Program Record (EERE Offices of Fuel Cell and Vehicle Technologies)	
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Title: Water Consumption for Light-Duty Vehicles' Transportation Fuels	
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Approved by: Pat Davis (10/2014), Sunita Satyapal	**Date:** 02/19/2016

Item

This record documents the results of a life-cycle analysis of the amount of surface and ground water retrieved from the source and consumed (i.e., does not include rain water) in the production of transportation fuels for use in light-duty vehicles (LDVs) in the United States, assuming current technology for fuels production, electricity, and vehicles. Water consumption ranges from 10 to 48 gallons per 100 miles driven (gphm) for today's gasoline internal combustion engine LDVs (ICEVs) on E10[1] (9 to 28 for pure gasoline), 7 to 31 for battery electric vehicles (BEVs) running on today's grid electricity, less than 1 for BEVs on solar photovoltaic (PV) electricity, 5 to 42 for fuel cell electric vehicles (FCEVS) on hydrogen from various production pathways, and 34 to 97 for FCEVs on hydrogen from electrolysis using today's grid electricity. For gasoline ICEVs on corn-based E85,[2] a range of water consumption needed for irrigation, with regional variability, results in 12 to 260 gphm.

Description

This analysis estimates water consumption in the transportation fuel/vehicle pathway (Figure 1). Water consumption is defined as water that is taken from a surface or groundwater source and not directly returned to the same source, including evaporative losses[3] (King and Webber 2008). This is distinguished from water "withdrawal," which refers to water that is withdrawn from a surface or groundwater source. Water usage (or water used) is used more generally in the literature and cannot always be assumed to be water consumption or water withdrawal. In this report, water usage is synonymous with water consumption. Likewise, King and Webber define the term "water intensity" as water consumption and withdrawal related to the production of a unit of transportation fuel and its use in vehicles. More specifically, it is defined as "water usage per mile driven" (King and Webber 2008). Although some facilities (mainly electric power plants) in the pathways considered in this analysis use saline water

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[1] Most E10 currently used in the United States is a mixture of 10% corn ethanol and 90% reformulated gasoline blendstock for oxygenate blending (RBOB) by volume. RBOB is a subgrade gasoline designed for blending with ethanol such that the final blend meets all regulatory and fuel specification standards for finished gasoline.

[2] E85 is a term that refers to high-level gasoline-ethanol blends containing 51% to 85% ethanol by volume, depending on geography and season. This analysis assumes that the average ethanol content of E85 is 75% by volume (denatured), following the blending ratio that the U.S. Energy Information Administration (EIA) uses in its Annual Energy Outlook. This analysis assumes a 2% gasoline denaturant by volume for consistency with the Renewable Fuel Standard (RFS) definition of an ethanol equivalent gallon.

[3] Evaporative losses include the additional evaporation that takes place downstream from a facility using water (e.g., when releasing water back to the source and the released water is hotter than water withdrawn from the source).

and/or reclaimed water,[4] this work focuses primarily on water consumption intensities (amount per unit of energy). The water intensities are independent of whether the water is blue, saline, or reclaimed. Although data on the use of blue versus saline or reclaimed water is incomplete, this analysis presents limited statistics on the shares of these types of water for electric power plants.

Water "embedded" in a resource refers to the water that was consumed to produce the resource being used. For example, water "embedded" in the transport of coal to a power plant refers to the water consumed during the production of the diesel fuel used in the truck used to transport the coal. Similarly, water "embedded" in electricity consumption refers to the water that was consumed in the production of electricity (for example to power an electrolyzer).

Unlike greenhouse gases, water consumption has a regional aspect because water is less abundant in some regions than others. A regional analysis can be useful in relating the water intensity of a technology pathway to the region's water availability. However, the scope of this analysis is limited to presenting the median value and a bounding range at the national level. This analysis does not consider the hydrologic cycle.

Pathways analyzed include: gasoline blended with 10% corn ethanol by volume (E10[5] and E85[6]), diesel, natural gas, electricity (U.S. grid and solar photovoltaics), and hydrogen (from natural gas, water electrolysis, biomass, and coal gasification with carbon capture and sequestration). For corn ethanol, we employed corn irrigation information from an Argonne National Laboratory study that drew from USDA surveys conducted in 1998, 2003, and 2008. Based on the assumptions used, the following results for the full fuel cycle were observed:

- In terms of water consumed per unit of fuel energy ("water intensity"), diesel and gasoline without ethanol are comparable, at 3–8 gallons per gasoline-equivalent gallon (gge), but are more water-intensive than compressed natural gas (CNG) or electricity from renewables.
- The water intensity of several hydrogen fuel pathways is within 25% of conventional E10 while a few have higher water intensities (20% to 40% higher than corn E10). Corn-based E85 ethanol, U.S. electricity,[7] and hydrogen from electrolysis with U.S. electricity show higher water intensities per unit of energy than do other fuel production pathways considered.
- When expressed in terms of water consumed per miles driven, water intensity is also a function of the fuel economy. The relative difference in water intensity per gge between U.S. grid electricity and other fuels becomes less when expressed as per miles driven.

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[4] Reclaimed water used for energy or industrial purposes may include municipal treated wastewater, treated water from coal mine pool, or other types of reclaimed water. http://204.154.137.14/technologies/coalpower/ewr/pubs/reclaimed%20water.pdf.

[5] Most E10 currently used in the United States is a mixture of 10% corn ethanol and 90% reformulated gasoline blendstock for oxygenate blending (RBOB) by volume. RBOB is a subgrade gasoline designed for blending with ethanol such that the final blend meets all regulatory and fuel specification standards for finished gasoline.

[6] E85 is a term that refers to high-level gasoline-ethanol blends containing 51% to 85% ethanol by volume, depending on geography and season. This analysis assumes that the average ethanol content of E85 is 75% by volume (denatured), following the blending ratio that EIA uses in its Annual Energy Outlook. This analysis assumes a 2% gasoline denaturant by volume for consistency with the Renewable Fuel Standard (RFS) definition of an ethanol equivalent gallon.

[7] "U.S. electricity" is the average U.S. grid electricity minus hydroelectricity (excluded because it is difficult to allocate evaporative losses between end uses, e.g., recreational boating on reservoirs vs. power production).

Fuel Cycle Steps

This analysis does not consider water associated with plant/infrastructure construction and dismantling.

In Figure 1, “Fuel Materials Extraction or Feedstock Production” refers to: (a) water consumed for the extraction of fossil fuel materials or (b) irrigation water consumed for growing biomass (e.g., corn). For most transportation fuels, “fuel materials” refer to raw materials extracted such as coal, crude oil, natural gas, etc., and feedstock refers to cultivated biomass such as corn. Both fossil fuel materials and biomass feedstock must undergo conversion, refining, or processing into usable fuels.

“Transport of Fuel Materials or Feedstock” involves water consumption embedded in the energy consumed to transport coal, crude oil, corn, or other material to the “Fuel Production” site (e.g., the oil refinery, the biofuels production plant, or the hydrogen production plant). For example, crude oil transportation is primarily through: (a) oil tankers and railcars that mainly use residual oil and diesel fuel, and (b) pipelines using electricity to drive pump motors.

Water consumption for fuel production includes water used directly, e.g., for processing (e.g., refining, reforming, fermentation, or electrolysis), for cooling in the production plant, and water used indirectly, i.e., embedded in the energy input (e.g., electricity or natural gas) required for the fuels production operation. Water embedded in the energy used for fuel transport, delivery, and dispensing (e.g., transporting fuels from refineries to retail stations, pumping fuels into vehicles at retail fueling stations) is the last water consumption subgroup in each pathway.

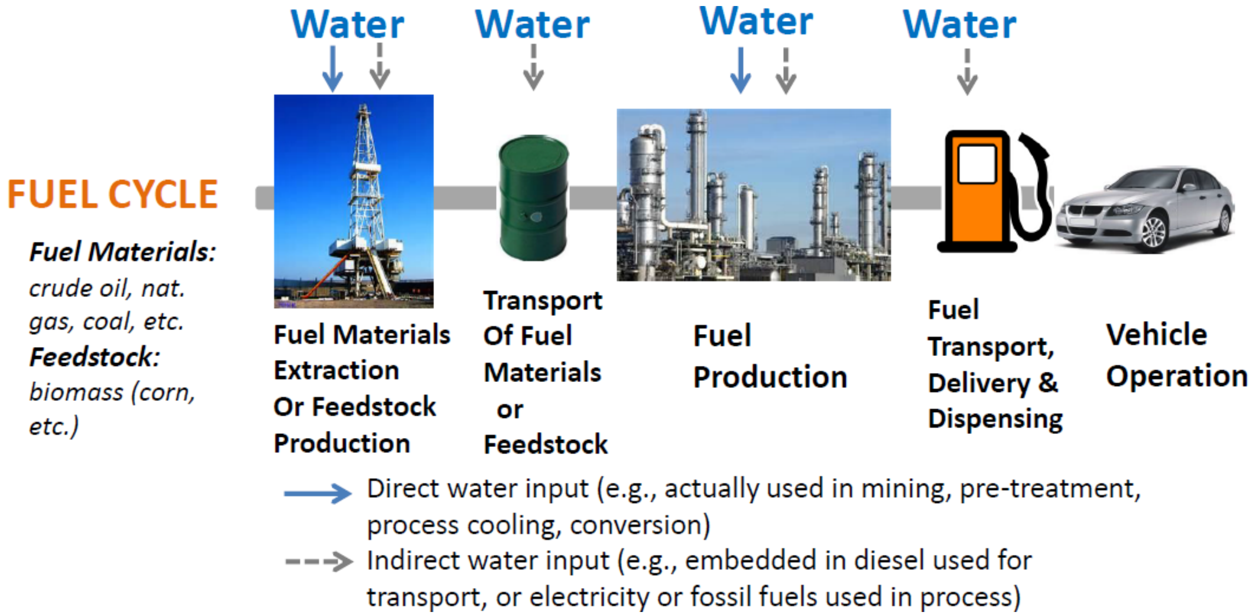

Figure 1. Water consumption in transportation fuel/vehicle Pathway (excludes plant/infrastructure construction and dismantling)

Fuels and Vehicle Pathways

Table 1 describes the transportation fuel/vehicle pathways discussed in this report.

Table 1. Pathways Analyzed (Current Technology)

Pathway	Description
Pure Gasoline - ICEV (for benchmarking)	Internal combustion engine vehicle (ICEV) on gasoline (almost all U.S. gasoline is E10 as of 2013, so this serves as a benchmark to see how various gasoline/ethanol mixtures differ from pure gasoline)
Diesel ICEV	ICEV on diesel from petroleum
Gasol ICEV Corn E10	ICEV on a mixture of 90% petroleum gasoline and 10% corn ethanol (by volume)
Gasol ICEV Corn E85	ICEV on gasoline-ethanol blends containing 75% undenatured ethanol (by volume) from corn grains (51% to 83% depending on geography and season)
CNG ICEV	ICEV on compressed natural gas (CNG)
BEV Grid Electricity	Battery electric vehicle (BEV 100) using average U.S. grid electricity (100-mile nominal range, 70-mile realistic, on-road range)[8]
BEV Solar PV	BEV 100 on photovoltaic electricity
FC Distrib N.Gas SMR	Fuel cell hybrid electric vehicle (FCEV) on H_2 produced from natural gas via steam methane reforming (SMR) at a retail fueling station that is the counterpart of a gasoline station
FC Distrib Electrol. Grid	FCEV on H_2 produced via electrolysis of H_2O using grid electricity at a retail fueling station
FC Distributed Solar PV	FCEV on H_2 produced via electrolysis using photovoltaic power at a retail station
FC Centr NG SMR w. gas.pipl.	H_2 is produced at a central SMR location and pipelined to retailing stations
FC Centr NG SMR CCS gas.pipl.	As above, but with carbon capture and sequestration (CCS)
FC Cntrl Wind w. gas.pipl.	FCEV on H_2 produced via electrolysis using wind power at a central location (pipelined out)
FC Centr Biom gas.pipl.	FCEV on H_2 via hybrid poplar gasification at a central location (pipelined out)
FC Centr Biom liquid H2	FCEV on H_2 produced via hybrid poplar gasification at a central location, with subsequent liquefaction of H2 for truck delivery to retail stations
FC Centr Coal CCS gas.pipl.	FCEV on H_2 produced via coal gasification with CCS (pipelined out)

Total water consumption is calculated as the aggregate of water consumption per energy unit output of each fuel cycle step and reported as gallons per million Btu and gallons per gge. When fuels are used in vehicles, differences in the efficiency of the respective powertrains (e.g., internal combustion engine vs. electric motor or fuel cell) will affect the amount of fuel expended per mile of driving. To account for fuel economy, water consumption results for each transportation fuel pathway are expressed as per 100 miles driven for various midsize vehicles. Fuel economy assumptions for a 2013 midsize car class are used to estimate water consumption per 100 miles (Table 2).[9]

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[8] On-road correction factor from Elgowainy et al. 2010.

[9] To better focus on the effect of factors such as irrigation, cooling technology at power plants, etc., variability of fuel economy was not considered in this study (see Table 2).

All gasoline internal combustion engine vehicles (Gasol ICEVs) can use E10 and a slightly different version of the car can use higher blends, up to E85. Internal combustion engines are a relatively mature technology, but a number of options are still available to automakers to improve their fuel economy. Automakers have R&D programs to meet stricter fuel economy and GHG emissions standards for 2025. BEVs are relatively new technology, and technological improvements can be expected to increase their fuel economy over several years. FCEVs, another new technology, can likewise be expected to achieve higher fuel economy over the next several years. The purpose of this analysis is to provide a snapshot of life-cycle water consumption assuming 2013 vehicular technology. As fuel economies increase in the future, water consumption per mile will decrease from the values derived in this analysis.

Table 2. 2013 Midsize Cars: On-Road Vehicle Fuel Economy (mpgge)[10]

Gasoline (E10) Vehicle	**27**	Diesel Vehicle	**32**	Nat. Gas Vehicle	**26**
Battery Elec. Vehicle	**86**	Fuel Cell Elec. Vehicle	**53**		

In Figure 2, the low, median, and high values are based on analyses such as Meldrum et al. 2013 for various types of electricity.[11] For hydrogen from biomass gasification, the “high” value was taken from a related technology, coal gasification to hydrogen, because the H2A hydrogen-from-biomass model is based on a point estimate, not a range.[12] Tables 4 through 15 provide additional information on several key assumptions used in this analysis. This analysis includes sea water consumed by power plants located near the coast. If sea water were excluded, the water intensity results would be somewhat lower than shown.

Ranges in water consumption for electricity and fuels production (including upstream from power plants and processing plants for materials/feedstock such as oil, natural gas, biomass, and coal) reflect a combination of variability in source data (analytical uncertainty resulting from different data sources) and variability in contributing technologies. Also, while this analysis is on a life-cycle basis, the implications of water consumption depend strongly on local contexts—availability where the water is consumed—in contrast to greenhouse gas emissions (for which local implication is not significant).

Results

This section presents and discusses the results and major assumptions which have a strong impact on results. More details on data and assumptions used herewith are provided in the assumptions and supporting data section at the end of this record. Figure 2 shows the estimated amount of water associated with the production and delivery of a gge of fuel. This analysis does not consider other transportation modes (medium and heavy-duty trucks, for example). However, the water intensity per gasoline gallon of fuel estimates can be a basis for estimating water intensity per mile for other transportation modes that could have very different fuel economy ranges from cars and light trucks. Water consumption of the corn E85 pathway dwarfs that for all other transportation fuels. Of the remaining pathways, the FCEV distributed electrolysis (grid electricity), FCEV coal with carbon capture and sequestration (CCS), FCEV biomass with liquid hydrogen delivery, and BEV 100 grid electricity

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[10] Gasoline ICEV fuel economy is based on current cars’ information at fueleconomy.gov. CNG cars are a few percent less fuel efficient than comparable gasoline cars (e.g., gasoline Honda Civic versus CNG Civic). The BEV fuel economy is net of charging/battery losses (assumed 12%). On-road fuel economy numbers for the BEV 100 and FCEV are from the Argonne National Laboratory Autonomie model that was exercised in 2014 for midsize cars.

[11] The numerical result shown for each bar is the median value.

[12] H2A production models were developed with DOE funding to enable researchers to quickly estimate the levelized production costs of hydrogen from alternative materials/feedstock, using traceable assumptions. http://www.hydrogen.energy.gov/h2a_prod_studies.html

pathways consume more water than other pathways, mainly because of electricity's high water intensity and the significant electricity consumption in these pathways.[13]

Hydropower was excluded in view of the lack of consensus on allocating evaporation to electricity generation, particularly for reservoirs with other uses such as recreation and flood control. Since hydropower is prevalent in the Northwest (a particular region), leaving it out when looking at the U.S. average grid was deemed to be acceptable for an analysis of water intensity.

When vehicle efficiency is incorporated (i.e., functional unit is per 100 miles), vehicles with higher fuel economy differentiate themselves to a greater degree (Figure 3). For example, the BEV grid electricity pathway approaches most FCEV pathways and is comparable to the FCEV biomass pathways. Likewise, the FCEV pathways separate further from the ICEV pathways when the basis shifts from per gge to per 100 miles. With the exception of the grid-based electrolysis and solar PV electrolysis pathways, the water results for hydrogen cluster in the vicinity of 5–42 gallons of water per 100 miles, corresponding to fuel cycle consumption at 2.5–21 gallons per kg hydrogen. The FCEV pathways and BEV grid electricity pathway use more water than the pathways for diesel and CNG.

The following results for the full fuel cycle were observed:

- In terms of water consumed per unit of fuel energy ("water intensity"), diesel and gasoline without ethanol are comparable, at 3–8 gallons per gge, but are more water-intensive than compressed natural gas (CNG) or electricity from renewables.
- The water intensity of several hydrogen fuel pathways are within 25% of conventional E10 while a few have higher water intensities (20% to 40% higher than corn E10). Corn-based E85 ethanol, U.S. electricity,[14] and hydrogen from electrolysis with U.S. electricity show higher water intensities per unit of energy than do other fuel production pathways considered.
- When expressed in terms of water consumed per miles driven, water intensity is also a function of the fuel economy. The relative difference in water intensity per gge between U.S. grid electricity and other fuels becomes less when expressed as per miles driven.
- The most water-intensive hydrogen pathways include electrolysis with grid electricity. The major contributor in this pathway is the water consumption for cooling at power plants. The embedded water in electricity dominates the water consumption in the electrolytic process or the water consumed for cooling at the hydrogen production facilities.
- The most water-efficient BEV and FCEV pathways are associated with wind and solar photovoltaics (PV) as sources of electricity. For hydrogen from wind or PV-powered electrolysis, water input to the electrolyzer for actual hydrogen production dominates the life-cycle water consumption because there is no major cooling requirement.

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[13] The ratio of freshwater use to saline water use for thermoelectric power generation is about 70%:30% (U.S. Geological Survey 2004; U.S. Geological Survey 2009). Factoring in saline water consumption, freshwater consumed in electricity generation could be further reduced. However, saline water use varies substantially from region to region, depending on the availability of saline aquifers (Wu and Peng 2011). Therefore the reduction of water use factors for BEVs would have to be estimated on a regional basis.

[14] "U.S. electricity" is the average U.S. grid electricity minus hydroelectricity (excluded because it is difficult to allocate evaporative losses between end uses, e.g., recreational boating on reservoirs vs. power production).

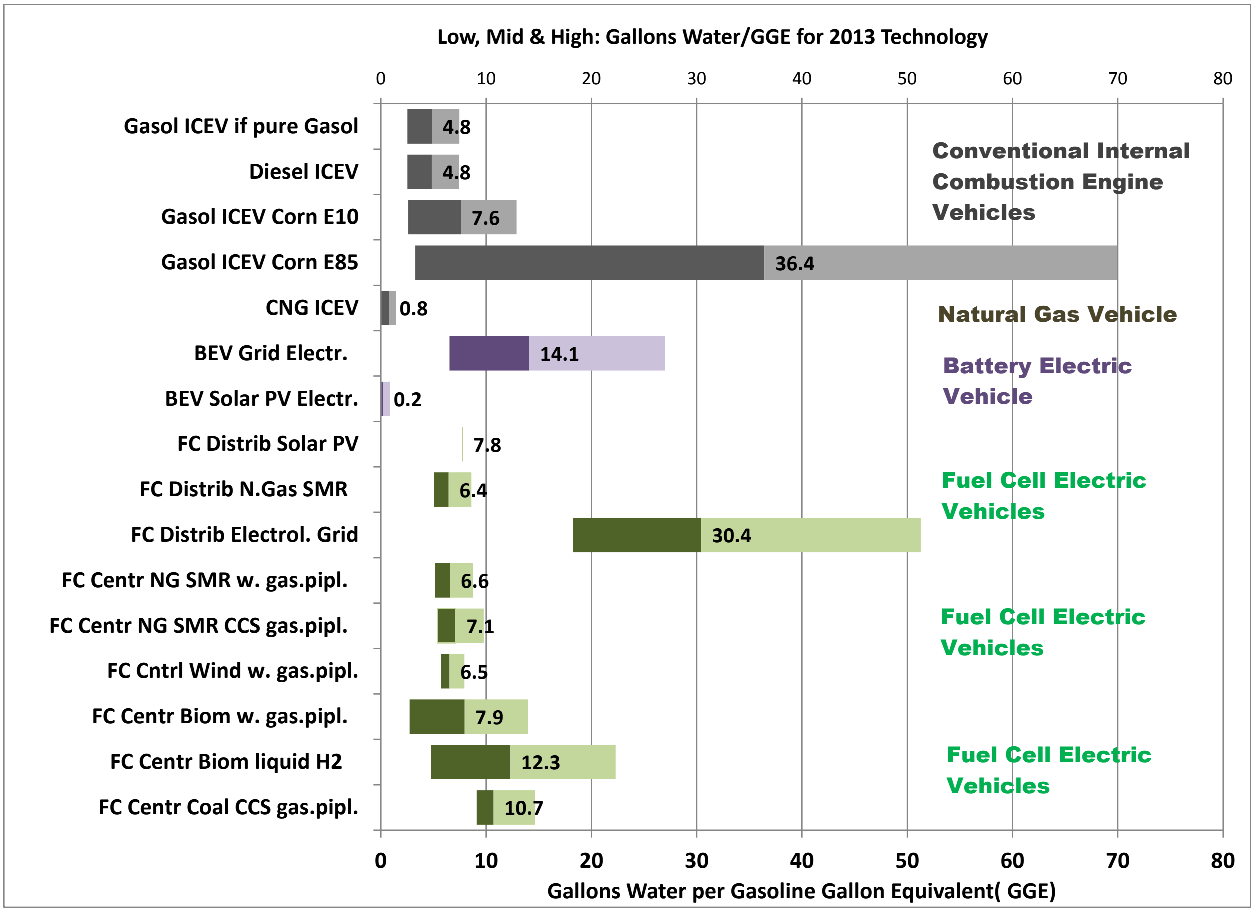

Figure 2. Water consumed per gasoline gallon equivalent (gge) of fuel

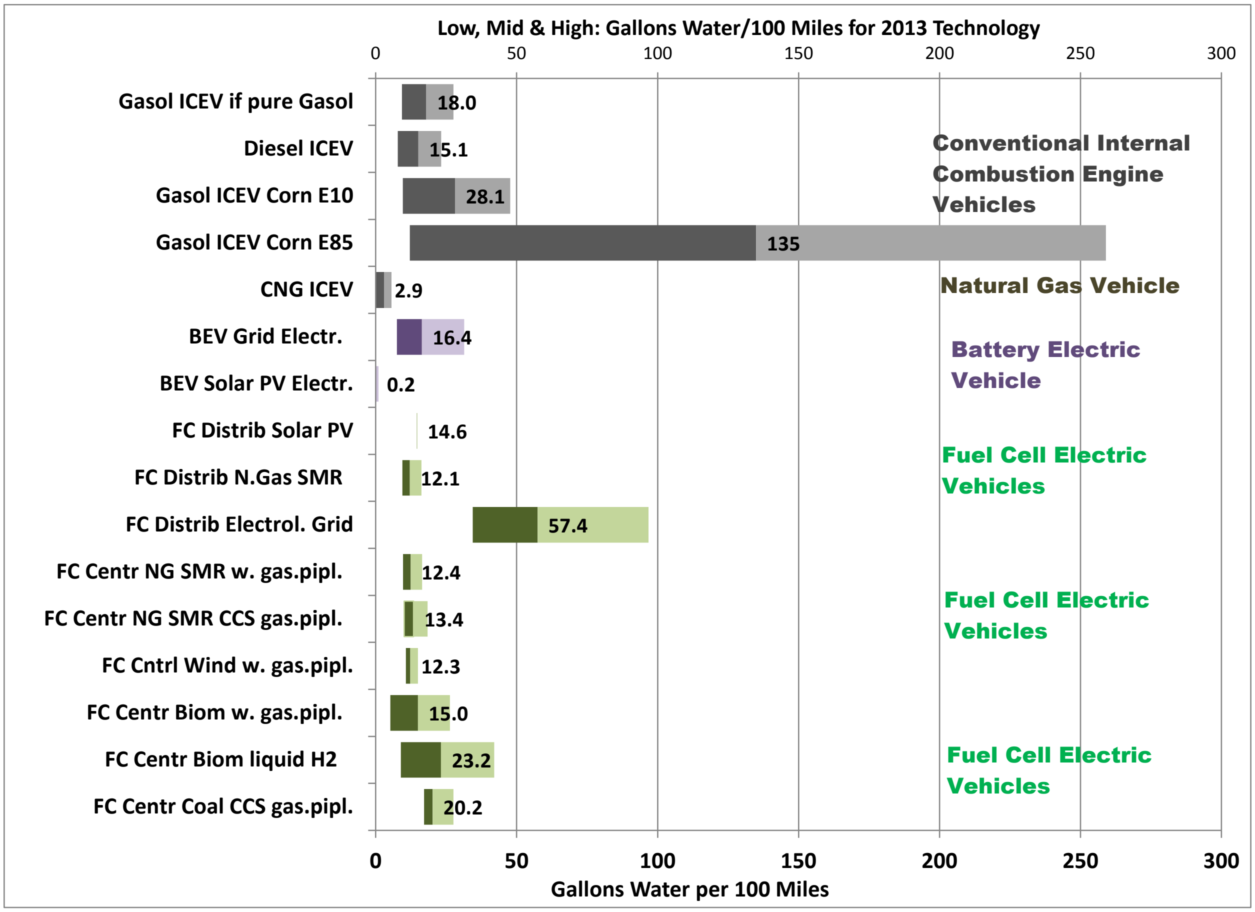

Figure 3. Water consumption per 100 miles driven

More details on the relative contribution of each pathway stage are presented in Figure 4 (all the bars for pathways shown at full length) and Figure 5 (with the longest bars truncated to enhance legibility of the shorter bars for the other pathways). Results for each step of the transportation fuel cycle are summarized in Table 3. The wide range of water consumed to produce corn (primarily for corn irrigation) can be seen in the results for gasoline ethanol blends. Each pathway is represented by three bars (low, median, high).

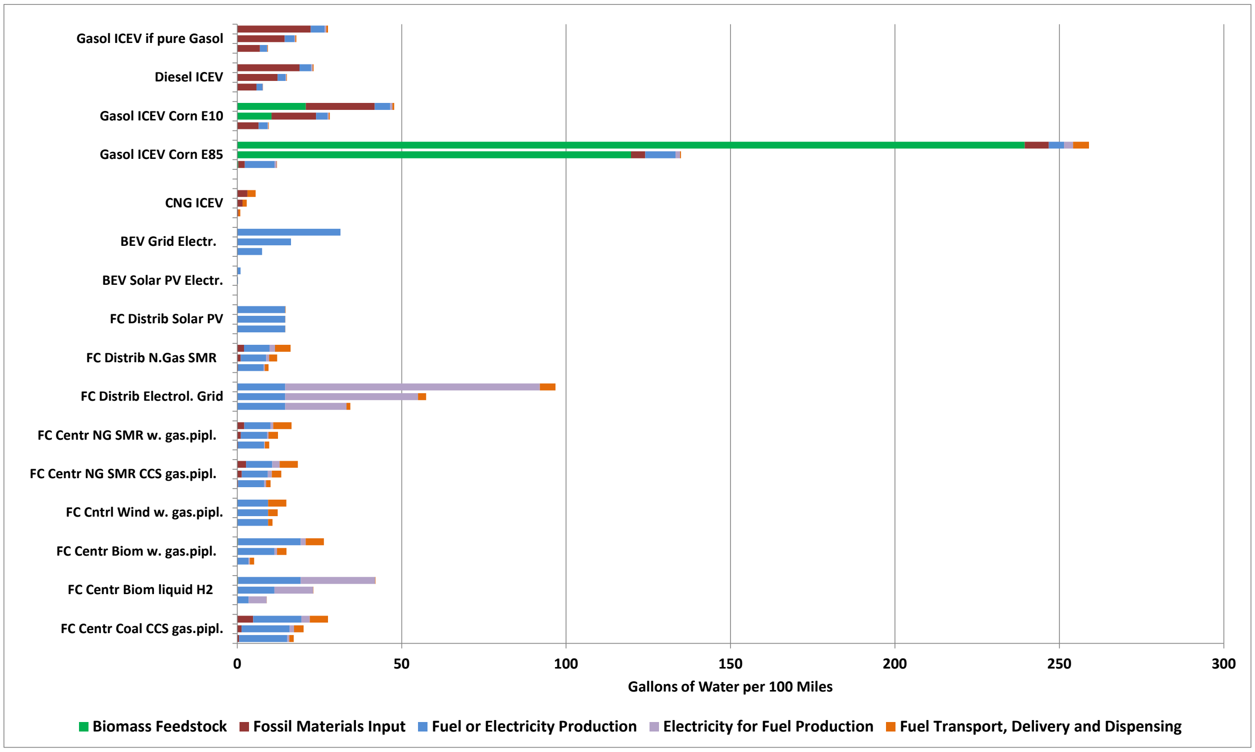

Figure 4. Breakout of water consumption per 100 miles driven (low, median, high)

Note: The category "Fuel or Electricity Production" includes transportation fuels production (e.g., diesel in a refinery, corn ethanol in a biorefinery, electricity in a power plant, hydrogen in a steam methane reforming plant, etc.). "Electricity for Fuel Production" shows embedded water consumption associated with the electricity input to a fuel production process (e.g., at a refinery).

Figure 5 shows the same information as Figure 4, but with the longest bars allowed to extend off scale in order to improve the readability of the shorter bars that remain. As previously described, the largest contributing steps are cooling associated with electricity production from fossil fuels and irrigation associated with corn production. Their impact can be better understood by taking a closer look at the composition of grid electricity and at corn production, which are addressed next.

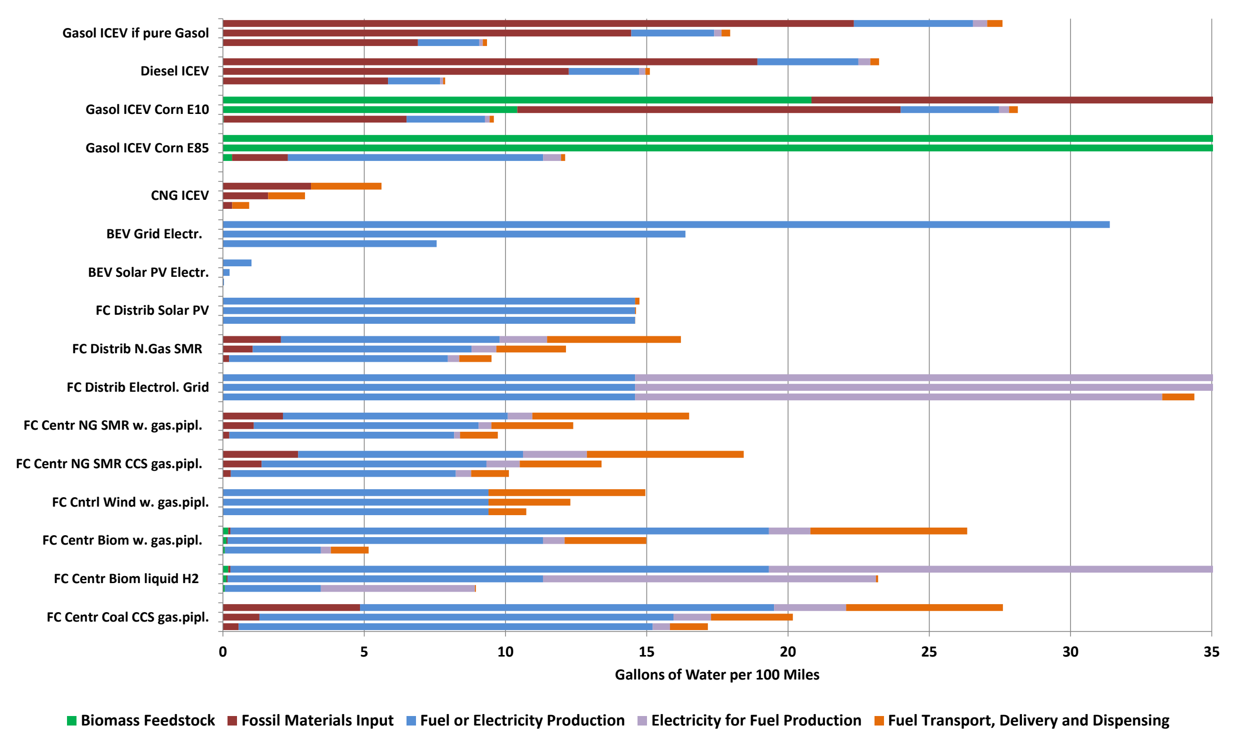

Figure 5. Breakout of water consumption per 100 miles (selected bars truncated) (low, median, and high cases)

Table 3. Water Consumption Results for Each Stage, Gallons per 100 Miles (Median/(Low–High)

	Biomass Feedstock (includes Transport)	Fossil Materials Input (incl Transport.)	Fuel and Electricity Production	Electricity Used For Fuel Production	Fuel Transport, Delivery and Dispensing	Total Life Cycle
Gasol ICEV if pure Gasol	0.00 (0.00–0.00)	14.45 (6.90–22.33)	2.93 (2.18–4.22)	0.26 (0.12–0.50)	0.31 (0.15–0.55)	18.0 (9.3–27.6)
Diesel ICEV	0.00 (0.00–0.00)	12.24 (5.85–18.92)	2.49 (1.84–3.57)	0.22 (0.10–0.42)	0.16 (0.07–0.31)	15.1 (7.9–23.2)
Gasol ICEV Corn E10	10.42 (0.03–20.83)	13.57 (6.47–21.00)	3.48 (2.77–4.68)	0.36 (0.17–0.69)	0.31 (0.15–0.54)	28.1 (9.6–47.7)
Gasol ICEV Corn E85	119.72 (0.32–239.44)	4.34 (1.98–7.32)	9.21 (9.03–4.65)	1.38 (0.64–2.73)	0.28 (0.15–4.86)	134.9 (12.1–259.0)
CNG ICEV	0.00 (0.00–0.00)	1.60 (0.33–3.12)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	1.30 (0.60–2.49)	2.9 (0.9–5.6)

	Biomass Feedstock (includes Transport)	Fossil Materials Input (includes Transport)	Fuel and Electricity Production	Electricity Used For Fuel Production	Fuel Transport, Delivery and Dispensing	Total Life Cycle
BEV Grid Electr.	0.00 (0.00–0.00)	0.00 (0.00–0.00)	16.37 (7.56–31.39)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	16.4 (7.6–31.4)
BEV Solar PV Electr.	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.23 (0.04–1.01)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.2 (0.0–1.0)
FC Distrib Solar PV	0.00 (0.00–0.00)	0.00 (0.00–0.00)	14.59 (14.59–14.59)	0.00 (0.00–0.00)	0.04 (0.01–0.15)	14.6 (14.6–14.7)
FC Distrib N.Gas SMR	0.00 (0.00–0.00)	1.05 (0.22–2.05)	7.74 (7.74–7.74)	0.88 (0.41–1.68)	2.47 (1.14–4.74)	12.1 (9.5–16.2)
FC Distrib Electrol. Grid	0.00 (0.00–0.00)	0.00 (0.00–0.00)	14.59 (14.59–14.59)	40.37 (18.66–77.43)	2.47 (1.14–4.74)	57.4 (34.4–96.8)
FC Centr NG SMR w. as.pipl.	0.00 (0.00–0.00)	1.09 (0.22–2.13)	7.96 (7.96–7.96)	0.45 (0.21–0.87)	2.89 (1.34–5.55)	12.4 (9.7–16.5)
FC Centr NG SMR CCS gas.pipl.	0.00 (0.00–0.00)	1.37 (0.28–2.66)	7.96 (7.96–7.96)	1.18 (0.54–2.26)	2.89 (1.34–5.55)	13.4 (10.1–18.4)
FC Cntrl Wind w. gas.pipl.	0.00 (0.00–0.00)	0.00 (0.00–0.00)	9.40 (9.40–9.40)	0.00 (0.00–0.00)	2.89 (1.34–5.55)	12.3 (10.7–15.0)
FC Centr Biom w. gas.pipl.	0.12 (0.06–0.19)	0.04 (0.01–0.08)	11.16 (3.39–19.06)	0.76 (0.35–1.47)	2.89 (1.34–5.55)	15.0 (5.2–26.3)
FC Centr Biom liquid H2	0.12 (0.06–0.19)	0.04 (0.01–0.08)	11.16 (3.39–19.06)	11.79 (5.45–22.61)	0.08 (0.04–0.12)	23.2 (9.0–42.0)
FC Centr Coal CCS gas.pipl.	0.00 (0.00–0.00)	1.29 (0.55–4.85)	14.66 (14.66–14.66)	1.33 (0.61–2.55)	2.89 (1.34–5.55)	20.2 (17.2–27.6)

Grid Electricity

Thermo-electric generation technologies (i.e., coal, nuclear, and natural gas) account for a large fraction of U.S. electricity. With hydropower removed from the grid mix considered in this study, these technologies are the dominant consumers of cooling water[15] (EIA 2014; NETL 2009). Over 98% of thermo-electric plants use water as their cooling medium (EIA 2011); the amount of water consumed depends on the cooling technology deployed. For example, “once-through” (i.e., open loop) systems withdraw large amounts of water but return much of that water to the source. Closed-cycle technologies withdraw less water but a much greater proportion of that water is consumed, mostly via evaporative losses in cooling towers (EPRI 2002). Dry (i.e., air) cooling technology exists, but it can reduce the efficiency of a power plant by as much as 10% (EPA 2001). It currently represents only about 1% of generation capacity and 2% of electricity production (Union of Concerned Scientists 2012).

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[15] Table 9 shows the range in gallons of water per MWh electricity.

This analysis used information from Meldrum et al. 2013 for water consumed by different power technologies (e.g., sub-critical pulverized coal, natural gas combined cycle, etc.) and using different cooling technologies (open loop, cooling tower, etc.).[16]

Corn Ethanol Production

The wide range of water consumed for corn ethanol production reflects regional variation in corn irrigation requirements. 72%–98% of water consumed in corn ethanol production is used to irrigate the corn crop in 1998–2008 (Wu et al. 2011). The production weighted average for the three major corn producing USDA farm regions[17]—Corn Belt, Great Lakes, and Northern Plains—is 84 gallons of water consumption per gallon of ethanol (this served as the upper bound in this analysis and unirrigated corn served as the lower bound). The lower and upper bounds shown in Figures 2 and 3 are based on corn without irrigation versus corn with irrigation, with the median being the average of the two. See the "Assumptions and Supporting Data" section for more information.

Conclusions

Water consumed per 100 miles driven ranges from about 5 to about 48 gallons across the majority of FCEV pathways (other than electrolysis using U.S. grid electricity), the BEV grid pathway, and the corn E10 ICEV pathway. The water intensity of the FCEV grid electricity pathway is high relative to the BEV, corn E10 ICEV, and other FCEV pathways. The BEV on grid electricity and all FCEV pathways consume more water per 100 miles driven than the conventional diesel and CNG pathways, but are much less water intensive than the corn E85 ICEV pathway.

As long as thermo-electric generating technologies account for a significant fraction of grid electricity generation, water consumption will remain high for those transportation fuels whose production is dependent on the use of grid electricity. For example, the relatively high water intensity of hydrogen production from grid-based electrolysis (relative to other FCEV pathways) is due to the substantial amount of electricity required (about 53 kWh/kg H_2) to drive the electrolysis process. BEVs are also largely dependent on grid electricity; almost all of the water consumed for this pathway is indirectly consumed as water embedded in cooling at thermo-electric power plants (relatively high water intensity per GGE of the BEV grid pathway). However, the greater efficiency of BEV vehicles relative to other vehicle technologies enables the BEV grid pathway to achieve a more favorable ranking when water intensity is expressed as water consumed per 100 miles driven.

Assumptions and Supporting Data

Table 4 summarizes the sources of low, median, and high values.

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[16] The referenced study included only plants using fresh water. Although water use rates estimated by Averyt et al. (2013) from values reported to EIA suggest lower water consumption for plants using ocean water than those using fresh water, those authors question the reliability of the underlying data (J. Meldrum communication with T. Nguyen 9-22-2014). This analysis treats the referenced study's consumption results as blue water consumption.

[17] Which produced 95% of the corn ethanol in the United States.

Table 4. Sources of Low, Median, and High Values

Power Plants	Meldrum et al. 2013 cited low, median, and high values for nuclear, renewable and fossil fuels plants.
Conventional Oil Extraction	Wu et al. 2011 cited low and high. Median was derived as the average.
Tight Oil Extraction	Mantell 2013 cited a range of values from which we selected low and high, and took the average for median.
Refining Process and Cooling Water	Wu et al. 2011 cited low and high for refinery process and cooling water. Median was derived as the average. Separation of cooling water from total was estimated as shown below (see cooling at refineries).
Cooling at Refineries	ConocoPhillips NPDES provided a single value that was assumed and used to separate cooling from total refinery consumption.
Corn Irrigation (ethanol)	Wu et al. 2011 cited numbers for three major corn regions. Used weighted average for high. Assumed no irrigation for low. Median was derived as the average.
Coal Extraction	Meldrum et al. 2013 cited low, median, and high values for surface vs. underground. Used coal industry's breakdown of surface vs. underground production and Meldrum et al.'s data to get weighted average.
Shale Gas Extraction	Mantell 2013 and Clark et al. 2013 cited a range of values from which we selected low and high, and took the average for median. For water embedded in diesel and electricity, used Clark et al. 2011's diesel and electricity consumption for four major shale plays (took low/high from there; median was derived as the average).
Conventional Natural Gas Extraction	Meldrum et al. 2013 cited low, median, and high values for water. Diesel and electricity consumption assumed at 1/3 of shale gas extraction for use with water intensities for diesel and natural gas.
Hybrid Poplars Irrigation (hydrogen)	Netzer et al. 2014 identified acreage in Oregon and Washington where hybrid poplars would require no or little irrigation. No irrigation was assumed for hybrid poplars as an interim assumption, pending revision based on further research.

Midsize Car's Fuel Economy

Year 2013 technology's fuel economy assumptions (Table 2) for the FCEV and BEV 100 were from Argonne National Laboratory's simulation of advanced midsize cars using their Autonomie model,[18] the March 2014 analysis supporting EERE's recent benefits analysis for its Transportation Office. For gasoline/E85 non-hybridized cars, the current U.S. average fuel economy was assumed. The non-hybridized diesel car's fuel economy was assumed to be 20% higher than the gasoline car's.

Crude Oil Extraction and Refining

Estimates of water consumption for the extraction of conventional crude oil were based on Wu et al. 2011 after modifying their results to account for recent increases in domestic tight oil production.

In 2011, tight oil comprised 33% of U.S. onshore (lower 48) domestic crude oil production while conventionally extracted oil accounted for 67% (EIA 2013a, Figures 96 and 97). Mantell 2013

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[18] The Autonomie model and published work using the model and its predecessor (PSAT model) is described at http://www.autonomie.net/overview/index.html.

presented information on water use per well, estimated ultimate recovery (EUR),[19] and the resulting water consumption per mmBtu for tight oil extraction. The consumption estimates from major formations cited by Mantell 2013, including Eagle Ford, Niobrara, Cleveland/Tonkawa, and Mississippi Lime, were applied to estimate low, median, and high water consumption for tight oil extraction. The amount of water consumed for domestic crude oil extraction reflected the contributions of conventional oil versus tight oil. For crude oil refining, Wu et al. 2011 noted that about half of oil refinery water consumption is for cooling tower use, and about 96% of refinery water consumption is for cooling and for boiling operations (i.e., steam generation).

Corn Ethanol Production

As with oil refining, estimates of water consumption for producing ethanol from corn (fermentation process) were based primarily on Wu et al. 2011. For corn ethanol, cooling water use is reportedly 53% of the total water consumption in the dry mill (Wu et al. 2011). Therefore cooling water consumption in corn ethanol production would be 3 gal water/gal ethanol x 53%, i.e., approximately 1.6 gal water/gal ethanol.

Three U.S. Department of Agriculture (USDA) farm regions (Regions 5, 6, and 7) together accounted for 95% of ethanol production in 2006. Average annual precipitation for these regions ranged from about 22 inches (Region 7) to about 38 inches (Region 5). Wu et al. 2011 used data on corn irrigation requirements for the three regions—Region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas)—to produce a range of water consumption for corn ethanol production. This analysis used the weighted average for the United States and defined the lower and upper bounds as corn without irrigation versus corn with irrigation, with the median being the average of the two. The analysis also accounted for water for other farm related inputs such as diesel fuel for tractors and natural gas for fertilizers. To account for the water credit associated with co-products of the refining process (primarily distillers dried grain and solubles, or DDGS, for corn ethanol), only 67% of water consumed for irrigation of corn and water consumed at the bio-refinery was attributable (energy basis) to corn ethanol production (again based on Wu et al. 2011).

Electricity

Based on AEO 2014, U.S. grid generation consists primarily of coal, natural gas, nuclear, and renewables-derived electricity (Table 5). As previously stated, this analysis assumes current technology and therefore the 2013 grid mix was used.

The major renewable sources are: hydro, wind, wood (includes wood, municipal solid wastes, and other biomass), geothermal, and solar. Hydro was excluded. Since hydro accounts for slightly more than half of the renewable generation in 2013, the resulting shares for the other fuel sources changed slightly from values in Table 5 after hydro was subtracted out.

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[19] The estimated ultimate recovery (EUR), according to the U.S. Geological Survey (USGS), is derived from an analysis of the rate of production of a well. The production data are plotted with respect to time, and a hyperbolic or exponential decline curve is fit to the data. The intersection of the decline curve with the x axis terminates the forecast span of the well. The EUR is the sum of all oil or gas that is forecast to have the potential to be produced up to the termination point (USGS 2005).

Table 5. Electric Generation Share from AEO 2014

	2011	**2012**	**2013**
Coal	42.2%	37.3%	40.1%
Petroleum	0.7%	0.6%	0.5%
Natural Gas	24.7%	30.3%	27.5%
Nuclear Power	19.3%	19.0%	18.6%
Renewable Sources	12.6%	12.4%	12.9%
Other	0.5%	0.5%	0.4%

Estimates of water consumed for electricity production were calculated based on the generation shares shown in the table, and using the data and assumptions described below. Estimates of water consumption at the power plant (Tables 8–10) and estimates of water consumption by fuels for electricity before transport to the power plant (Table 11) are shown separately. Total cooling water consumption in U.S. electricity production (Table 13) is a function of water consumed at the power plant, water consumed in the production of fuels, and water embedded in the losses from transmission and distribution (T&D) of electricity to the point of use. T&D losses account for approximately 6.5% of the original generation at power plants.[20]

Table 6. Generation by Cooling Technology, 825 Plants from USGS Analysis of EIA 2010 Data (GWh)

	Once-Through Saline	**Once-Through Fresh**	**Recirculating Pond**	**Recirculating Tower**	**Complex***	**Total**
Oil	4,892	72		205		***5,169***
Nuclear	160,038	215,991	86,114	272,506		***734,649***
NGCC	33,483	16,938	4,767	432,426		***487,614***
Natural Gas Steam	10,233	20,449	7,845	12,657		***51,184***
Coal	35,519	556,564	122,777	727,587		***1,442,447***
Complex					610,374	***610,374***
Total	***244,165***	***810,014***	***221,503***	***1,445,381***	***610,374***	***3,331,437***

Source: USGS 2014

*Complex: plants with multiple cooling systems

Table 6 from a 2014 U.S. Geological Survey (USGS) study shows electric generation in gigawatt-hours (GWh) from EIA for thermo-electric plants, including coal, natural gas combined cycle (NGCC) and natural gas combustion (steam) turbines, nuclear, and oil by cooling technology (USGS 2014). The table includes data for only 825 plants out of thousands (plants with missing or questionable data were excluded) and does not include plants employing dry cooling towers. The "complex" category covers plants with multiple cooling technologies. Information from this table was used to derive the fractional share data in Table 7. In computing the fractional share data, the complex category was eliminated because there was insufficient information to prorate the individual cooling technologies. Furthermore, the once-through fresh and saline categories were combined, and the small amount of oil plants' generation was combined with that of natural gas steam (i.e., not NGCC) plants.

Meldrum et al. 2013 shows ranges of water consumption per MWh for power plants broken out by fuel and cooling technology. From that study, a set of low, median, and high values was derived as shown in

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[20] EIA 2012. Annual Energy Review for Year 2011.

Table 8. In this analysis, the focus is solely on water associated with power plant operation, not with construction and dismantling. Thus construction and dismantling estimates from Meldrum et al. 2013 were not included here.

Table 7. Fraction of Thermo-Electric Generation Grouped by Cooling Technology and Generation Type (primarily fresh water, with some using saline or reclaimed water)

	Once Through	Recirculating Pond	Recirculating Tower	Total
Nuclear	13.8%	3.2%	10.0%	27.0%
NGCC	1.9%	0.2%	15.9%	17.9%
Gas Steam and Oil	1.3%	0.3%	0.5%	2.1%
Coal	21.8%	4.5%	26.7%	53.0%
Total	***38.7%***	***8.1%***	***53.1%***	***100.0%***

Table 8. Range from Meldrum et al. 2013 for U.S. Thermo-Electric Plants, Gallons of Water Consumed per MWh for Power Plant Cooling, Excluding T&D Losses

	Once Through	Recirculating Pond	Cooling Tower
		Median Values	
Nuclear	400	610	720
NGCC	100	240	189
Gas Steam	290	270	730
Coal	140	740	530
		Low Values	
Nuclear	100	400	580
NGCC	20	240	42.3
Gas Steam	190	270	560
Coal	71	300	200
		High Values	
Nuclear	400	720	890
NGCC	230	240	270
Gas Steam	410	270	1100
Coal	350	1000	1300

The cooling water intensities for major power plant types is derived by combining the electricity generation share data in Table 7 with the cooling water intensity data in Table 8. Table 9 shows the median, low, and high estimates of gallons of water per MWh for the four major types of thermo-electric plants (weighted by cooling technology).

Table 9. Cooling Water Consumption of Thermo-Electric Plants, Gallons per MWh (weighted by cooling technology shares, before T&D losses)

	Low	Median	High
Nuclear	543	313	619
NGCC	180	41.9	266
Nat. Gas Steam	388	286	548
Coal	388	156	885

Table 10 shows the results after conversion to gallons per MWh to gallons per million Btu electricity, and for renewable generation per million Btu (also from Meldrum et al. 2013).

Table 10. Cooling Water Consumption in U.S. Electricity Production, Gallons per Million Btu of Electricity (including T&D losses)

Power Technology	2013 (AEO 2014) w/o Hydro	Low	Median	High
NGCC	21.51%	13.1	56.5	83.2
NG Combustion and Steam Turbines	7.87%	89.5	121	172
Coal	42.87%	48.8	122	277
Nuclear	19.95%	98.2	170	194
Other (Oil, Biomass, CSP, etc.)	2.61%	89.5	121	172
Wind	4.34%	0.03	0.16	0.63
Geothermal	0.44%	56.8	78.3	178
Solar PV	0.41%	0.29	1.8	7.6
U.S. Grid Average	***100.0%***	***52.9***	***111***	***194***

Water consumption results for upstream fuel cycle activities before power plants include fuels production, transportation and processing, e.g., extraction and pre-processing of coal, extraction and processing of natural gas from shale vs. conventional natural gas, transmission or transportation for each fuel. The results were converted from per-MWh to per-mmBtu basis and shown in Table 11.

Table 11. Water Intensity Associated with Fuels-Related Processes (before reaching power plants), Gallons per Million Btu of Electricity (before T&D losses)

Power Technology	% 2013 (AEO 2014)	Low	Average	High
NGCC	21.51%	1.48	7.19	14.0
NG Combustion and Steam Turbines	7.87%	2.09	10.2	19.9
Coal	42.87%	4.29	10.0	37.6
Nuclear	19.95%	7.38	21.9	94.5
Other (Oil, Biomass, CSP, etc.)	2.61%	2.09	10.2	19.9
Wind	4.34%	0.0	0.0	0.0
Geothermal	0.44%	0.0	0.0	0.0
Solar PV	0.41%	0.0	0.0	0.0
U.S. Grid Average	***100.0%***	***3.8***	***11.3***	***40***

The share of “other” plants (oil-fired and others) from EIA is so tiny that the assumption of upstream water consumption associated with their fuels being similar to natural gas power plants (non-NGCC) was deemed acceptable for the purpose of simplifying the analysis.

Table 12 was obtained by adding the results from Table 10 (after grouping the “other” plants together with natural gas steam plants) and Table 11 (after increasing the values in this table by 6.5% to account for T&D losses). Meldrum et al. shows little water consumption by renewable electric plants (e.g., water for geothermal fluids at geothermal plants or for mirror washing at concentrated PV plants, etc.).

Table 12. Water Intensity in U.S. Electricity Production, Gallons per Million Btu (except for the last row) of Electricity (including upstream processes and T&D losses)

Power Gener. Technology	2013 Share	Low	Median	High
NGCC	21.51%	14.7	64.2	98.2
NG Combus and Steam Tur.	7.87%	91.8	132	193
Coal	42.87%	53.3	132	317
Nuclear	19.95%	106	194	295
"Other"	2.61%	91.8	132	193
Wind	4.34%	0.03	0.16	0.63
Geothermal	0.44%	56.8	78.3	178
Solar PV	0.41%	0.29	1.8	7.6
Grid Average/mmBtu		**57.1**	**123**	**237**
Grid Average/kWh		**0.19**	**0.42**	**0.81**

Note: This table includes water consumption associated with the entire life cycle. Hydropower was excluded in view of the lack of consensus with respect to allocating evaporation to electricity generation, particularly for reservoirs with significant uses such as recreation and flood control.

The feedstock sources for electricity production are discussed next.

Natural Gas Extraction and Processing

Meldrum et al. 2013 and Clark et al. 2011 were the primary sources for water consumption for the extraction and processing of conventional natural gas, with Meldrum et al. being the source for water consumption associated with operations at gas extraction sites and Clark et al. 2011 being the source for diesel and electricity consumed for gas extraction (i.e., water embedded in these fuels). Mantell 2013 and Clark et al. 2013 provided water consumption estimates per mmBtu of shale/tight gas. Mantell also showed that processing can add from 0 to 2 gallons per mmBtu of gas, a wide range. For processing, the low value was assumed to be 0.2 gallon per MWh (Meldrum et al.) or 0.026 gallons per mmBtu, and the high value was assumed to be 2 gallons per mmBtu. The sum of extraction and processing water is approximately 1.3 gallons per million Btu for conventional gas versus 3.8 for shale gas (median values). However, extraction and processing is only a small fraction of the life-cycle water intensity of electricity from natural gas, and the difference between the water intensity of electricity from conventional natural gas and that from shale gas is less than 15%.[21]

Finally, estimates of water use in gallons/mmBtu were weighted according to the current (c. 2011) U.S. natural gas production mix (EIA 2013a), resulting in a source-weighted range of 0.6–6 gallons of water/mmBtu natural gas for the extraction and processing phase.

Coal Extraction and Processing

For coal production, data from Meldrum et al. 2013 (Table 13) was complemented with other estimates (National Mining Association 2013) of the proportion of domestic coal produced from surface (66%) versus underground (34%) mining. This provides some sense of the variability in water consumption for coal production that can occur, depending on mining methods.

Coal mining-related activities such as dust control, re-vegetation of land disturbed by surface mining, the practice of beneficiation (i.e., “prepping”), and other plant operations (plant service, potable water requirements, boiler makeup water, ash handling, and flue-gas desulfurization process make-up water),

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[21] Clark et al. 2013 showed that the water intensity of electricity from NGCC power plants is approximately 1.1 liter/kWh for conventional natural gas and 1.25 liters/kWh for shale gas.

all consume water and can add further variability to water consumption estimates. The use of these practices varies with mining methods, regional water availability, and coal quality. For example, NRC 2007 mentioned that coal from Wyoming's Powder River basin is simply sized and screened in preparation for market, due to regional water scarcity, its relatively low ash content, and other physiochemical properties.

Table 13. Water Consumption for Coal Extraction and Processing, Gallons per MWh

	Low	Median	High
Extraction - surface	0.1–0.5	3	13
Extraction - underground	8	27	180
Extraction - type not specified	12	45	120
Processing	9	18	50

Note: Table 3 of Meldrum et al. 2013 shows 1,000 gallons/MWh for processing. This high value could be an outlier, and so 50, a harmonized value derived from Table 2 of Meldrum et al. 2013, was used instead.

Source: Meldrum et al. 2013, Tables 2 and 3

The practice of dust control involves spraying down un-vegetated land surfaces and unpaved roads in order to reduce the production of airborne dust. Re-vegetation refers to the practice of mitigating the impact of mining operations by planting vegetation across the mined area after mining activity has ended. Beneficiation involves a suite of processes that are performed when raw coal is sent to a coal preparation plant (usually on-site or close to the coal mine). First, coal is separated into different sizes using a combination of crushing and screening devices. Then some form of density separation process (e.g., heavy media separation vessels and cyclones, froth flotation and wet spiral separators) can be employed to remove non-combustible ash and rock, as well as chemical components such as sulfur, sodium, and trace elements.

According to Mavis (2003), "water use in coal mining varies according to the method of mining, the equipment used, and the availability of water". Underground mines in West Virginia rely on the use of water for cooling the cutting surfaces of mining machinery and for inhibiting friction-induced ignition of coal fines or gas. Surface mines in the Western United States do not use water in actual mining, but they do suppress dust on haul roads with water and aqueous solutions of calcium chloride and magnesium chloride.

Meldrum et al. 2013 reported the results of their analysis for coal (summarized in Table 13). Using their data, we lumped the category "Extraction – not specified" with underground extraction in this analysis.

Uranium Extraction and Processing

Water consumption for uranium mining and enrichment was taken from Meldrum et al. 2013. To calculate a technology-weighted consumption for domestic uranium production, the following assumptions were made, based on production reports for the year 2012 (Cameco 2013; EIA 2013d):

- 91% of domestic uranium is mined using the in situ leaching method
- 9% of domestic uranium is mined using the conventional mill method
- All domestic uranium is enriched using the gaseous centrifuge method (gaseous diffusion's share has been shrinking and may be zero soon).

Solar Power Production

Water consumption was based on Meldrum et al. 2013, ignoring power plant construction and dismantling. It was assumed that all commercial installed capacity for solar PV power generation uses flat panel technology (SEIA 2013). From AEO 2014, 5.75 billion kWh are from PV and 1.19 billion kWh from solar thermal technologies. Since solar energy represents a very small share of U.S. electricity and the CSP share is a small fraction of solar power production, only PV was assumed in this analysis. The small amount of life-cycle water for PV is from occasional washing of the panels.

Wind Power Production

Water consumption for energy production from wind was based on Meldrum et al. 2013, ignoring power plant construction and dismantling.

Woody Biomass Production (for Gasification to Hydrogen)

A recent study completed for the California Energy Commission (Netzer et al. 2014) estimated that up to 30% of a total of 13 million acres in Oregon and Washington would need little or no irrigation. Currently it is assumed that the hybrid poplars in commercial plantations are not irrigated (assumption subject to revision, pending future research).

Geothermal Electricity Production

Assumptions for geothermal electricity production were derived from Meldrum et al. 2013 and GEA 2013 as follows:

- Water consumed for geothermal power plant construction was excluded; only operational water consumption was considered
- Enhanced Geothermal Systems (EGS) were excluded from the analysis because they are not yet an operational technology
- 47% of U.S. geothermal energy capacity uses dry steam technology
- 29% of U.S. geothermal energy capacity uses steam flash technology
- 24% of U.S. geothermal energy capacity uses binary technology with either wet (water-cooled) or hybrid wet-dry cooling.

Water consumption for geothermal energy production was weighted as a function of the share of each technology (dry steam, steam flash, and binary).

Grid Electricity Production

Water consumption at domestic electric power plants was based on water consumption by power plant type reported in Meldrum et al. 2013. The water consumed attributable to fuel materials input (i.e., coal, natural gas, nuclear, and renewable fuels) production (as opposed to power plant operations and cooling) came from Meldrum et al. (coal, nuclear, PV, and wind), and from this analysis's use of information from other sources for oil, natural gas, and biomass.

Hydrogen Production

Data used to estimate water consumption across the hydrogen production pathways were obtained from:

1) Case studies developed using the Hydrogen Analysis (H2A) spreadsheet models (H2A 2012)
2) Assumptions and parameters obtained from the "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model" (GREET 2013) developed and maintained by Argonne National Laboratory (ANL).
3) Information that industry provided to the GREET team at ANL on the electrolysis and natural gas SMR processes for producing hydrogen (Elgowainy et al. 2014, 2015)

Information from these sources was used to supplement the biomass gasification and coal gasification pathways, as outlined below.

Hydrogen from Biomass Gasification

For process water, the H2A case study for hydrogen from biomass gasification (H2A 2012) reported water use of 79.26 gal water/kg hydrogen. This appears to be water withdrawal for a once-through cooling system rather than water consumption. Thus rather than using this value, a range of cooling water consumption was estimated using two other sources (Spath et al. 2005 and NETL 2010b) as described below:

- Spath et al. 2005 developed detailed process designs using the Advanced Simulator for Process Engineering (Aspen Plus) model to investigate the economics of producing hydrogen from gasification of woody biomass. By combining cooling tower evaporation reported in the Energy Balance table with the Goal Design hydrogen production at operating capacity, the lower end of water consumption was obtained.
- The upper end of water consumption was based on the design of a coal gasification plant (NETL 2010b) as described below.

Hydrogen from Coal Gasification with CCS

The H2A case study for hydrogen from coal gasification (H2A 2012) reported a single estimate (of 2.91 gal water/kg hydrogen) for process water consumption. Therefore estimates of process and cooling water consumption were derived from a recent study that analyzed potential plant configurations to determine baseline performance and cost of producing hydrogen from natural gas or coal (NETL 2010b). Process and cooling water estimates were derived from cases 2-1 and 2-2 in the NETL report, which estimated performance and costs for a baseline coal gasification hydrogen plant using a cooling tower with circulating water pumps. Overall plant water balances for cases 2-1 and 2-2 were determined (Exhibits 5-8 and 5-9 in NETL 2010b). Process water consumption was derived from reported raw water usage for quench/wash, venture scrubber water, and condenser makeup water. Water consumption for cooling was derived from raw water usage for the gasification plant's cooling tower.

Hydrogen from Natural Gas Steam Methane Reforming with CCS

Since NETL has shown that power plant efficiency decreases when carbon capture is added, it was assumed that a central hydrogen plant would see a 16% decrease in its efficiency with CCS, a somewhat higher loss than NETL 2009's finding that a NGCC plant would experience a 14% efficiency decrease if carbon capture were added to its operation (50.8% to 43.7%).

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