%.
[b] Estimated water footprint for Canadian pine = 1.141 m^3 of water per kg of wood [59,60] with 17.9 MJ/kg HHV for bio-oil; the yield is 0.599 kg of bio-oil per kg of dry wood [61] and conversion efficiency (η_{ml}) of 33%.
[c] Based on water consumption coefficients developed in Singh et al. [18].
[d] Subcritical water demand coefficients developed earlier (at a conversion efficiency of 35%) [23] were used to estimate these coefficients through Eq. (3).

Table 3
Input data for water demand coefficients of nuclear pathways.[a]

Pathway	Upstream stage	Power generation stage							
		Once-through cooling		Cooling tower		Cooling pond		Dry cooling	
	WCUP/WWUP (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)
Nuclear-Centrifugal enrichment	0.21	1.52	178.03	2.73	4.17	2.31	4.17	0.27	0.42
Nuclear-Diffusion enrichment	0.33/0.53								

[a] Coefficients were based on the median values of statistics revision from the literature [15] and assumed at the same conversion efficiency (η_{ml}) of 33%.

Table 4
Input data for water demand coefficients of solar-thermal and geothermal pathways.[a]

Pathway	Upstream stage	Power generation stage					
		Cooling tower		Hybrid cooling		Dry cooling	
	WCUP/WWUP (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)
Solar-thermal-Power tower	0.61	3.07	3.07	0.64	0.64	0.10	0.10
Solar-thermal-Parabolic trough	0.61	3.37	3.64	1.29	1.29	0.30	0.30
Solar-thermal-Fresnel	0.61	3.79[b]	3.79[b]	–	–	0.38[c]	0.38[c]
Solar-thermal-Concentrating dish	0.61	0.02[d]					
Geothermal-Binary	0.01	–	–	1.74	1.74	1.10	1.10
Geothermal-Flash	0.01	0.06[b]	0.06[b]	–	–	–	–
Geothermal-EGS	0.01	–	–	–	–	1.93	1.93

[a] Coefficients were based on the median values of statistics revision from the literature [15] and assumed at the same conversion efficiency η_{ml} detailed in Table 1.
[b] Assumed with a cooling tower of equal consumption and withdrawals coefficients [72].
[c] Estimated with the assumption of 10% from the associated cooling tower coefficients.
[d] No cooling system is needed and coefficients were assumed for other water uses such as washing.

cycle, the water consumption coefficient for nuclear energy through diffusion enrichment using a cooling tower (3.06 L/kW h) can be improved by 14% (2.64 L/kW h) if the cooling system is replaced by a cooling pond and can be improved further by 30% (1.84 L/kW h) if the pond is replaced by once-through cooling and by 33% (to 0.6 L/kW h) through dry cooling. This low coefficient (0.6 L/kW h) achieved through dry cooling is very close to the corresponding water consumption coefficient of a concentrating dish (0.63 L/kW h). The proper choice of a cooling system in this example during power generation compensates for the water consumption during the fuel cycle.

The water consumption coefficients for the complete life cycle of coal-based and gas-fired power generation are in the range 0.96–3.21 L/kW h [23] and 0.07–2.57 [22], respectively. 24 of the 60 pathways for renewable energy developed in this study are within the range of the water consumption coefficients of coal-based power generation. Water consumption coefficients for all biomass pathways (1 through 32 in Table 6), pathway 41, pathway 44, pathway 47, and pathway 55 are higher than the water consumption coefficients for coal-based power generation. Water demand coefficients for geothermal flash technology and solar photovoltaic manufactured with thin film and operated through flat panels are very close to the corresponding minimum coefficients of gas-fired power generation. Water demand coefficients of nuclear power generation with cooling ponds are very close to the corresponding maximum water demand coefficients of gas-fired power generation.

5. Sensitivity analysis

The assumed conversion efficiencies detailed in Table 1 were used as inputs to ModelRisk [25] to study the impact of uncertainty in power plant performance on the water demand coefficients

Table 5
Input data for water demand coefficients of photovoltaic, wind, and hydroelectricity pathways.[a]

Pathway	Upstream stage		Power generation stage			
			Flat panel		Concentrated PV	
	WCUP (L/kW h)	WWUP (L/kW h)	WCC (L/kW h)	WWC (L/kW h)	WCC (L/kW h)	WWC (L/kW h)
Crystalline silicone	0.31	0.36	0.02	0.02	0.11	0.11
Thin film	0.02	0.07				
	WCUP (L/kW h)	WWUP (L/kW h)	WCC (L/kW h)		WWC (L/kW h)	
Wind	$3.8 * 10^{-4}$	0.098	0.0049		0.0057	
Hydroelectricity[b]	0.00	0.00	68.18		68.18	

[a] Coefficients were based on the median values of statistics revision from the literature [15] and assumed at the same conversion efficiency η_{ml} detailed in Table 1.
[b] Water demand coefficients were developed considering the national average rate of evaporation from reservoirs in the U.S [73]. Upstream water demand coefficients were not considered.

Table 6
Base case water demand coefficients for power generation from renewable energy pathways.

NO.	Pathway	Complete life cycle		Power generation only	
		Water Consumption coefficient (L/kW h)	Water Withdrawals coefficient (L/kW h)	Water Consumption coefficient (L/kW h)	Water Withdrawals coefficient (L/kW h)
1	Biomass-Wood chips-Direct combustion-Once-through cooling	623.81	749.79	1.36	127.34
2	Biomass-Wood chips-Direct combustion-Cooling tower	624.65	624.98	2.20	2.53
3	Biomass-Wood chips-Direct combustion-Cooling pond	624.58	625.00	2.13	2.55
4	Biomass-Wood chips-Direct combustion-Dry cooling	622.67	622.70	0.22	0.25
5	Biomass-Wood chips-Bio-oil-Once-through cooling	1163.17	1289.15	1.36	127.34
6	Biomass-Wood chips-Bio-oil-Cooling tower	1164.01	1164.34	2.20	2.53
7	Biomass-Wood chips-Bio-oil-Cooling pond	1163.94	1164.36	2.13	2.55
8	Biomass-Wood chips-Bio-oil-Dry cooling	1162.03	1162.06	0.22	0.25
9	Biomass-Corn stover-Direct combustion-Once-through cooling	260.74	386.72	1.36	127.34
10	Biomass-Corn stover-Direct combustion-Cooling tower	261.58	261.91	2.20	2.53
11	Biomass-Corn stover-Direct combustion-Cooling pond	261.51	261.93	2.13	2.55
12	Biomass-Corn stover-Direct combustion-Dry cooling	259.60	259.63	0.22	0.25
13	Biomass-Corn stover-Bio-oil-Once-through cooling	327.92	453.90	1.36	127.34
14	Biomass-Corn stover-Bio-oil-Cooling tower	328.76	329.09	2.20	2.53
15	Biomass-Corn stover-Bio-oil-Cooling pond	328.69	329.11	2.13	2.55
16	Biomass-Corn stover-Bio-oil-Dry cooling	326.78	326.81	0.22	0.25
17	Biomass-Wheat straw-Direct combustion-Once-through cooling	319.66	445.64	1.36	127.34
18	Biomass-Wheat straw-Direct combustion-Cooling tower	320.50	320.83	2.20	2.53
19	Biomass-Wheat straw-Direct combustion-Cooling pond	320.43	320.85	2.13	2.55
20	Biomass-Wheat straw-Direct combustion-Dry cooling	318.52	318.55	0.22	0.25
21	Biomass-Wheat straw-Bio-oil-Once-through cooling	467.16	593.14	1.36	127.34
22	Biomass-Wheat straw-Bio-oil-Cooling tower	468.00	468.33	2.20	2.53
23	Biomass-Wheat straw-Bio-oil-Cooling pond	467.93	468.35	2.13	2.55
24	Biomass-Wheat straw-Bio-oil-Dry cooling	466.02	466.05	0.22	0.25
25	Biomass-Switchgrass-Direct combustion-Once-through cooling	673.49	799.47	1.36	127.34
26	Biomass-Switchgrass-Direct combustion-Cooling tower	674.33	674.66	2.20	2.53
27	Biomass-Switchgrass-Direct combustion-Cooling pond	674.26	674.68	2.13	2.55
28	Biomass-Switchgrass-Direct combustion-Dry cooling	672.35	672.38	0.22	0.25
29	Biomass-Switchgrass-Bio-oil-Once-through cooling	825.03	951.01	1.36	127.34
30	Biomass-Switchgrass-Bio-oil-Cooling tower	825.87	826.20	2.20	2.53
31	Biomass-Switchgrass-Bio-oil-Cooling pond	825.80	826.22	2.13	2.55

(continued on next page)

Table 6 (*continued*)

NO.	Pathway	Complete life cycle		Power generation only	
		Water Consumption coefficient (L/kW h)	Water Withdrawals coefficient (L/kW h)	Water Consumption coefficient (L/kW h)	Water Withdrawals coefficient (L/kW h)
32	Biomass-Switchgrass-Bio-oil-Dry cooling	823.89	823.92	0.22	0.25
33	Nuclear-Centrifugal enrichment-Once-through cooling	1.73	178.24	1.52	178.03
34	Nuclear-Centrifugal enrichment-Cooling tower	2.94	4.38	2.73	4.17
35	Nuclear-Centrifugal enrichment-Cooling pond	2.52	4.38	2.31	4.17
36	Nuclear-Centrifugal enrichment-Dry cooling	0.48	0.63	0.27	0.42
37	Nuclear-Diffusion enrichment-Once-through cooling	1.84	178.56	1.52	178.03
38	Nuclear-Diffusion enrichment-Cooling tower	3.06	4.70	2.73	4.17
39	Nuclear-Diffusion enrichment-Cooling pond	2.64	4.70	2.31	4.17
40	Nuclear-Diffusion enrichment-Dry cooling	0.60	0.95	0.27	0.42
41	Solar-thermal-Power tower-Cooling tower	3.67	3.67	3.07	3.07
42	Solar-thermal-Power tower-Hybrid cooling	1.25	1.25	0.64	0.64
43	Solar-thermal-Power tower-Dry cooling	0.70	0.70	0.10	0.10
44	Solar-thermal-Parabolic trough-Cooling tower	3.98	3.98	3.37	3.37
45	Solar-thermal-Parabolic trough-Hybrid cooling	1.89	1.89	1.29	1.29
46	Solar-thermal-Parabolic trough-Dry cooling	0.90	0.90	0.30	0.30
47	Solar-thermal-Fresnel-Cooling tower	4.39	4.39	3.79	3.79
48	Solar-thermal-Fresnel-Dry cooling	0.98	0.98	0.38	0.38
49	Solar-thermal-Concentrating dish	0.63	0.63	0.02	0.02
50	Solar-Photovoltaic-Crystalline Silicon (C-Si)-Flat paneled	0.33	0.38	0.02	0.02
51	Solar-Photovoltaic-Crystalline Silicon (C-Si)-Concentrated PV	0.42	0.47	0.11	0.11
52	Solar-Photovoltaic-Thin film-Flat paneled	0.05	0.09	0.02	0.02
53	Solar-Photovoltaic-Thin film-Concentrated PV	0.14	0.18	0.11	0.11
54	Wind	0.005	0.104	0.005	0.006
55	Hydroelectricity	68.182	68.182	68.182	68.182
56	Geothermal-Binary-Hybrid cooling	1.75	1.75	1.74	1.74
57	Geothermal-Binary-Dry cooling	1.11	1.11	1.10	1.10
58	Geothermal-Flash-Cooling tower	0.06	0.07	0.06	0.06
59	Geothermal-Flash-Dry cooling	0.05	0.08	0.04	0.07
60	Geothermal-Enhanced geothermal system (EGS)-Binary-Dry cooling	1.94	1.94	1.93	1.93

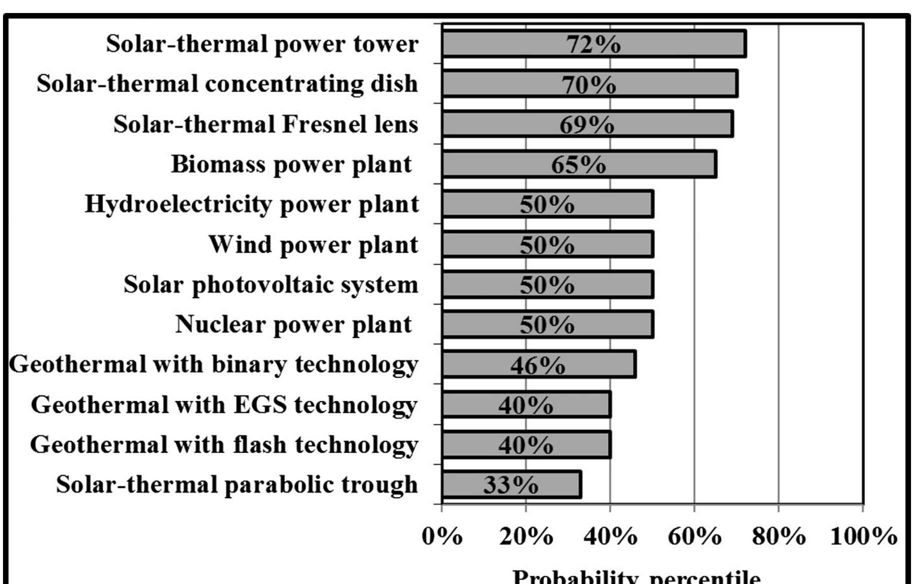

Fig. 4. Probability percentiles of the most likely conversion efficiencies of renewable energy technologies.

through Monte Carlo simulations. Fig. 4 shows the probability percentile of each conversion efficiency considered for the base case compared to the maximum and minimum values.

Performance profiles are developed theoretically through equations to correlate conversion efficiency to water demand coefficients [23,75]. The effect is studied separately for the two stages

Table 7
WCUP and WWUP distributions for the upstream stage of renewable energy pathways with different values for M1 and M2.

Pathway	Values (L/kW h) at a probability of 10%[c]		Values (L/kW h) at a probability of 90%[c]		Factor of merit (L/kW h)	
	WCUP	WWUP	WCUP	WWUP	M1[a]	M2[b]
Nuclear-Diffusion enrichment	0.35	0.56	0.31	0.50	0.11	0.175
Solar-Photovoltaic-C-Si	0.0032	0.58	0.0072	0.26	0.04	0.047
Solar-Photovoltaic-Thin film	0.037	0.11	0.016	0.049	0.003	0.009
Wind	0.00005	0.1251	0.00003	0.0812	0.00001	0.038

[a] Calculated using Eq. (1), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCUPs from input tables (Tables 2–5).
[b] Calculated using Eq. (2), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WWUPs from input tables (Tables 2–5).
[c] M1 and M2 were used with Eqs. (1) and (2), respectively, to calculate the WCUP and the WWUP using a Monte Carlo probability triangular distribution of conversion efficiency.

Table 8
WCUP and WWUP distributions for the upstream stage of renewable energy pathways with the same M1 and M2.

Pathway	WCUP/WWUP (L/kW h) at a probability of 10%[b]	WCUP/WWUP (L/kW h) at a probability of 90%[b]	Factor of merit M1 = M2[a] (L/kW h)
Nuclear-Centrifugal enrichment	0.22	0.20	0.07
Solar-thermal-Power tower	1.02	0.55	0.12
Solar-thermal-Parabolic trough	0.71	0.43	0.09
Solar-thermal-Fresnel	0.78	0.56	0.07
Solar-thermal-Concentrating dish	0.76	0.57	0.13
Geothermal-Binary	0.02	0.006	0.0008
Geothermal-Flash	0.01	0.007	0.0011
Geothermal-EGS	0.01	0.008	0.0009
Wood chips-Direct combustion	818.36	566.49	205.41
Wood chips-Bio-oil	1527.45	1057.36	383.40
Corn stover-Direct combustion	341.06	236.07	85.60
Corn stover-Bio-oil	429.38	297.23	107.77
Wheat straw-Direct combustion	418.49	289.69	105.04
Wheat straw-Bio-oil	612.41	423.92	153.71
Switchgrass-Direct combustion	883.68	611.70	221.80
Switchgrass-Bio-oil	1082.91	749.62	271.81

[a] Calculated using Eq. (1), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCUPs from input tables (Tables 2–5).
[b] M1 was used with Eq. (1) to calculate the WCUP/WWUP using a Monte Carlo probability triangular distribution of conversion efficiency.

of primary fuel extraction or construction (upstream stage) and for the power generation stage.

5.1. Upstream stage

The distribution of WCUPs at probabilities of 10% and 90% is shown in Table 7 for pathways with different M1 and M2 values. The corresponding distribution of pathways with the same M1 and M2 values is shown in Table 8. When a pathway has the same M1 and M2 value, this indicates that the WWUP is the same as the WCUP, and no water is returned to the source. Wind energy takes the lead here, followed by geothermal, solar, and nuclear. Water demand coefficients for wind energy are always less than 0.15 L/kW h under all probability percentiles as shown from the output of the Monte Carlo simulation in Table 7. Water demand coefficients during the upstream stage are lower for these technologies due to the fact that either no fuel is required or very low water is needed, as in the case of nuclear power, and only materials and construction consume water.

The WWUPs for biomass upstream pathways are all assumed to be equal to the corresponding WCUPs (M1 = M2). The intensive water used in the production stage of the biomass feedstock gives them the highest WCUPs of all the renewable energy pathways.

5.2. Power generation stage

Table 9 shows the water demand coefficients for the power generation stage at probability percentiles of 10% and 90%, besides the factors of merit. Of all the renewable energy technologies, wind energy still has the lowest water demand coefficients during power generation. Nuclear energy with a once-through cooling system has the highest impact on water withdrawals during the power generation stage (165.30 and 192.10 L/kW h at 10% and 90% probabilities, respectively). Biomass pathways outperform in water demand coefficients during the power generation stage compared to nuclear energy pathways.

Factors of merit are useful comparison tools for pathways following the same track. For example, the biomass power generation stage with a cooling tower has an M3 of 1.08 L/kW h while the same pathway based on nuclear energy has an M3 of 1.34 L/kW h, which indicates that at the same conversion efficiency, this biomass pathway always performs better than the corresponding nuclear pathway.

6. Conclusions

Sixty pathways of power generation from renewable energy were developed along with water demand coefficients for each pathway to cover water consumption and water withdrawals coefficients at the base case conversion efficiency. The effects of conversion efficiency variation on the water demand coefficients were studied through a comprehensive uncertainty analysis. Wind energy has the most positive impact on water demand and can alleviate the intensive water required to generate power. The highest water withdrawals coefficient during the power generation stage is from nuclear energy with a once-through cooling system and is 165.30 at a probability of 90% and 192.10 L/kW h at a probability of 10%. Direct combustion of corn stover has the lowest water demand coefficient (about 260 L/kW h for consumption and 260–387 L/kW h for withdrawals) among all the biomass pathways. The water required to irrigate crops grown for biomass negatively affects the water demand for biomass technology pathways. Considering the complete life cycle, dry cooling during power generation that can effectively compensate for the intensive water use during the fuel cycle. The lower conversion efficiencies of nuclear energy and solar-thermal pathways compared to other thermoelectric technologies negatively impacts the water demand coefficients. Improving conversion efficiency is one of the essential factors to consider when studying the level of water demand for a certain technology. The mostly likely conversion efficiencies selected for the base case in this study had the probability range

Table 9
WCUP and WWUP distributions for the power generation stage of renewable energy pathways.

Pathway	WCC (L/kW h) at a probability of 10%[e]	WCC (L/kW h) at a probability of 90%[e]	WWC (L/kW h) at a probability of 10%[f]	WWC (L/kW h) at a probability of 90%[f]	Factor of merit (L/kW h)			
					M3[a]	M4[b]	M5[c]	M6[d]
Biomass-Once-through cooling	1.99	1.17	187.16	110.25	0.67	62.72	–	–
Biomass-Cooling tower	3.23	1.90	3.71	2.19	1.08	1.24	–	–
Biomass-Cooling pond	3.13	1.85	3.74	2.21	1.05	1.25	–	–
Biomass-Dry cooling	0.32	0.19	0.37	0.22	0.11	0.12	–	–
Nuclear-Once-through cooling	1.63	1.41	192.10	165.30	0.75	87.69	–	–
Nuclear-Cooling tower	2.94	2.53	4.50	3.87	1.34	2.05	–	–
Nuclear-Cooling pond	2.49	2.15	4.50	3.87	1.14	2.05	–	–
Nuclear-Dry cooling	0.29	0.25	0.45	0.39	0.13	0.21	–	–
Geothermal-Flash-Dry cooling	0.06	0.03	0.10	0.04	0.005	0.008	–	–
Solar-thermal-Power tower-Cooling tower	5.71	2.72	5.71	2.72	0.77	0.77	–	–
Solar-thermal-Power tower-Hybrid cooling	1.20	0.57	1.20	0.57	0.16	0.16	–	–
Solar-thermal-Power tower-Dry cooling	0.18	0.09	0.18	0.09	0.02	0.02	–	–
Solar-thermal-Parabolic trough-Cooling tower	4.07	2.22	4.07	2.22	0.59	0.59	–	–
Solar-thermal-Parabolic trough-Hybrid cooling	1.56	0.85	1.56	0.85	0.23	0.23	–	–
Solar-thermal-Parabolic trough-Dry cooling	0.36	0.19	0.36	0.19	0.05	0.05	–	–
Solar-thermal-Fresnel-Cooling tower	5.00	3.47	5.00	3.47	0.47	0.47	–	–
Solar-thermal-Fresnel-Dry cooling	0.50	0.35	0.50	0.35	0.05	0.05	–	–
Geothermal-Binary-Hybrid cooling	3.40	1.04	3.40	1.04	0.15	0.15	–	–
Geothermal-Binary-Dry cooling	2.14	0.65	2.14	0.65	0.10	0.10	–	–
Geothermal-Flash-Cooling tower	0.08	0.04	0.08	0.04	0.007	0.007	–	–
Geothermal-EGS-Binary-Dry cooling	2.20	1.58	2.20	1.58	0.19	0.19	–	–
Solar-thermal-Concentrating dish	0.02	0.018	0.02	0.018	–	–	0.004	0.004
Solar-Photovoltaic-Flat paneled	0.04	0.02	0.04	0.02	–	–	0.003	0.003
Solar-Photovoltaic-Concentrated PV	0.18	0.08	0.18	0.08	–	–	0.015	0.015
Wind	0.006	0.004	0.007	0.005	–	–	0.002	0.002
Hydroelectricity	71.70	65.00	71.70	65.00	–	–	61.36	61.36

[a] Calculated using Eq. (3), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCCs from the input tables (Tables 2–5).
[b] Calculated using Eq. (4), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCCs from the input tables (Tables 2–5).
[c] Calculated using Eq. (5), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCCs from the input tables (Tables 2–5).
[d] Calculated using Eq. (6), the conversion efficiencies (η_{ml}) from Table 1, and the corresponding WCCs from the input tables (Tables 2–5).
[e] M3 and M5 were used with Eqs. (3) and (5), respectively, to calculate the WCCs using a Monte Carlo probability triangular distribution of conversion efficiency.
[f] M4 and M6 were used with Eqs. (4) and (6), respectively, to calculate the WCCs using a Monte Carlo probability triangular distribution of conversion efficiency.

of 33–72% based on the maximum and minimum ranges. Studies of water demand for power generation technologies have to be integrated with other environmental, economic, and social aspects in order to make decisions for sustainable development.

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