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Wells to Wheels: Water Consumption for Transportation Fuels in the United States†

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The sustainability of energy resources such as transportation fuels is increasingly connected to the consumption of water resources. Water is required for irrigation in the development of bioenergy, reservoir creation in hydroelectric power generation, drilling and resource displacement in petroleum and gas production, mineral extraction in mining operations, and cooling and processing in thermoelectric power generation. Vehicles powered by petroleum, electricity, natural gas, ethanol, biodiesel, and hydrogen fuel cells consume water resources indirectly through fuel production cycles, and it is important to understand the impacts of these technologies on water resources. Previous investigations of water consumption for transportation fuels have focused primarily on key processes and pathways, ignoring the impacts of many intermediate, interrelated processes used in fuel production cycles. Herein, the results of a life cycle analysis of water consumption for transportation fuels in the United States using an extensive system boundary that includes the water embedded in intermediate processing and transportation fuels are presented. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model provides a comprehensive framework and system boundary for transportation fuel analysis in the United States. GREET was expanded to include water consumption and used to compare the water consumed per unit energy and per km traveled in light-duty vehicles. Many alternative fuels were found to consume larger quantities of water on a per km basis than traditional petroleum pathways, and it is therefore important to consider the implications of transportation and energy policy changes on water resources in the future.

1 Introduction

The production of energy exerts an increasingly important influence on natural resources and the environment. Energy production processes consume water resources and accelerate fluxes of water from land surfaces to the atmosphere. Increases in population, energy and food demand now strain previously abundant sources of water. For these reasons, it is important to characterize the relationships between consumption of water resources and the production of energy.

The transportation sector consumed 28% of the total primary energy in the United States (US) in 2013[1]. World-wide energy consumption in the transportation sector is projected to increase by 63% from 2010 to 2040[1]. A current focus of transportation energy policies in the US and elsewhere is on the reduction of emissions of greenhouse gases (GHGs). For example, the US Energy Independence and Security Act of 2007 (EISA) expanded the Renewable Fuel Standard (RFS) to promote fuels that reduce life cycle GHG emissions relative to conventional fuels[2], and the European Union enacted the Renewable Energy Directive to promote renewable energy production[3]. In California, the Low Carbon Fuel Standard (LCFS) calls for a reduction of at least 10% in the carbon intensity of transportation fuels[4]. In addition to impacts on GHG emissions, it is increasingly important to consider the impacts of transportation fuels on water resources.

Transportation fuels are produced using interconnected pathways composed of numerous individual production processes. Many of these production processes generate intermediates that are later consumed for the ultimate purpose of generating transportation. Each process in a pathway may consume water resources, so it is necessary to analyze the water consumed throughout the pathway to understand the net impact that a fuel will have on water resources. For example, biodiesel and ethanol production consume water in both the agricultural operations used to produce biomass and in the conversion of the biomass to fuel; thermoelectric power generation consumes water in fuel cycle operations and cooling in thermoelectric power plants; hydroelectric power plants require water-consuming reservoirs to generate electricity; hydrogen fuel cells consume water as a feedstock for

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the fuel and for cooling excess energy generated by the process; petroleum and natural gas require water for recovery and subsequently for processing.

A complete accounting of the water resource impacts of transportation fuel production necessitates a life cycle analysis (LCA) of the entire supply chain for each production pathway. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is an analytical tool that can be used to perform LCAs of transportation fuels[5]. GREET provides a comprehensive framework for a robust LCA of the impacts of different transportation fuels on water resources.

LCAs of water consumption are challenging to perform due to differences in definitions and terminology associated with water data. Water that is withdrawn by power plants and other industries is often more easily quantified than the amount of water actually consumed by the process. Many estimates of water resource impacts of production processes are based on withdrawals even when the majority of the water is returned to the watershed or groundwater source where it originated. A large portion of the water consumed in agricultural processes is supplied by precipitation rather than irrigation withdrawals from a water resource. The quantities of water consumed in agricultural processes by precipitation and irrigation are sometimes referred to as the green water and blue water, respectively[6]. Accounting for both the precipitation and irrigation water consumed in agricultural processes overestimates the anthropogenic influence on water resources because indigenous flora consume water in the absence of any agriculture. An additional complication in water accounting is the inherently spatial and temporal variability of the climate, which can affect both production and consumption of water resources in a given location.

The goals of this study were to develop a comprehensive baseline LCA of water resource consumption associated with transportation fuel production, highlight the uncertainties and implications in the results, and identify important outstanding gaps in the data. There have been other LCAs performed on water consumption associated with transportation; however, these analyses ignored the water embedded in many intermediate resources such as transportation fuel and intermediate chemicals[7] or utilized economic input-output modeling to fill process data gaps[8]. To fill these gaps in the analysis, an extensive inventory of process-level water consumption factors was developed for the major transportation fuel pathways in the US consistent with the GREET structure. The inventory was then used with the GREET framework to quantitatively estimate the anthropogenic-induced water consumption associated with the various transportation fuels. The results provide extensive and comprehensive analysis into the connections between transportation energy and water resources. The values outlined in this study are not necessarily representative of water consumption for specific projects, however, due to large spatial and temporal variability of water use in energy production processes.

2 Methodology

GREET contains estimates of the life cycle energy use and emissions of hundreds of transportation fuel production pathways. The fuels analyzed in this study include petroleum gasoline and diesel, corn-based ethanol, soy-based biodiesel, compressed natural gas (CNG), electricity generated from different sources in the US grid, and compressed hydrogen gas (H_2). The results were extended to assess blended fuels including gasoline mixed with 10% corn-based ethanol by volume (E10) and gasoline mixed with 85% corn ethanol by volume (E85) and 20% soybean-based biodiesel (B20) for use in internal combustion engine vehicles (ICEV). Collectively these fuels account for the majority of current and predicted near-future energy consumption in passenger vehicles in the US[1].

The life cycle water consumption associated with the fuels was computed using functional units of L of water per GJ. Electricity generation pathways were also compared in L of water per kWh, and pathways for hydrogen fuel cells were analyzed in L of water per kg H_2. The vehicle fuel efficiencies were used to extend the water consumption estimates from an energy basis to units of L of water per 100 kilometers of transportation in light-duty vehicles (LDV) powered by E10, E85, petroleum diesel, soy biodiesel, B20, compressed natural gas vehicles (CNGV), battery electric vehicles (BEV) using electricity from the major sources in the US grid, and fuel cell electric vehicles (FCEV) powered by hydrogen gas produced from natural gas, electricity, coal, and biomass.

2.1 Definitions of Water Consumption

Water is ubiquitous on Earth and is plentiful on a global scale. Freshwater resources on land surfaces, however, are a limited renewable resource. Freshwater resources are produced from precipitation and move across land surfaces where they are consumed naturally by evaporation and transpiration or may be diverted and used to enhance agriculture, capture waste heat in industrial facilities, extract other natural resources, or supply drinking water to municipalities. Definitions of water consumption were taken for consistency with the goal of this analysis, which was to estimate the freshwater consumed for anthropogenic purposes in processes relevant to transportation fuel production in the United States. Water consumption in this context is water withdrawn from a freshwater resource and not returned either because of evaporation, transpiration, deep injection, or major quality degradation. The water consumption accounting and definitions associated with individual fuel supply chain processes were developed for consistency with this definition.

Industrial facilities such as thermoelectric power plants and petroleum refineries require water for cooling and processing. The amount of water withdrawn for industrial processes may be much larger than the amount consumed. While characterization of water withdrawals is important to local ecology, this analysis focused only on water consumption given the context of US average values. Figure 1 shows a schematic of the flows of water into and out of a water-consuming facility and the associated definition of water consumption. The quantity of water consumed in industrial facilities is primarily determined by process requirements unlike water use in other processes and as a result water consumption tends to exhibit less spatial and temporal variability.

Agricultural processes require water to enhance the growth of

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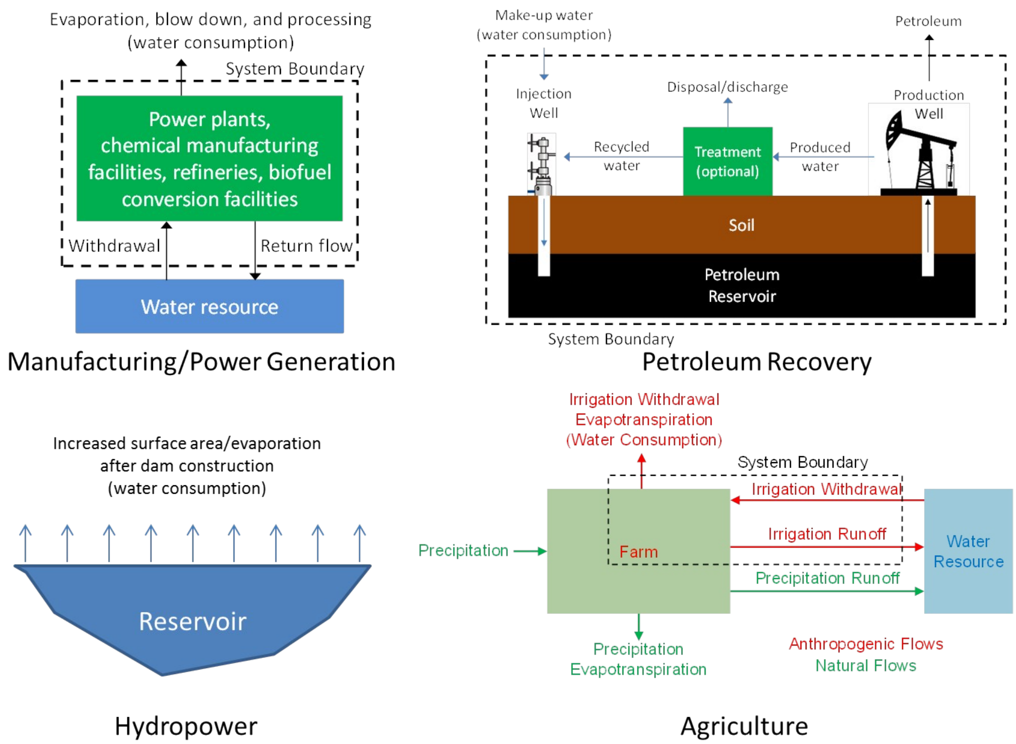

Fig. 1 Definitions of water consumption. Upper left: Flows of water into and out of manufacturing facilities and power plants. Upper right: Flows of water and petroleum in recovery operations. Lower left: Increased evaporation from construction of hydropower facilities. Lower right: Natural and anthropogenic flows of water on an agricultural land segments.

biomass. In agricultural operations, much of the production water requirement can be supplied by precipitation. Irrigation water is often used to improve agricultural yields or make crop production possible. Some of the irrigation water supplied to an agricultural operation returns to surface and groundwater bodies, but the remainder that is consumed represents the primary anthropogenic impact of the process on water resources. For this analysis, water consumption associated with agriculture was defined as the evapotranspiration of water withdrawn for irrigation. Figure 1 shows a schematic of the water flows in an agricultural production process. No attempts were made to quantify changes in evapotranspiration associated with land use changes from native grasses and forest to farms.

Mining and recovery operations for petroleum, natural gas, geothermal energy, and other resources require water for drilling, extraction and beneficiation. The amount of water needed to produce a given quantity of petroleum changes over the life cycle of a given well and varies with both the location and the extraction technology utilized. Low-quality (saline) water exists naturally in petroleum reservoirs, and during crude oil recovery some of this water is co-produced with crude oil. Sometimes the produced water is recycled to enhance recovery; other times it is treated; other times it is disposed of through deep well injections as shown in Figure 1. Water consumption for mining and recovery processes was defined as water injected into the reservoirs that originated from outside the formation.

The recovery of natural gas from conventional deposits requires water for drilling operations and cooling. Oil and gas-producing shale formations require water for hydraulic fracturing to enable production. Extraction of other minerals requires water for solution mining, beneficiation, and cleaning. The quality of any water used in mining/resource recovery technologies is often substantially diminished and cannot be returned to a water resource. For this analysis, all water withdrawals for mining and recovery operations were assumed to be consumed. The impacts of diminished quality water from mining/recovery operations on local resources and return flows of treated water to resources from mining operations were not quantified.

The construction of dams for generation of electricity from hydropower substantially modifies the hydrology of the associated watershed. Dams permanent modify landscapes from existing natural and/or anthropogenic purposes into artificial reservoirs. The formation of these reservoirs increases the water surface exposed to the atmosphere thereby increasing evaporation from the entire river system. In large river systems with multiple dams, the construction of new dams for hydropower may impact water availability downstream through increased evaporation as shown in Figure 1. For this analysis, the increased evaporation from reservoirs due to hydroelectric power generation was taken as the definition of water consumption.

2.2 System Boundaries

The system boundaries for the life cycle water consumed in the production of the transportation fuels in this study include mining and recovery operations, agricultural production of biomass, agri-

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cultural chemicals manufacturing, biofuel conversion, crude oil and natural gas refining and processing, and transportation and distribution. Fuel consumption and the associated life cycle water consumption for processing and transportation was assumed to come from a combination of diesel fuel, gasoline fuel, residual fuel oil, natural gas, coal, liquefied petroleum gas, hydrogen gas, and electricity from the US electric grid. The water consumed in the construction of infrastructure, the water consumption associated with vehicle manufacturing and disposal, and the impacts of land use changes on water resources were not considered in this assessment. Because of the long lifetime associated with infrastructure, it is unlikely that construction and manufacturing of infrastructure would have a large effect on water consumption.

The production of each of each of these fuels can be conceptualized as a pathway consisting of a series of parallel processes. Because the fuel production from each pathway requires fuel from the other pathways, however, the embedded water in each of the fuels associated with other fundamental process inputs must calculated simultaneously. For example, petroleum refining requires electricity, electricity generation utilizes coal as a feedstock, and coal transportation requires petroleum. Thus in reality all of the pathways are interdependent.

Figure 2 shows the various well-to-wheel pathways for the major US transportation fuels characterized in this study. The petroleum fuel pathways (diesel and gasoline blendstock) consist of on-shore or off-shore crude oil recovery or bitumen extraction from oil sands followed by refining. The corn ethanol and soy biodiesel pathways include agricultural chemical production followed by farming and then fuel conversion. The CNG pathway is composed of gas recovery followed by processing and compression. Electricity for BEVs and other production processes is generated at power plants following the fuel production cycle for coal, natural gas, nuclear fuel, and petroleum and renewable resources including hydropower, wind, biomass, municipal waste, geothermal and solar power. Hydrogen can be generated from natural gas using steam methane reforming (SMR), from electricity using electrolysis, or from coal or biomass using gasification. Each of these pathways was extended from pumps to wheels using the associated fuel efficiency, although the water consumption associated with vehicle manufacturing and operation was not included in this analysis. In addition to the water consumed in each process in the various pathways, the GREET framework enables inclusion of the embedded water in the transportation and processing fuels.

2.3 Life Cycle Inventory Data

Estimates of the water consumed per unit output for each of the relevant transportation processes were developed from an extensive literature survey, industry data, and analysis of number of publicly-available databases. An overview of the processes represented in GREET and the results of the inventory are summarized elsewhere [9] including a recommended list of water consumption factors (WCFs) representing the water consumed per unit output from each process. These WCFs were used as the default values in this analysis. However, the variability in the WCFs for each pathway shown in Figure 2 was analyzed more extensively to highlight the impacts of spatial, temporal, technological, methodological and other variability on life cycle water consumption.

2.4 Life Cycle Water Consumption Calculation

The life cycle water consumption was computed for each pathway using the 2014 version of GREET.net [10]. GREET.net contains an extensive inventory of energy production data for the United States that can be used to determine the individual contributions of processes and intermediates to the life cycle in an energy system. The water consumption inventory and the data in the GREET.net platform were used to calculate life cycle water consumption and the contribution of individual processes to the life cycle. The literature survey documented in the inventory was used to assess the range of values for the various feedstock sources and different processing technologies to highlight the variability in the life cycle estimates.

3 Fuel Pathways and Process-Level Water Consumption Estimates

The following sections briefly summarize each of the pathways analyzed in this study including estimates and ranges of the amount of water consumed per unit output of individual processes shown in Figure 2. A detailed explanation of the values for key individual technologies associated with each pathway is provided in the associated supplementary information and elsewhere [9]. The data in the supplementary information are presented in Imperial units for consistency with literature sources and GREET; herein the results are summarized in standard units.

3.1 Petroleum Gasoline and Diesel

Crude oil that is used in petroleum refineries in the United States to produce gasoline and diesel originates from domestic onshore and offshore wells and from foreign imports. The quantities of water and crude oil produced and consumed are unique to every formation and depend on the geology of the reservoir and the extraction technology used for recovery. Water is injected into wells for void replacement, pressurization, and reservoir stimulation. This water generally does not need to be of good quality and thus may have a minimal impact on local water resources. For example, offshore wells utilize seawater and many on-shore wells utilize local brackish water for recovery operations. The lower bound for freshwater resource consumption associated with petroleum recovery is zero. Offshore production composed slightly more than 17% of total US domestic production in 2013 [1].

As described in more detail in the supplementary information and elsewhere [9], WCFs for onshore technologies were compiled for consistency with existing GREET crude recovery processes. For conventional production, 2.5 L of water per GJ of crude oil are required for drilling [11] associated with primary production while 358 L of water per GJ of crude oil are consumed for secondary production or water flooding [12]. For enhanced recovery technologies, estimates include 330 L of water per GJ of crude oil for steam injection [13], 82 L per GJ for caustic injection [13], and 358 L per GJ for injection of carbon dioxide [14]. Production of bitu-

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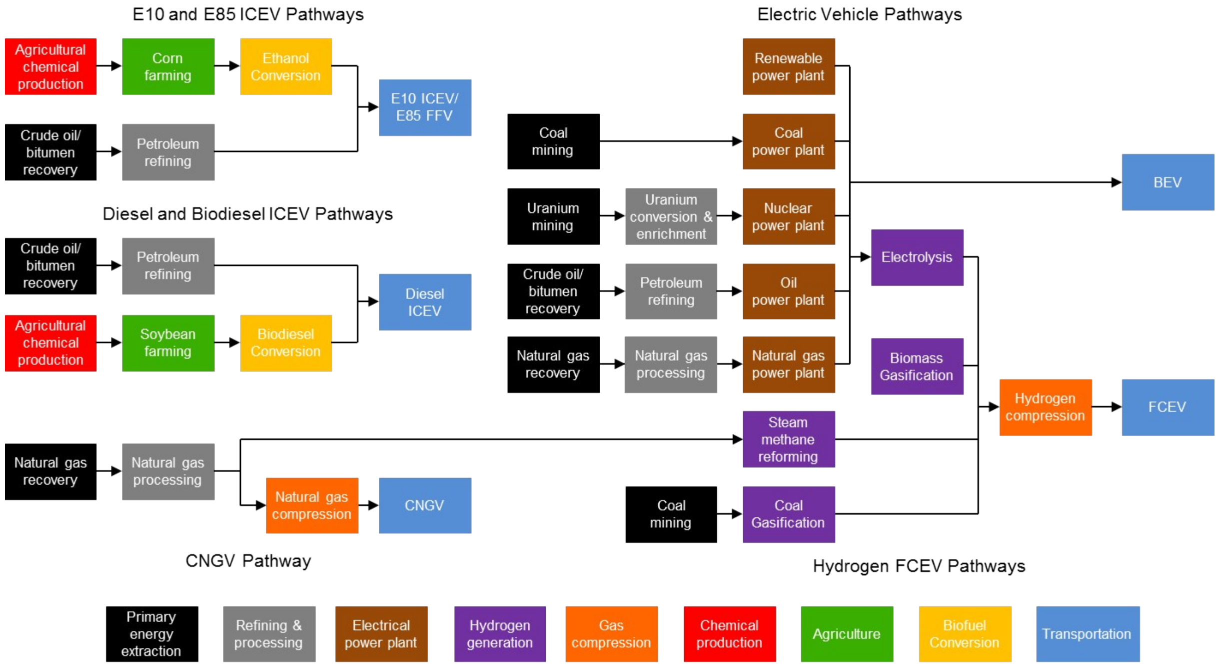

Fig. 2 Well-to-wheels pathways for transportation fuels and passenger vehicles analyzed in this study.

men from Canadian oil sands requires 19.2 L per GJ in operations using in-situ production and 94 L per GJ in operations utilizing surface mining[15]. A recent study[16] estimated 11.5 L per GJ and 39 L per GJ are used in the production of Bakken and Eagle Ford shale oil, respectively, primarily for hydraulic fracturing.

Following recovery, crude oil is refined into a number of products including gasoline and diesel. Petroleum refineries use water for a number of different purposes including cooling and steam generation for distillation, cracking and reforming. Elgowainy *et al.* [17] analyzed 70% of the US refining capacity using a linear programming model. As described in detail elsewhere[9] that analysis was extended to determine the amount of water consumed to produce individual refinery products. The estimated WCFs associated with conventional US gasoline and diesel were 24 and 28 L of water per GJ, respectively.

3.2 Biofuels

A number of different biomass sources can be converted into liquid transportation fuels such as ethanol, methanol, and biodiesel. The vast majority of bioenergy production in the United States, however, is derived from corn for ethanol production and soybeans for biodiesel production[1]. The corn ethanol and soy biodiesel pathways consist of production of agricultural chemicals followed by farming to produce biomass and then conversion to fuel and other co-products in a biorefinery. The water consumption associated with corn ethanol or soy biodiesel depends heavily on the farming practices and regional climate where the feedstock is produced. Water consumption analysis of these biofuels therefore must consider spatial variability, temporal variability, and co-product allocation methodology.

Production of corn ethanol and soy biodiesel feedstock requires nitrogen-based fertilizers such as urea, ammonium nitrate, and ammonium phosphates derived from ammonia production through the Haber process. The production of ammonia relies heavily on natural gas and thus dominates the life cycle energy and greenhouse gas emissions for agricultural chemicals[18]. Phosphorous, potassium, and agricultural lime derived from mining operations are used to enhance production of both corn and soy biomass. Phosphate mining operations require water to generate slurries for transport and for beneficiating the mining products. Potassium is produced using solution mining, which requires substantial amounts of water. Limestone is extracted from quarries and then cut and ground into smaller pieces, which generates excess heat requiring cooling water. A number of other chemical processes are used to generate finished products for agriculture that consume small amounts of additional water for cooling. WCFs for each of these technologies were developed as described elsewhere[9].

Agricultural operations used to generate biomass rely on precipitation but often require additional irrigation water to increase yields or make the agricultural process feasible as shown in Figure 1. As described in detail in the supplementary information, data from previous Censuses of Agriculture and associated Farm and Ranch Irrigation Surveys[19–22] were used to estimate state-level water consumption and production consistent with previous studies[23]. These data were aggregated to develop a range of WCFs associated with production of corn and soybeans. The feedstock for ethanol biorefineries was assumed to come from the states of Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin consistent with previous life cycle analysis of corn ethanol production[24], while soybean irrigation and production data were aggregated nationwide. Figure 3 shows state-level water consumption associated with corn and soybean production for each agricultural census. The water

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consumption associated with corn farming was dominated by Nebraska, which consumed over 80% of the total water each year despite producing less than 20% of the corn. Soybean farming water consumption shares were more distributed, although they were still dominated by a few states with Nebraska, Arkansas, Kansas, and Mississippi collectively accounting for over 80% of the total water consumption each year despite representing less than 20% of the total soybean production.

Corn and soybean biomass are converted into biofuels in biorefineries across the United States. Corn grain can be converted into ethanol with either a wet- or dry-mill fermentation process that uses catalytic enzymes to increase yields and process efficiencies. Water is needed to create slurries and to dissipate waste heat generated in the reactors. Corn ethanol refineries generate useful co-products including electricity and distillers grains with solubles (DGS) that are used as animal feed. Soy biodiesel is produced by extracting soy oil from the beans and then converting the oil into biodiesel using the transesterification reaction. These processes co-produce soy meal (an animal feed) and glycerin, which is used for a number of industrial purposes including food and pharmaceutical product development. The overall burden of biofuels on water consumption depends in part of the allocation to co-products. Wang *et al.*[25] discussed allocation of life cycle environmental burdens of corn ethanol and soy biodiesel between multiple products including the mass, energy, market value basis and the displacement method. The displacement method has been used for biofuel regulations development including the RFS and LCFS[2,4]. Each of these allocation methods were used with the latest data from GREET to examine the significance of the allocation method on the water consumption intensity of corn ethanol and soy biodiesel as shown in detail in the supplementary information.

3.3 Compressed Natural Gas

CNG has been used as a transportation fuel in public transit buses in the United States for many years and is an increasingly attractive alternative transportation fuel for LDVs. CNG production from shale formations has recently become economical due to advancements in horizontal drilling and hydraulic fracturing technologies, which dramatically increases available supplies. CNG can also be produced from biogenic sources, which provides a sustainable alternative to fossil-based carbon fuels. The CNG production pathway consists of recovery followed by processing, transportation, and compression. Petroleum, electricity, and gas are consumed throughout CNG production which increases the water consumption burden of the final product.

In 2013, the US produced over 30 trillion cubic feet of gas from sources including shale gas wells (39.6%), conventional gas wells (37.5%), oil wells (18.1%), and coalbed wells (4.8%)[1]. Conventional recovery operations require water for well drilling and cementing of wellbores. After construction of a well, no water is needed during operation. So while a large amount of water may be required initially during the well development, when amortized over the well life cycle the amount of water per unit gas produced may be relatively small.

Hydraulic fracturing increases the water intensity of shale gas relative to conventional gas production. Clark *et al.*[26] analyzed water consumption associated with conventional gas production and compared it with shale gas production from the Barnett, Fayetteville, Haynesville, and Marcellus formations using data from each formation. Water for conventional drilling and cementing was estimated to range from 0.25 - 0.57 L per GJ of estimated ultimate recovery (EUR). For hydraulic fracturing, Clark *et al.*[26] computed the water consumed per unit natural gas produced based on EUR for each of the shale plays based on data from thousands of individual wells. Water consumption ranged from a minimum of 3.9 L per GJ for the Haynesville to 29 L per GJ in the Fayetteville with an average value of 12.7 L per GJ for fracturing.

Following recovery, raw natural gas must be processed and purified before it can be transported to prevent corrosion and damage in pipelines and to minimize pollution associated with its consumption downstream. Raw gas contains a number of impurities including CO_2 and H_2S that can be preferentially absorbed in high pH aqueous solutions. Gas processing consumes energy and requires water for cooling. Gleick[13] indicated that 6.1 L of water per GJ are consumed in natural gas processing. Natural gas transportation and compression to CNG consume no water directly, although the intermediate products used in these processes (e.g., electricity) add to the water consumption burden of the finished natural gas product.

3.4 Electricity

Electricity is generated from a number of different primary energy sources in the US grid including coal, natural gas, petroleum, nuclear power, hydropower, wind, geothermal power, biomass, and solar power. Shares for different power plants in the US mix used in GREET 2014 are shown in Table 1. The water consumption mechanisms associated with electric power generation include direct consumption as shown previously in Figure 1 and indirect consumption in fuel production cycles. Coal, petroleum, natural gas, and nuclear power plants each possess a fuel cycle that consumes water. Thermoelectric power plants including coal, nuclear, oil, natural gas, geothermal, biomass, and concentrated solar power plants consume water primarily for cooling waste heat from energy conversion processes. The amount of cooling water consumed depends on the plant's energy efficiency and cooling technology. Technologies used for process cooling include wet once-through cooling, recirculating cooling with either a cooling tower or a pond, and dry cooling. Wind, solar photovoltaic, and hydropower plants do not require cooling water. Hydropower plants, however, rely on reservoir storage where water is consumed by evaporation as shown in Figure 1.

A shown in Table 1, coal-fired power plants comprised the largest share of the US electric grid mix in 2013. Coal is produced throughout the US in surface and underground mines. Coal mining requires water for dust control, vegetation re-establishment, and beneficiation. As described elsewhere[9], US average water consumption factors of 9.3 and 16.5 L per GJ were estimated for both surface and underground mining, respectively. Literature

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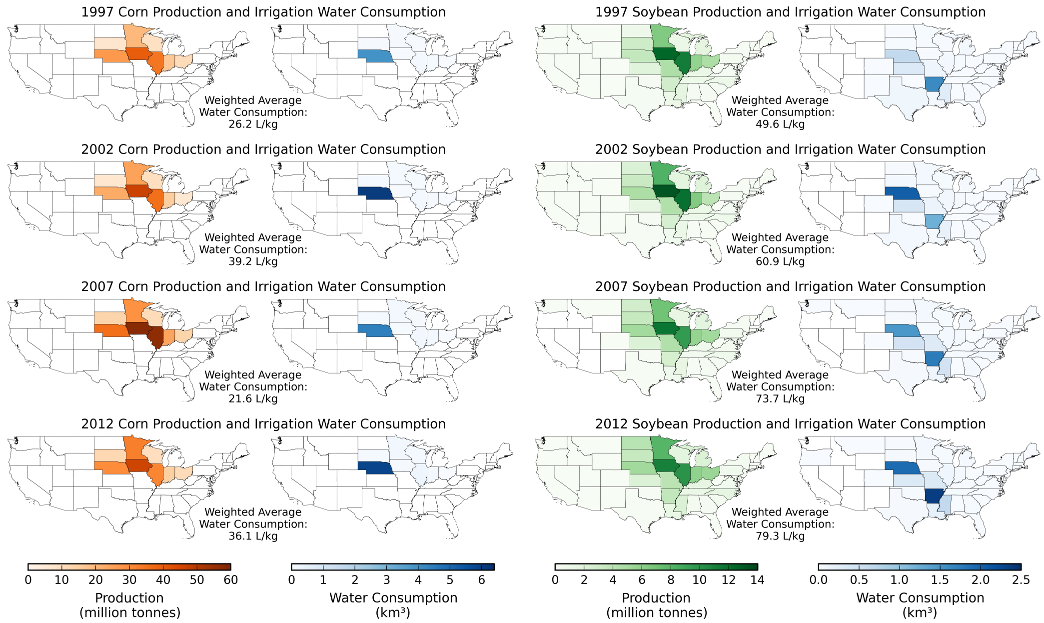

Fig. 3 Corn and soybean production and water consumption estimates.

Table 1 2013 Electricity Generation in the US.

Energy Source	Electricity Generation, TWh[1]	Share
Coal	1615.73	41.47%
Petroleum	17.95	0.46%
Natural Gas	1018.79	26.1%
Nuclear	758.14	19.5%
Wood and Other Biomass	11.22	0.3%
Hydroelectric	264.99	6.8%
Geothermal	16.78	0.4%
Wind	164.59	4.2%
Solar Photovoltaic	5.75	0.2%
Concentrated Solar	1.19	0.03%
Biogenic Waste	18.22	0.22%

estimates for water consumption in coal mining range from 1.8 L per GJ[13] to 57.7 L per GJ[27]. Following mining, coal is transported to power plants where it is combusted to generate electricity. The majority of US coal power plants use steam turbines to generate electricity, although some facilities use an integrated gasification combined cycle that improves energy efficiency but at a higher capital cost. Wu and Peng[28] estimated WCFs for coal power plants with dry cooling, once-through cooling, wet cooling towers, and cooling ponds of 0, 1.13, 2.65, and 2.65 L per kWh, respectively, and a technology-weighted average of 2.04 L per kWh for coal-fired steam power plants. Meldrum *et al.*[29] reported a median WCF of 1.21 L per kWh for coal combined cycle power plants.

Residual oil produced in petroleum refineries is used to generate a small share of US electricity using a combination of steam turbines, combustion turbines, and internal combustion engines. Water is consumed in petroleum recovery and refining to produce residual oil using the processes described previously. Like other thermoelectric power plants, water is consumed for cooling in petroleum-fired steam turbines. Combustion turbines and internal combustion engines do not typically require water for cooling. Wu and Peng[28] compiled cooling technology shares and WCFs for fossil fuel power plants for dry cooling, once-through cooling, wet cooling towers, and cooling ponds of 0, 1.13, 1.81, and 0.42 L per kWh, respectively, and a technology-weighted average of 1.17 L per kWh for oil power plants in the US.

Natural gas-fired power plants compose a large and growing share of US electric power generation. As described previously, natural gas is produced from conventional and shale gas formations followed by processing and transportation. Natural gas is used to generate electricity in power plants in the US grid with a mixture of combustion turbines, steam cycle turbines, internal combustion engines, and combined cycle power plants. As in the case of other thermoelectric power plants, water consumption in natural gas power plants is primarily associated with cooling. Gas combustion turbines and internal combustion engines do not require cooling water and were assigned WCFs of zero. WCFs of 1.47 and 0.79 L per kWh were estimated for steam turbine and combined cycle power plants by aggregating technology shares and WCFs compiled by Meldrum *et al.*[29] and Wu and Peng[28].

Nuclear power plants accounted for almost 20% of US electricity generation in 2013. The nuclear fuel cycle consists of mining and milling of natural uranium oxides (U_3O_8) followed by conversion to uranium hexafluoride (UF_6), then enrichment of the fissile U^{235} isotope from natural levels of approximately 0.7% to 3.5%, followed by fabrication of uranium dioxide (UO_2) fuel rods. Each of these steps consumes water directly for processing and/or cooling. Existing GREET technology shares and median WCFs from Meldrum *et al.*[29] were used to estimate an average of 1430 L of water consumed directly per gram of U^{235} fuel produced in the US. The nuclear fuel is transported to nuclear power plants and used to generate heat like other thermoelectric power plants. Nuclear power plants utilize a variety of cooling technologies for waste heat dissipation. Wu and Peng[28] estimated WCFs

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for nuclear power plants with dry cooling, once-through cooling, wet cooling towers, and cooling ponds of 0, 1.51, 3.02, and 1.89 L per kWh, respectively, and a technology-weighted average of 2.19 L per kWh for nuclear power plants in the US.

Hydropower generated over 6% of the electricity in the US mix in 2013. Dams used by hydroelectric power plants create artificial reservoirs that impact the ecology and hydrology of the region including generation of an evaporative flux to the atmosphere. The water that is evaporated by hydropower-generating reservoirs is unavailable for other purposes downstream of the dam and is characterized as water consumption. The quantity of water consumed per unit electricity generated is a complicated function of the geometry of the reservoir, the local climate, and other characteristics of the dam. Torcellini *et al.* [30] estimated that on average 69.1 L of water are consumed per kWh of hydroelectricity generated in the US using a combination of observed annual pan evaporation rates and electricity generation data.

Biomass, municipal solid waste, and landfill gas generate a small share of electricity in the US grid using combustion to drive the steam cycle like other thermochemical methods. The biomass is derived from forest residues and other agricultural waste products that are not irrigated[28], so the fuel cycle for biomass and municipal waste power plants consume no water. Water is consumed indirectly for biomass collection and transportation to power plants. Wu and Peng [28] indicated that 2.30 L per kWh are consumed in biomass and municipal waste power plants for cooling.

Geothermal power plants generate electricity in the US grid using flash steam, enhanced geothermal steam, and binary cycle technologies. Flash steam plants extract high temperature, high pressure water from deep underground and release it to a chamber where it is vaporized and used to drive the steam cycle. Enhanced geothermal steam plants inject supplemental water into geothermal reservoirs that is vaporized, collected at the surface, and then used to drive the steam cycle. Binary cycle plants bring warm water to the surface and use it to vaporize a second fluid with a lower boiling point. The other fluid is then used to drive a turbine and generate electricity. Clark *et al.* [36] performed a utility-scale assessment of water consumption in geothermal power plants in the US. They indicated that dry-cooled geothermal plants consume 0.15 L of water per kWh for dust control, maintenance, and domestic use. Dry cooling is commonly used in the US because most geothermal plants are located in arid regions. Clark *et al.* [36] indicated that 2.6 - 14.4 L of water per kWh with a mean value of 9.1 L per kWh are used in wet-cooled geothermal flash power plants, while 5.7 - 17.4 L of water per kWh with a mean value of 6.4 L per kWh are used in wet-cooled geothermal binary power plants. Water consumption in enhanced geothermal power plants depends on the loss rate of the water injected to generate steam. Clark *et al.* [36] estimated that 3.6 L of water per kWh are consumed for enhanced geothermal power plants based on a 5% loss rate.

Wind and solar power plants have no fuel cycle or associated water consumption. Because the electricity generation technologies do not use heat, wind and solar photovoltaic power plants also require no water for cooling. According to Meldrum *et al.* [29], 0.004 L of water per kWh are consumed in wind power plants for cleaning. Concentrated solar power plants utilize dish stirlings, troughs, and other light-concentrating devices to capture solar energy and drive the steam cycle and thus require water for cooling. Estimates from Meldrum *et al.* [29] were aggregated to 0.98 L of water per kWh for concentrated solar power plants.

3.5 Compressed Hydrogen Gas

Hydrogen fuel can be generated from a number of different feedstocks including natural gas via steam methane reforming (SMR), electricity via electrolysis, and coal, coke, or a number of different kinds of biomass via gasification. The vast majority of H_2 in the US is produced via SMR, although a small share is also derived from electrolysis primarily in instances when higher purity H_2 is required. Gasification is not currently utilized for large scale H_2 production in the US, although coal gasification is widely used in a few other countries[37].

Large-scale H_2 production presents many scaling and market penetration challenges that would impact the H_2 fuel life cycle. Central production facilities could utilize economics of scaling to improve process efficiency, reduce water usage, and treat air pollutants. Distributed production facilities would not require distribution after the H_2 conversion process. The H2A production model has been developed by the US Department of Energy's (DOE) Hydrogen and Fuel Cells Program to analyze the technical and economic feasibility of large-scale H_2 production in the US[38]. The process parameters and assumptions from the latest H2A production studies form the basis for the H_2 pathways in GREET.

In the SMR process, steam is reacted with natural gas at high temperature to create a synthetic gas (syngas) mixture of carbon monoxide, hydrogen, and carbon dioxide. The carbon monoxide in the syngas is reacted with additional steam exothermically to produce H_2 fuel and carbon dioxide in a water-gas shift reaction. Carbon dioxide and trace amounts of carbon monoxide can be separated from the H_2 fuel using a pressure swing absorber or other appropriate technology. Water in the SMR process is needed both as a feedstock to produce the hydrogen and for process cooling. Because the process water must of good quality, additional water is consumed in the water pretreatment process. As described elsewhere[9], data from the literature and an industry survey revealed that 6.4 - 32.1 L of water are consumed per kg H_2 with an average of 11.7 L per kg H_2 in central SMR production while 21.9 - 28.4 L per kg H_2 with a mean of 15.9 L per kg H_2 are used for distributed hydrogen production via SMR. In the central production case, 23%, 56%, and 21% of the water consumption were associated with water treatment, process water, and cooling water, respectively, while in the distributed case the breakdown was 57% for water treatment and 43% for process water.

In coal gasification, a syngas mixture is generated by reacting the coal feedstock with steam. As in the case of SMR, the carbon monoxide in the syngas is reacted with steam to produce H_2 and carbon dioxide in a water-gas shift reaction that is then separated from the by-products using an appropriate technology. A WCF for coal gasification in central facilities of 31.4 L per kg

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H_2 was developed from a detailed process design[39] as described elsewhere[9]. Approximately 71% of the water consumption was associated with cooling, which was assumed to be performed with wet cooling towers. Other gasification studies of different fuels have indicated that dry or hybrid wet-dry cooling processes are also feasible[40], so the WCF for a facility could hypothetical be reduced to 9.1 L per kg H_2 produced.

Cellulosic biomass can also be gasified to generate a syngas mixture and then converted into H_2 fuel. A number of different feedstocks can be used for H_2 fuel production including herbaceous energy crops such as switchgrass, woody energy crops such as willow and poplar trees, agricultural residues such as corn stover, and forestry residue[41]. A WCF for biomass gasification of 16.3 L per kg H_2 was developed based on a detailed process design for a wood chip gasification facility from the literature[42] as described elsewhere[9]. Approximately 56% of the total water consumption was associated with production of excess steam to drive the reaction. Assuming dry cooling could be economically substituted for wet cooling, the WCF could potentially be reduced to 7.2 L per kg H_2 fuel produced. Water consumption from several cellulosic biomass feedstocks was analyzed including forest residue, farmed switchgrass, and willow trees. Production of these biomass feedstocks was assumed to require no irrigation.

In electrolysis, H_2 fuel is generated by splitting water into oxygen and hydrogen gases using electrical energy. Impurities in the water lead to unwanted by-products, so the water must be treated initially to high quality levels using a membrane and/or ion exchange process. Water is consumed in during pre-treatment, electrolysis, and cooling processes. As described elsewhere[9], an industry survey indicated that 30.2 and 25.7 L of water are consumed per kg H_2 for central and distributed electrolysis.

4 Results and Discussion

The latest data in GREET 2014 were used with a range of WCFs to estimate the significance of the various processes to the life cycle water consumption associated with each transportation fuel pathway. The following sections describe the results and the implications for transportation fuel and water resource sustainability. Details of the analysis appear in the supplementary information.

4.1 Petroleum Gasoline and Diesel Life Cycle Water Consumption

Petroleum refineries utilize a combination of fuels, electricity and hydrogen for processing crude oil into finished products. Each of these process inputs carries embedded water consumption, which contributes to the water consumption associated with the finished products. The contribution of the recovery operations, refinery processes, and these other process inputs were analyzed as shown in Figure 4. The electricity used in both recovery operations and in the refinery constitute 19.9% and 17.6% of the gasoline and diesel life cycle, respectively; processing and transportation fuel consumption represent 10.9% and 6.4% of the gasoline and diesel life cycle water consumption. Previous water consumption analyses of transportation fuels[7,8] have ignored water embedded in these intermediate resources. Gasoline has more impact than diesel due to the use of more intermediate resources (and associated embodied water) in processing despite having higher process water consumption requirements. These results illustrate the importance of the water consumed in these resources to the overall water consumption burden of conventional petroleum fuels.

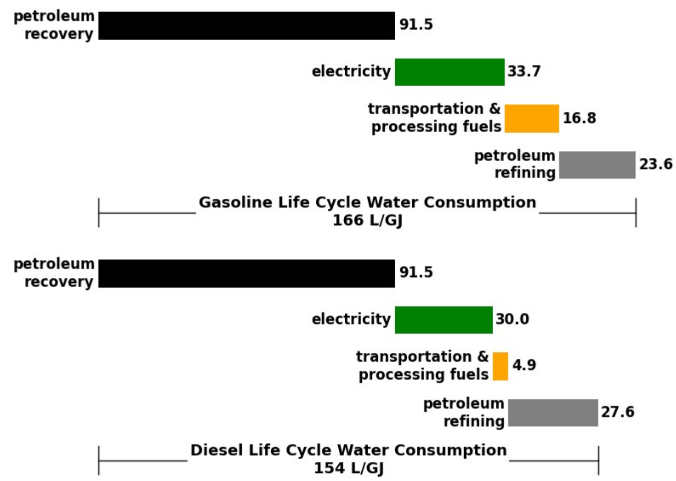

Fig. 4 Petroleum gasoline and diesel life cycle water consumption breakdown.

4.2 Biofuel Irrigation Water Consumption Variability

The water consumption life cycle for biofuels is dominated by irrigation water consumed in the feedstock production. The water consumption intensity of a field crop in a given year is a function of many variables including expected price, climate, irrigation water availability, and technological improvements in irrigation distribution systems and crop drought resistance. Figure 5 shows a plot of the aggregated corn and soybean WCFs for each census year. To investigate the significance of climate variability on water consumption, annual precipitation totals for the Corn Belt and the Soybean Belt were taken from the National Climate Data Center (NCDC) Climate at a Glance Dataset[43]. The state of Ohio on the Eastern end of the Corn Belt is a major producer of both corn and soybeans with 4.2% and 6.9% of 2012 production totals, respectively, despite accounting for less than 0.1% of the aggregated water consumption for both corn and soybeans in 2012 due to its temperature climate. The Ohio climate (with an average annual precipitation from 1900 to 2001 of 38.22[43]) was assumed to be representative of a baseline case for rain-fed corn and soybean production. The water deficit relative to the Ohio average for both the Corn and Soybean Belts was computed for each census year as shown in Figure 5. In the case of corn, the precipitation and associated water consumption factor explained the majority of the variability in the data ($r^2 = 0.62$). However, for soybeans the precipitation deficit was weakly correlated with the water consumption ($r^2 = 0.14$). Land use changes from soybean to corn production may explain the increasing trend in soybean water consumption intensity. As shown in Figure 5, corn acreages increased dramatically between 2002 and 2007 to meet the RFS mandate and increased again in 2012, while soybean production

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dropped in 2007 and then increased in 2012. It is possible that increases in corn acreage displaced soybeans to marginal land with higher water consumption intensity. Corn planted acreages were highly correlated with the soybean water intensity ($r^2 = 0.86$).

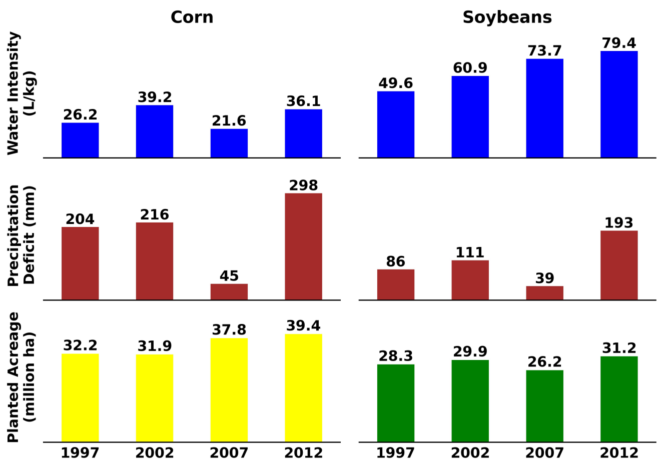

Fig. 5 Impacts of precipitation, land use change, and technological progress on irrigation water consumption.

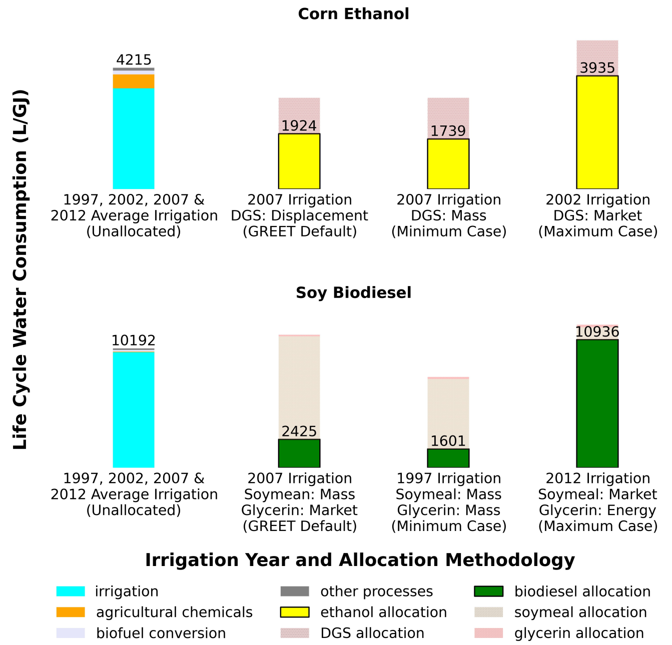

Fig. 6 Variability in US average corn ethanol and soy biodiesel life cycle water consumption associated with seasonal variability and allocation methodology.

4.3 Corn Ethanol and Soy Biodiesel Life Cycle Water Consumption

The US average life cycle water consumption for corn ethanol was estimated using production and irrigation data from each combination of the four censuses and the allocation methodologies. The significance of each individual process in the corn ethanol production was also analyzed without any allocation using the average of the four censuses as shown in Figure 6. As expected, irrigation accounted for the largest portion of the total water consumption at 77.5%, followed by agricultural chemical production at 15.1% and biofuel conversion at 4.2%. The remaining 3.1% was associated with water embedded in transportation and processing fuels, electricity, etc. The production of intermediates including agricultural chemicals and other processing fuels accounts for almost 20% of the life cycle water consumption. This result highlights the importance of these intermediate products in life cycle accounting. A substantial amount of this water was traced to limestone mining, which uses over 80,000 L per tonne of $CaCO_3$ produced[44]. Due to its significance in the life cycle, these findings imply that a more detailed investigation of water consumption in limestone mining is warranted.

The default allocation methodology in GREET 2014 is displacement of a combination of corn, soymeal, and urea for the DGS that are co-produced in corn ethanol refineries based on a previous study[25]. The average irrigation WCF for the four censuses and an allocation based on the displacement method were used to compute the life cycle water consumption for corn ethanol as shown in Figure 6 and described in detail in the supplementary information. Of the four allocation methodologies, the mass basis provided the greatest allocation to the DGS (45.2%), while the market basis provided the least allocation (23.8%). As shown previously in Figure 3, the irrigation WCF for corn farming was greatest in 2002 and least in 2007. Among the combinations of irrigation WCFs and allocation methodologies, the 2007 irrigation WCF with a mass-based allocation to the DGS minimizes the life cycle water consumption in the ethanol, while the 2002 irrigation WCF with a market-based allocation to the DGS maximizes the life cycle water consumption in the ethanol as shown in Figure 6. These two extremes represent a range of 1739 to 3935 L per GJ for the water consumption intensity of corn ethanol in the United States. Improved technologies could decrease the water intensity in the future, although increased corn farming in arid regions and climate change could also increase the water intensity.

As in the case of corn ethanol, the data from each of the four censuses and a number of different allocation methodologies could be used to estimate the life cycle water consumption for soy biodiesel. The contributions of the individual processes in the soy biodiesel production pathway were analyzed without any allocation using the average of the four censuses as shown in Figure 6. Irrigation accounted for over 97% of the life cycle water consumption while the biodiesel conversion process, agricultural chemicals, and other intermediate products representing 1.3%, 0.4%, and 1.2% of the total. Soybean farming uses no limestone and less nitrogen than corn farming but requires more irrigation water per unit production on average. For these reasons, irrigation is a much larger fraction of the life cycle water consumption of soy biodiesel relative to corn ethanol.

The default allocation methodologies in GREET 2014 for soymeal and glycerin are the mass basis and market basis, respectively, based on a previous study[25]. The average irrigation WCF from the four censuses and the default methodologies were

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used to allocate the water consumption burden to the soymeal and glycerin as shown in Figure 6. The mass basis provides the greatest allocation to both the soymeal (77.4%) and the glycerin (2.4%) among the allocation methodologies. The market basis provides the least allocation to the soymeal (6.2%), while the energy basis provides the least allocation to the glycerin (0.8%). The irrigation WCF associated with soybean farming has increased each year from 1997 to 2012 as shown in Figure 6. Thus the minimum life cycle water consumption estimate is derived from the 1997 irrigation WCF with a mass basis for soymeal and glycerin, while the minimum life cycle water consumption is derived from the 2012 irrigation WCF with the market based allocation for soymeal and an energy-based allocation for glycerin. These two extreme cases provide a range of 1601 to 10936 L of water consumed per GJ of soy biodiesel produced as shown in Figure 6. As in the case of corn ethanol, the water intensity of soy biodiesel could either increase or decrease in the future depending on technological progress and increased demand that could push soybean farming into more arid regions requiring more irrigation.

4.4 Compressed Natural Gas Life Cycle Water Consumption

Figure 7 shows the breakdown of the estimated life cycle water consumption for CNG derived from the conventional and shale formations using the recovery estimates from Clark *et al.* [26]. The most significant process in the life cycle is compression, which is associated with the water used to produce electricity from the US grid. Recovery represents less than 1% of the life cycle for conventional gas, while compression accounts for over 75%. The water consumption in the recovery process accounted for between 6% and 34% of the life cycle water consumption for the shale gas formations. The significance of recovery to the life cycle is interesting given the intense political debate over the impacts of new hydraulic fracturing technologies on water resources[45–47]. Although shale gas recovery consumes more than thirty times the water of conventional recovery operations, from a life cycle perspective the increase is generally less than that of the electricity used in the gas compression. The large amount of water consumed initially accounts for less than half of the water consumed throughout the entire shale gas pathway.

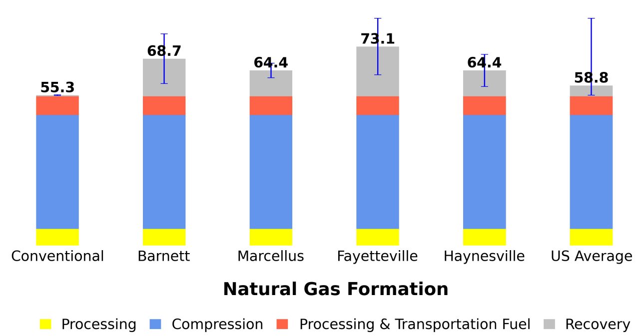

Fig. 7 Life cycle water consumption (L/GJ) of CNG derived from different formations.

4.5 Life Cycle Water Consumption Associated with Electricity Generation Technologies

The life cycle water consumption per kWh of electricity generated for power generation categories is shown in Figure 8. The range of values for each category is intended to reflect differences in energy generation and cooling technologies with the exception of hydropower, where the difference reflects the allocation range. In the cases of biomass, municipal waste, and wind technologies, there are no major technological differences that would impact water consumption so no range is provided.

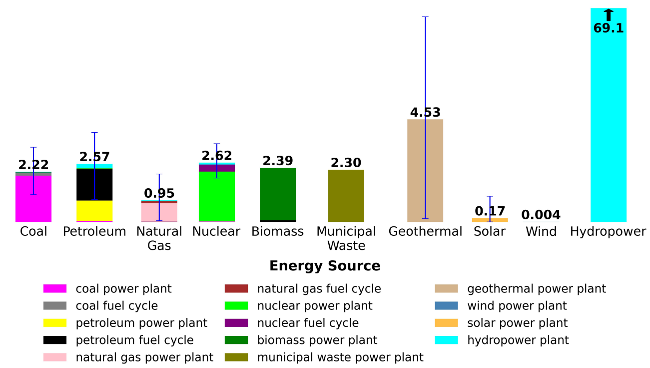

Fig. 8 Life cycle water consumption (L/kWh) associated with electric power generation facilities.

The life cycle water consumption associated with hydropower generation is over an order of magnitude greater than the other generation pathways. The estimate used in this analysis[30] is based on total evaporation from hydropower-producing reservoirs divided by total power generation. This approach suffers two primary limitations: failure to account for natural water consumption from background evapotranspiration on land surface that would occur regardless of the presence of the dam and a failure to allocate water consumption amongst different purposes including navigation, municipal and agricultural use storage, fishing, and recreation. Because of the significance of electricity on other pathways and the larger implications of the tradeoff of water for electricity, the relationship between water consumption and hydroelectric power generation should be investigated in more detail in the future.

The thermoelectric facilities (coal, petroleum, natural gas, nuclear, biomass, and municipal waste) consume similar quantities of water across their life cycles. The amount of water consumed depends on the quantity of heat to be dissipated and the cooling technology. The ranges for each technology are intended to reflect differences in the fuel cycle and the cooling technology shown in Figure 8 and are not representative of variability in individual facilities. With the exception of petroleum, the water consumption life cycle is dominated by the power generation process. However, the water used in the fossil and nuclear fuel cycles is a significant portion of the life cycle water consumption (coal: 7.8%, natural gas: 13.1%, nuclear: 16.1%, petroleum: 64.8%, biomass: 3.6%).

The majority of the variability in each of the thermoelectric facilities is associated with the cooling technology. Once-through cooling systems withdraw large quantities of water but return the

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water to the resource where it was withdrawn at a higher temperature. The water consumption associated with once-through cooling systems is intended to represent the increased evaporation from increased temperature downstream of the facility. The source of these estimates in the literature is not entirely clear, however, and warrants further investigation. Once-through cooling is the most economical option, although it presents the greatest impact on local ecology and is increasingly not permitted [13]. In recirculating cooling systems, the waste heat from power generation is dissipated to the atmosphere in a cooling tower or using an artificial pond thereby consuming more water than once-through systems. Dry cooling technologies can also be used to transfer heat to the atmosphere; however, these technologies decrease energy efficiency and increase capital costs.

In the coal pathway, over 92% of the water consumption occurs in the electricity generation process. The water consumption in the coal fuel cycle is highly uncertain/variable, however, and using the high end estimate for coal mining associated with dewatering [27] increases the life cycle water consumption by over 20% from 2.22 to 2.70 L per kWh. Further characterization of coal mining water consumption is warranted. As discussed previously, the petroleum fuel cycle consumes large quantities of water during the recovery stage. A relatively large share of oil-based power generation comes from internal combustion engines and turbines (23%) that do not consume water. However, these processes are less thermodynamically and economically efficient. A large share of natural gas-based generation is derived from combined cycle plants that are more energy efficient and as a result tend to consume less water.

Geothermal power exhibits the greatest variability in water consumption estimates amongst the pathways. Dry cooling is common for geothermal power, and each of the three geothermal technologies have a very different water requirement. In enhanced geothermal facilities, the make-up water requirements depend on the formation characteristics. In this analysis, estimates were derived primarily from Clark *et al.* [36]. That study provided an important collection of water consumption data; however, more information is needed to quantify technology shares, understand the impacts of spatial variability in the data, and quantify the long-term strategy for water production and sustainability associated with geothermal technologies.

Wind and solar photovoltaics consume a negligible amount of water relative to other electricity generation pathways. In regions where water availability is limited, the limited water requirements (both withdrawals and consumption) make these technologies are particularly attractive.

4.6 Water Consumption Embedded in Electricity Generation Mixes

Electricity generation in the lower 48 states in the US is regulated by eight regional entities: the Florida Reliability Coordinating Council (FRCC), Midwest Reliability Organization (MRO), the Northeast Power Coordinating Council (NPCC), the ReliabilityFirst Corporation (RFC), the SERC Reliability Corporation (formerly Southeast Electric Reliability Council, SERC), the Southwest Power Pool (SPP), the Texas Reliability Entity (TRE), and the Western Electricity Coordinating Council (WECC). The water consumption associated with power generated within each of the regional mixes, the US average, and the state of California (CA) were computed using GREET to analyze regional differences in the water intensity of electricity. The results are shown in Figure 9 and include water associated with electric power loss due to a grid efficiency of 93.5%.

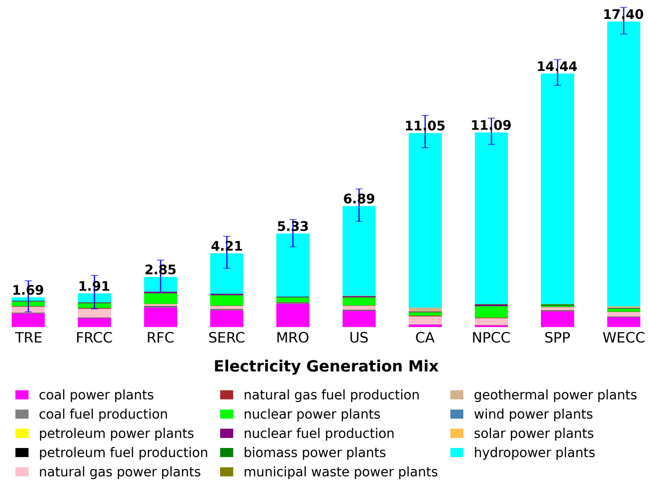

Fig. 9 Life cycle water consumption (L/kWh) from various US electricity generation mixes.

The water consumption associated with evaporation from artificial reservoirs used for hydropower dominated the US and CA electric power water consumption, accounting for 74% and 90% of the total, respectively. The water consumption per unit power generated from hydropower facilities likely varies significantly in each region; however, analyzing this variability was outside the scope of this analysis. The results indicate the importance of further characterization of these relationships and of the allocation methodology. The largest share of the life cycle water consumption from the thermoelectric pathways in the US mix was coal power plants (13.2%), followed by nuclear power plants (6.7%) and natural gas power plants (3.4%). The US average value of 6.89 L per kWh is similar to the previous estimate of 7.5 L per kWh by Torcellini *et al.* [30]. The range associated with the US average (6.12 - 7.86 L per kWh) and other mixes reflects the aggregated ranges from the min and max values in each pathway shown in Figure 8. The regional mix with the highest water intensity was WECC at 17.40 L per kWh. The WECC includes the Rocky Mountains and West Coast states. The WECC region produces more hydropower due to its mountainous landscape. The least water intense region was the TRE (Texas) at 1.69 L per kWh.

4.7 Water Consumption Associated with Compressed Hydrogen Gas Production Life Cycles

The life cycle water consumption for each H_2 fuel production pathway including the contributions of the conversion process, the process electricity, natural gas, gasification feedstocks, and the electricity used for compression are shown in Figure 10. The

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distributed electrolysis pathway exhibited by far the greatest life cycle water consumption due to the water embedded in the electricity, which can be traced in large part back to evaporation in reservoirs used for hydropower as discussed previously. However, central wind electrolysis-based H_2 fuel has the smallest water consumption impact since water is essentially only needed to supply the hydrogen atoms in the H_2 fuel (assuming that wind-based electricity is also used for compression).

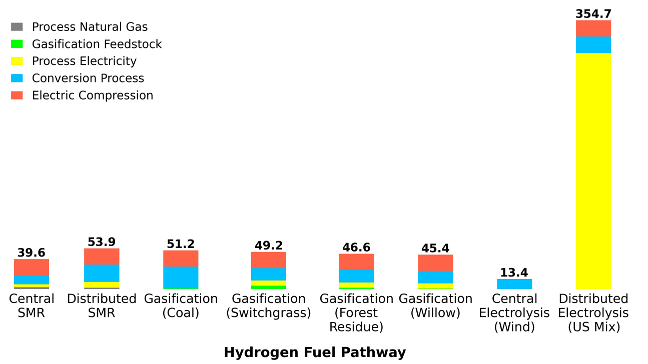

Fig. 10 Life cycle water consumption (L/kg H_2) associated with compressed H_2 fuel generation pathways.

The water consumption embedded in the electricity used for processing and compression accounted for approximately half of the life cycle water consumption for all pathways based on SMR and gasification. The majority of the remaining water consumption was associated with direct usage for cooling and processing in the H_2 fuel conversion. Assuming that dry cooling could economically be used in place of cooling towers in the fuel conversion processes, there is potential to decrease the water consumption impacts of SMR, coal and biomass gasification by approximately 30%, 40%, and 20%, respectively. Water consumption associated with the fuel cycle was relatively insignificant for the SMR and gasification pathways. As shown in Figure 10, the life cycle water consumption requirements associated with gasification pathways (coal, switchgrass, willow, and forest residue) were not substantially different.

Distributed generation systems are expected to be less water and energy efficient due to scaling and thus would consume more water. The results of this analysis indicate that a distributed SMR would increase the life cycle water consumption requirements by 40% from 39.6 L per kg H_2 to 53.9 L per kg H_2. However, distributed systems offer hidden advantages in transportation and delivery that were not included in this analysis.

4.8 Comparison of Different Fuels and Implications

The fuel production pathways described in the previous sections were compiled into functional units of L of water per GJ to compare the impacts of their life cycle on water consumption on a consistent basis as shown in Figure 11. The fossil fuel pathways generally have the least impact on water resources. Petroleum-based gasoline and diesel consume slightly more water than CNG because of the water consumption associated with enhanced recovery technologies. Despite public concern over the large amount of water associated with shale gas recovery, this analysis shows that the impact on a per unit energy basis is relatively small.

The corn and soy biofuel production exhibit the largest water consumption impact amongst the fuels with the exception of electricity from hydropower. The water consumption associated with irrigation for a particular crop may be much less than or much greater than the US average presented in Figure 11. The RFS biofuel regulations are based on pathways that do not account for regional differences in resource consumption. These differences may have a large impact on water consumption; e.g., corn from California requires far more irrigation than corn grown in the Eastern US. Given the relationships between energy and water (i.e., energy is used to produce water and water to produce energy), the importance of water consumption associated with bioenergy production in arid regions brings up larger questions of economic sustainability that are in need of deeper investigation. Additionally, the energy costs associated with these irrigation practices may have an impact on emissions life cycles.

The electricity generation pathways have both the smallest (wind) and largest (hydropower) impact on water resources consumption. The thermoelectric power generation pathways consume more than twice the water of fossil fuel pathways primarily for waste heat dissipation. Dry cooling technologies can be employed in power generation that would bring electricity water consumption estimates into a similar range as the baseline fossil fuels, although these technologies carry both a capital and energy penalty. As shown previously in Figure 9, over 70% of this water is associated with evaporation from hydropower reservoirs. Because electricity is a fundamental input for essentially all the other pathways, it is obvious that a detailed analysis of the water consumption associated with hydropower is in need of further characterization.

The pathways for centralized production of H_2 fuel showed similar water consumption footprints to the thermoelectric pathways on an energy basis. A large amount portion of the total is associated with water embedded in electric compression than can be traced to hydropower generation. Processing and cooling constitute the other major contributors to the H_2 pathways, so it is not surprising that their water consumption costs are similar to alternative electric power generation pathways.

The allocation methodology strongly influences the results for both corn ethanol and soy biodiesel. The market basis allocates the most water consumption to the fuels, while the mass basis allocates the least. A dry year with a market-based allocation can more than double the water consumption of the average year with other allocation methods. Allocation of the water consumption associated with hydropower reservoirs also significantly influences the electricity pathway.

The fuel economies summarized in the supplementary information were used to extend the water consumption to units of L per 100 km for light-duty vehicles as shown in Figure 12. The range is intended to represent technological and methodological (allocation) differences rather than the variability in a particular fuel to provide the feasible near-term changes for each technology. Over half of the water embedded in the baseline fuel (E10) is

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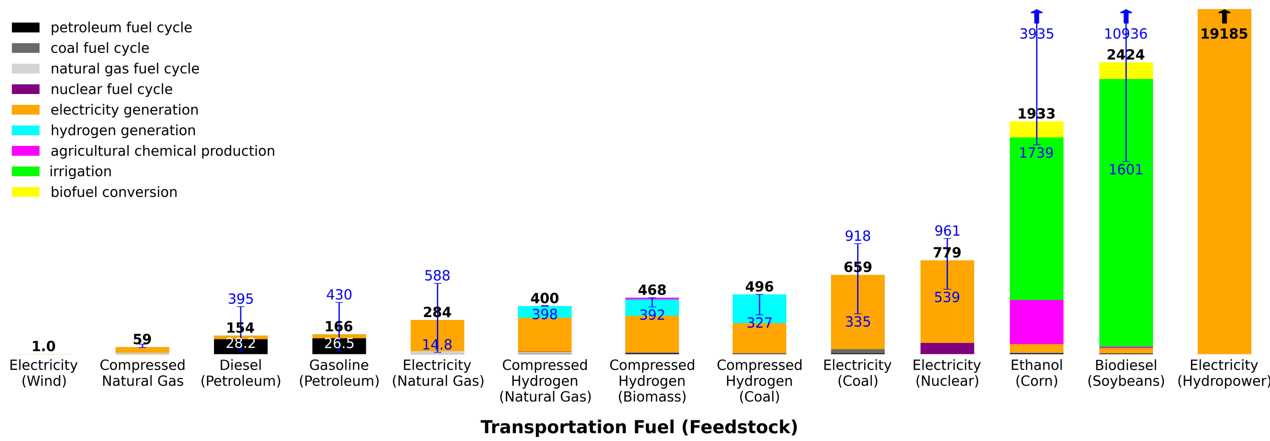

Fig. 11 Life cycle water consumption (L/GJ) associated with transportation fuel pathways.

associated with the ethanol even though it is only 10% of the fuel volume. Soy biodiesel consumes over 15 times as much water on a per km basis as petroleum diesel. In B20 diesel over 90% of the water consumption is associated with soybean irrigation. The CNGV exhibits the lowest burden on water consumption amongst the fuel pathways. The majority of the water is associated with electric compression of the fuel and not with the recovery process. Reforming the natural gas to H_2 for use in a FCEV more than doubles the water consumption intensity of transportation. Coal or biomass-based gasification in central facilities is expected to consume a similar amount of water as the SMR-based H_2 pathway. Electricity-based transportation exhibits high variability depending on the regional electricity mix. The fuel cycle has a relatively minor impact on the water consumption associated with electricity relative to power generation. The BEV is estimated to consume almost twice the water as the E10 baseline on average in the US. The larger implications of these estimates are unclear, however, since they are derived heavily from region-specific hydropower and irrigation estimates. In the TRE mix where there is very limited hydropower generation, the water consumption associated with 100 km of transportation is only 24.7 L which is similar to petroleum gasoline and diesel. A distributed electrolysis-based H_2 infrastructure for FCEVs has more than twice the water intensity per km as a distributed electricity-based infrastructure associated with BEVs. The difference is largely attributable to the energy inefficiency of the electrolysis process and the gas compression.

5 Conclusions

Large-scale shifts in transportation technologies to alternative fuels will have a significant impact on water resources. This study has highlighted the importance of the life cycle approach to water consumption analysis by analyzing the impacts of the full supply chain for various alternative fuels and vehicles on water resources. This analysis provides a baseline for future studies of regional water consumption, alternative vehicle market penetration, and allocation methodologies that will be needed to understand the implications of changes to the transportation infrastructure on water resources or assessment of other emerging energy production technologies such as alternative biofuels. Indirect water consumption associated with transportation and intermediate energy consumption is an important part of the life cycle for petroleum and natural gas fuels. Moves towards alternative fuels appear to have a greater impact on water resources than fossil fuels. Energy and environmental policy should consider the implications of alternative vehicles on water resources when planning changes to the transportation and energy infrastructure. The values outlined in this study should not be interpreted as absolute inputs for specific projects since many processes (e.g., agriculture, mining) exhibit high degrees of spatial and temporal variability. Actual projects must therefore be evaluated on their specifics and not on national or regional averages.

This study revealed a few areas in need of further research in the future. A comprehensive analysis of the regional variability and co-product allocation associated with hydropower generation is needed. A comparative analysis should be performed of the value of the electricity produced by reservoirs used primarily for hydropower versus the excess water consumed. Construction of excess water storage in large river networks may inefficiently allocate water for hydropower that could be used for other purposes downstream. The biomass feedstock for individual biorefineries may be produced locally or come from distant locations by rail. These differences will change the life cycle environmental impacts (both water and energy) of the fuel. The water consumption associated with secondary and tertiary petroleum recovery operations is based on a limited number of estimates of water injection rates and is in need of further characterization. Inconsistencies in state-level reporting requirements of injection into wells used for petroleum recovery complicate the analysis of petroleum water intensity.

6 Acknowledgements

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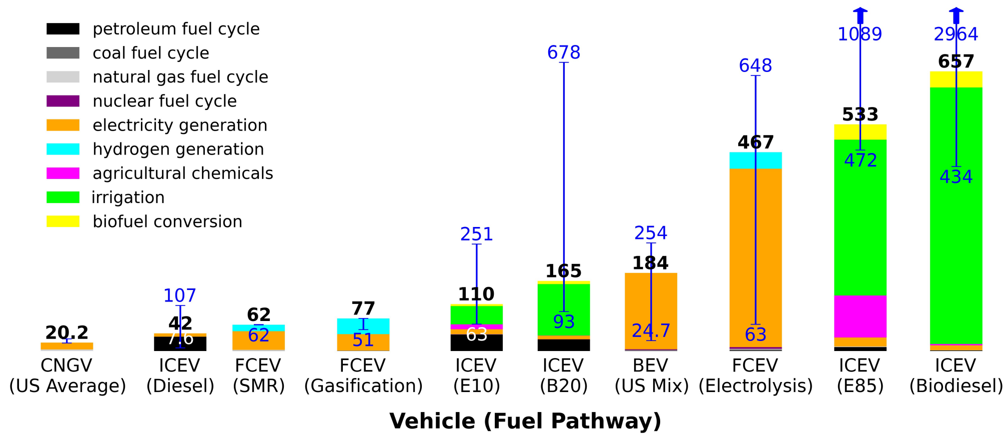

Fig. 12 Life cycle water consumption (L/100 km) associated with transportation in light-duty vehicles from select pathways.

References

1 Energy Information Administration, *Annual Energy Outlook, 2014*, United States Department of Energy Technical Report EIA-0383(2014), 2014.

2 US Environmental Protection Agency, *Renewable Fuel Standard Program*, 2007, `http://www2.epa.gov/renewable-fuel-standard-program`.

3 B. Eickhout, G. J. van den Born, J. Notenboom, M. v. Oorschot, J. Ros, D. Van Vuuren, H. Westhoek *et al.*, *Local and global consequences of the EU renewable directive for biofuels: Testing the sustainability criteria*, Netherlands environmental assessment agency (mnp) technical report, 2008.

4 California Air Resources Board, *Low-carbon fuel standard*, 2009, `http://www.arb.ca.gov/fuels/lcfs/lcfs.htm`.

5 M. Wang, *GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, Development, Use, and Results*, Argonne National Laboratory (ANL), Argonne, IL (United States) Technical Report ANL/ESD-39, 1999.

6 M. M. Aldaya, A. K. Chapagain, A. Y. Hoekstra and M. M. Mekonnen, *The water footprint assessment manual: Setting the global standard*, Routledge, 2012.

7 C. W. King and M. E. Webber, *Environmental Science & Technology*, 2008, **42**, 7866–7872.

8 C. D. Scown, A. Horvath and T. E. McKone, *Environmental science & technology*, 2011, **45**, 2541–2553.

9 D. J. Lampert, C. Hao, Z. Wang, M. Wu, J. Dunn, J. Sullivan, A. Elgowainy and M. Wang, *Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels*, Argonne National Laboratory (ANL), Argonne, IL (United States) Technical Report ANL-ESD-15/27, 2015.

10 A. N. Laboratory, *Argonne GREET Model*, 2014, `https://greet.es.anl.gov`.

11 G. H. Davis, A. L. Velikanov *et al.*, *Unesco technical papers in hydrology*, Unesco, 1979, ch. 17, pp. 1–33.

12 J. L. Bush, D. P. Helander *et al.*, *Journal of Petroleum Technology*, 1968, **20**, 933–943.

13 P. H. Gleick, *Annual Review of Energy and the environment*, 1994, **19**, 267–299.

14 B. Royce, E. Kaplan, M. Garrell and T. Geffen, *Minerals and the Environment*, 1984, **6**, 44–53.

15 M. Wu and Y. Chiu, *Consumptive water use in the production of ethanol and petroleum gasoline-2011 update*, Argonne National Laboratory (ANL) Technical Report ANL/ESD/09-1-Update, 2011.

16 B. R. Scanlon, R. C. Reedy and J.-P. Nicot, *Environmental science & technology*, 2014, **48**, 12386–12393.

17 A. Elgowainy, J. Han, H. Cai, M. Wang, G. S. Forman and V. B. DiVita, *Environmental science & technology*, 2014, **48**, 7612–7624.

18 M. C. Johnson, I. Palou-Rivera and E. D. Frank, *Algal Research*, 2013, **2**, 426–436.

19 National Agricultural Statistics Service, *2012 Census of Agriculture*, 2014.

20 National Agricultural Statistics Service, *2007 Census of Agriculture*, 2007.

21 National Agricultural Statistics Service, *2002 Census of Agriculture*, 2004.

22 National Agricultural Statistics Service, *1997 Census of Agriculture*, 1999.

23 Y.-W. Chiu and M. Wu, *Environmental science & technology*, 2012, **46**, 9155–9162.

24 H. Shapouri, J. A. Duffield and M. Q. Wang, *The energy balance of corn ethanol: an update*, United States Department of Agriculture, Economic Research Service Technical Report Agricultural Economic Report No. 814, 2002.

25 M. Wang, H. Huo and S. Arora, *Energy Policy*, 2011, **39**, 5726–5736.

26 C. E. Clark, R. M. Horner and C. B. Harto, *Environmental science & technology*, 2013, **47**, 11829–11836.

27 E. A. Grubert, F. C. Beach and M. E. Webber, *Environmental Research Letters*, 2012, **7**, 045801.

28 M. Wu and J. Peng, *Developing a tool to estimate water with-*

Energy & Environmental Science Accepted Manuscript

drawal and consumption in electricity generation in the United States., Argonne national laboratory (anl) technical report, 2011.

29 J. Meldrum, S. Nettles-Anderson, G. Heath and J. Macknick, *Environmental Research Letters*, 2013, **8**, 015031.

30 P. A. Torcellini, N. Long and R. Judkoff, *Consumptive water use for US power production*, National Renewable Energy Laboratory Technical Report NREL/CP-550-35190, 2003.

31 United States Army Corps of Engineers, *National Inventory of Dams*, 2015, http://nid.usace.army.mil/.

32 United States Environmental Protection Agency, *Emissions & Generation Resource Integrated Database*, 2015, http://www2.epa.gov/energy/egrid.

33 R. K. Farnsworth and E. S. Thompson, *Mean monthly, seasonal, and annual pan evaporation for the United States*, US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 1983.

34 W. E. Sanford and D. L. Selnick, *JAWRA Journal of the American Water Resources Association*, 2013, **49**, 217–230.

35 M. Pasqualetti and S. Kelley, *Phoenix, Arizona: Arizona State University School of Geographical Sciences*, 2008.

36 C. E. Clark, C. B. Harto, J. N. Schroeder, L. E. Martino and R. M. Horner, *Life Cycle Water Consumption and Water Resource Assessment for Utility-Scale Geothermal Systems: An In-Depth Analysis of Historical and Forthcoming EGS Projects*, Argonne National Laboratory (ANL), Argonne, IL (United States) Technical Report ANL/EVS/R-12/8, 2013.

37 Y. Man, S. Yang, D. Xiang, X. Li and Y. Qian, *Journal of Cleaner Production*, 2014, **71**, 59–66.

38 US Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cells Program, *DOE Hydrogen and Fuel Cells Program: DOE H2A Analysis Production Case Studies*, 2015, http://www.hydrogen.energy.gov/h2a_prod_studies.html.

39 L. K. Rath, *Assessment of hydrogen production with CO2 capture volume 1: baseline state-of-the-art plants*, National Energy Technology Laboratory Technical Report DOE/NETL-2010/1434, 2010.

40 T. J. Tarka, *Production of Zero Sulfur Diesel Fuel from Domestic Coal: Configurational Options to Reduce Environmental Impact*, National Energy Technology Laboratory Technical Report DOE/NETL-2012/1542, 2011.

41 M. Ni, D. Y. Leung, M. K. Leung and K. Sumathy, *Fuel processing technology*, 2006, **87**, 461–472.

42 P. Spath, A. Aden, T. Eggeman, M. Ringer, B. Wallace and J. Jechura, *Biomass to hydrogen production detailed design and economics utilizing the BCL indirectly heated gasifier*, National Renewable Energy Laboratory Technical Report TP-510-37408, 2005.

43 National Climate Data Center, *Climate at a Glance: Time Series*, 2015, http://www.ncdc.noaa.gov/cag/.

44 U. of Tennessee Center for Clean Products, *Limestone Quarrying and Processing*, Natural stone council technical report, 2008.

45 R. W. Howarth, A. Ingraffea and T. Engelder, *Nature*, 2011, **477**, 271–275.

46 M. Jiang, W. M. Griffin, C. Hendrickson, P. Jaramillo, J. VanBriesen and A. Venkatesh, *Environmental Research Letters*, 2011, **6**, 034014.

47 A. Vengosh, R. B. Jackson, N. Warner, T. H. Darrah and A. Kondash, *Environmental science & technology*, 2014, **48**, 8334–8348.

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