Topic Paper #31

Water Usage

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

National Petroleum Council

Future Transportation Fuels Study

Topic Paper

Water Usage Considerations

July 17, 2012

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Introduction

Water is used in significant quantities for producing energy. It is an essential part of the fuel lifecycle, from feedstock production to conversion to final fuels and power. Because water is a limited resource essential for sustaining life, an understanding of water requirements for different fuel options is required. In order to understand the relative impacts of water use in the production of transportation fuels, it is first important to place this use within the context of total global and U.S. water supply and dispositions. Water resource use is generally described by two measures: volumes withdrawn and volumes consumed.

Water consumption, a subset of total water withdrawn, is the more appropriate measure for resource utilization as this represents water that is removed from the watershed and thus made unavailable for future use. Consumption happens when water evaporates or is contaminated to the point of being unusable. In industrial and thermo-electric applications, for example, this is typically due to evaporative losses in cooling processes. Wastewater discharges of fresh water to oceans or disposal to saline aquifers also represent losses of water from a watershed because the freshwater is no longer available for use.

In addition to quantifying volumes of water, the quality of water is an important concern. Fresh water is the most significant since it represents a small fraction of the total global water resource and is critical for sustaining life. Processes that consume fresh water are highly scrutinized and must be evaluated to determine if the use of water resources is prudent.

Figure 1 provides the breakdown between fresh water withdrawn and consumed in the U.S., along with primary end users of that water. In total, approximately 100 billion gallons of fresh water is consumed per day, whereas the total withdrawals are 345 billion gallons per day. Irrigation for agriculture is the dominant consumer of fresh water in the U.S. Thermo-electric power generation withdraws about a third but consumes less than a twentieth of water resource. Industrial processes and mining, which includes extraction and processing of fossil hydrocarbon fuels, account for a small fraction of fresh water use.

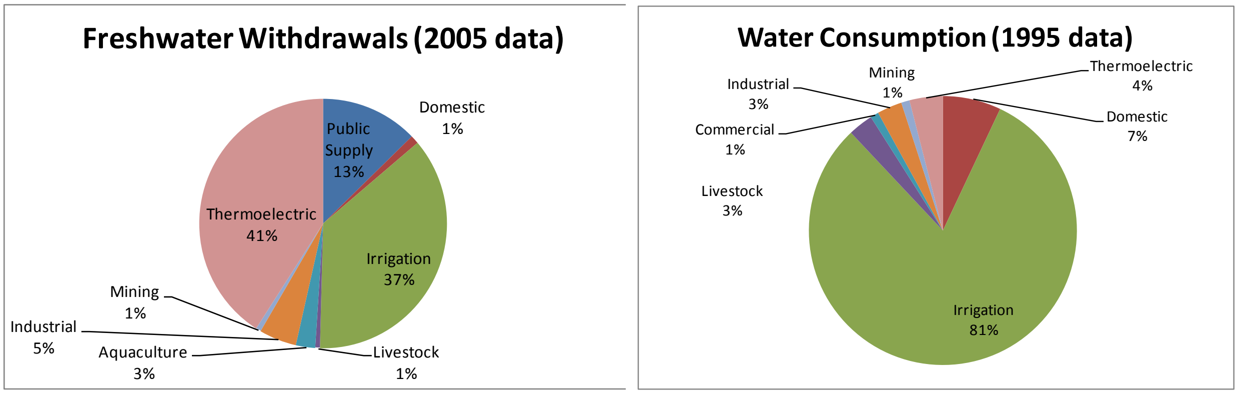

Figure 1. U.S. Freshwater Withdrawals and Consumption[1]

This report compares water consumption requirements for relevant fuels. It also shows the difference in water withdrawals for power plants with various cooling technologies. Figure 2 illustrates inputs, outputs and losses for water balance calculations. Water consumption for this report is considered on a lifecycle analysis basis, with the well (or mine, farm, etc.) to the vehicle tank (or battery) production chain establishing the system boundary. This will be referred to hereafter as well-to-tank (WTT).

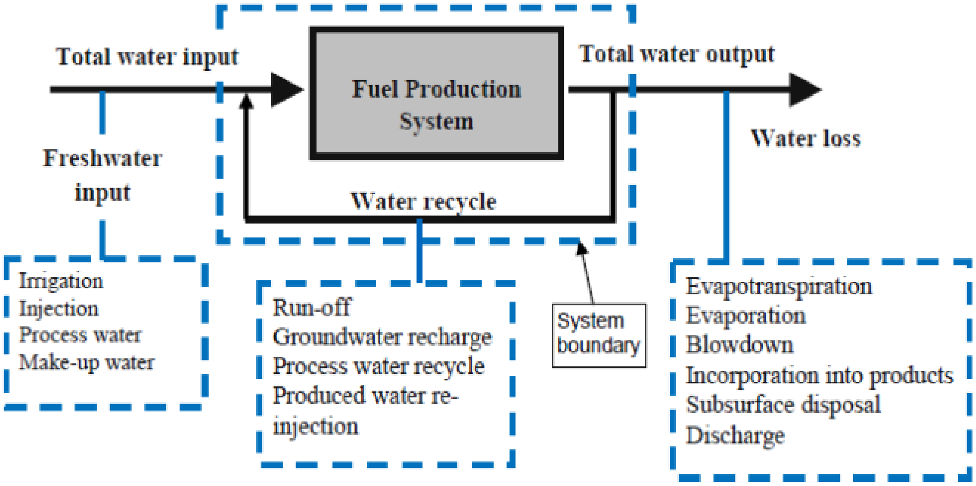

Figure 2. Water Balance for Energy Production Facility[2]

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[1] USDOE, Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water, 2006. http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf
Kenny, J.F., et al. *Estimated Use of Water in the United States in 2005*. Circular 1344. USGS, U.S. Department of the Interior. Reston, Virginia. 2009.

[2] Wu, Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline, Argonne National Laboratory, 2009. ANL/ESD/09-1

Water consumption for a given energy feedstock can vary significantly depending on feedstock production technology (e.g., electricity from various sources, biofuels from agriculture, oil production by primary recovery vs. waterflood, or gas production by primary recovery vs. hydraulic fracturing). Similarly, the process configuration of a fuel manufacturing facility or power plant impacts net water consumption. This includes the choice of cooling technology, plant operating conditions (e.g., power plant operating temperature), and extent of internal recycling of water. This report utilizes publically available literature to show ranges for fresh water consumption for fuel and energy pathways.

The impact of water on the economics of power and fuels production is related to: 1) the cost, availability and quality of the source water; 2) treatment required for use in the process; and 3) the treatment and regulatory compliance necessary for disposal of wastewater. These factors influence the choice of process technology and the extent of water reuse and recycling within the facility.

Fossil Fuels

Water use associated with transportation fuel production varies greatly between fuel types and is dependent upon the method of extraction and refining. Crude to fuel pathways discussed here include the refining of crudes from conventional, waterflood, CO2 flood, and steamflood recovery mechanisms. Pathways using unconventional resources are oil sands (in situ and mining) and the FT (Fischer-Tropsch) coal-to-liquids and gas-to-liquids processes. Literature values for the water use in gallons per MMBTU fuel produced are given as ranges for each pathway and pathway components (upstream versus downstream). In this report, upstream denotes all processes prior to refining and/or conversion, and downstream denotes processes from refining to distribution. Upstream processes consume more water than their downstream counterparts in the crude oil pathways. All pathways are shown in Figure 3.

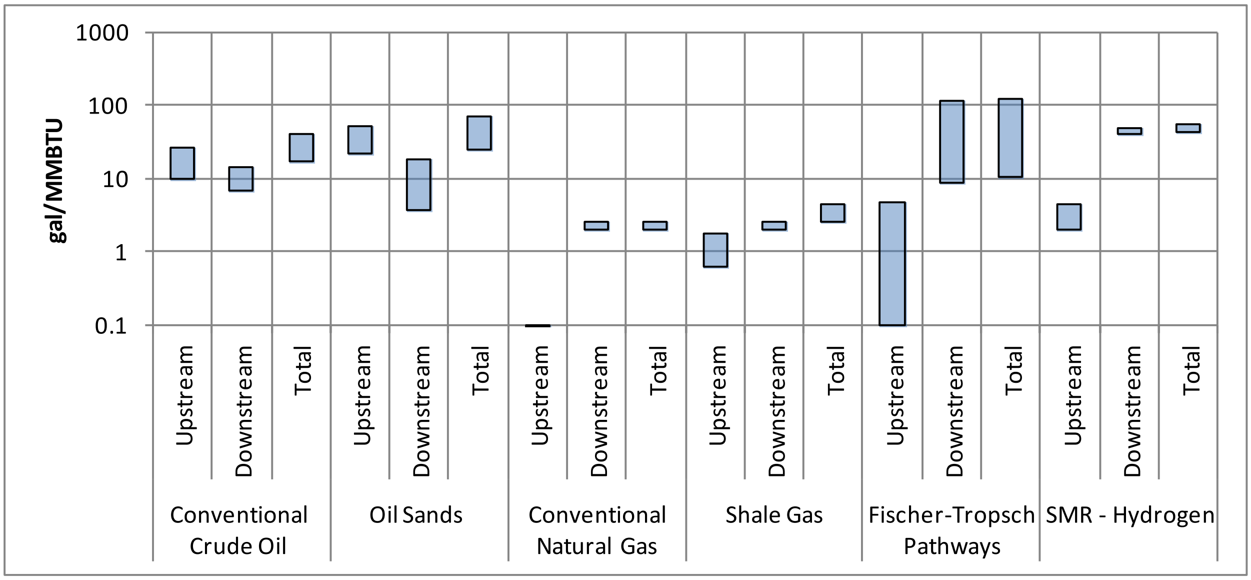

Figure 3. Well-to-Tank (WTT) Hydrocarbon Transportation Fuel Pathways – Fresh Water Consumption (Gal/MMBTU)

Crude oil is assumed to have energy equivalence of 5.8 million BTU per barrel (42 gallons).

Care must be taken when interpreting the water consumption ranges for the different pathways. The broad ranges can be based on regional differences in reservoir characteristics and how the water is recycled, re-used, or treated. Moreover, oil and gas field production characteristics change significantly over time, so the water requirements for a given production technology depend on the site-specific reservoir characteristics, which are a function of the age and production history of the field.

Crude Oil and Natural Gas Pathways

Petroleum extraction consumes relatively little fresh water. Fresh water is used for well construction processes such as drilling and completion in oil and gas resource development. Primary oil and natural gas production, which uses natural reservoir pressure to flow fluids to the wellbore, requires little water. Secondary methods of recovery, such as water flooding, require increasing amounts, as fresh water may sometimes be required to augment the volume of saline produced water that is re-injected back into the reservoir for pressure support. According to a study of U.S. oil production, the majority of the produced water (approximately 70%), is re-injected to maintain reservoir pressures. The remainder is either cleaned and discharged, or injected into disposal wells.[3] Enhanced oil recovery (EOR) methods, such as CO_2 or steam injection consume varying amounts of fresh water depending on the process. Unconventional sources of petroleum such as Canadian oil sands consume varying amounts of water depending on the recovery process. A recent analysis estimates the range of well-to-tank fresh water consumption for crude oil produced onshore in the U.S. is between 22 and 53 gallons per MMBTU, with a technology weighted average of 34 gallons per MMBTU.[4] Combining offshore production (as primary recovery with no water consumption) with the onshore production provides a range of fresh water consumption for all U.S. crude oil between 17 and 40 gallons per MMBTU, with a technology weighted average of 27 gallons per MMBTU, including downstream refining.

Enhanced oil recovery relies on the use of advanced processes such as supercritical CO_2 or steam, among other sources, to extract oil from formations where primary and secondary recovery methods leave behind economically recoverable quantities. Steamflood operations require significant volumes of water for steam generation. This water is often from fresh water sources, or extensively treated produced water. CO_2 flood operations require large volumes of water for controlling the mobility of oil and CO_2 in the reservoir (alternate CO_2 and water injection). This water generally is from saline, produced water sources and the process does not impose a significant burden on fresh water supplies.

The extent to which produced water is recycled and re-used also has a big impact on fresh water demands for oil and gas production. Where produced water has low salinity, it can be cleaned to meet beneficial reuse water quality specifications, and often it makes oil and gas production a net producer of fresh water. Fresh water supply limitations, increases in environmental performance expectations and advanced water treatment technologies are enabling increases in water reuse.

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[3] Wu, 2009

[4] Wu, 2009

Crude Oil Refining

Crude oil refining consumes fresh water for cooling, boiler feedwater, crude desalting, and other processes. This requires refineries to be located in areas with access to stable supplies of water. Refineries typically have extensive water treating facilities and discharge processed/cleaned excess water to surface streams or lakes.

Natural Gas

Conventional natural gas production requires very small (assumed to be negligible) amounts of water for well drilling and completion. Natural gas processing plants use water for cooling and power generation. The development of shale gas resources requires water for hydraulic fracturing of the shale formations to increase the permeability and enable gas to flow to the producing wells. Over the life of a shale gas well, the water consumption is surprisingly small, though significant volumes are needed over short time periods for hydraulic fracturing. Producers are reusing more of the flowback water at subsequent fracking sites. The requirements for water quality for the fracture fluids are still being optimized, moving towards higher limits on total dissolved solids (salinity), thus enabling greater reuse of flowback water. More detail on shale gas production is provided in a recent NPC report.[5]

Fischer-Tropsch Pathways

GTL (gas to liquids) and CTL (coal to liquids) pathways use fresh water for cooling, boiler feedwater, and process water. Minor amounts of water are associated with feedstock extraction. The amount of water required in CTL can depend on the amount of water entrained in the feedstock and other variables such as plant design.[6]

Hydrogen from Natural Gas

Natural gas is the feedstock for the primary method of hydrogen production used in petroleum refining, and potentially for use as a transportation fuel. For hydrogen production by steam methane reforming (SMR), the greatest water consumption is in the production of high-pressure steam and, to a lesser extent, the reforming and water gas shift reactions.[7] Typically it takes 40-50 gallons of water to produce an MMBTU of H_2 fuel.[8,9]

Electricity

Thermo-electric generation is one of the major users of fresh water in the U.S. Although it comprises over one third of all water withdrawals, it only accounts for 4% of fresh water consumption (shown in Figure 1). This discussion highlights water use characteristics of various methods of power generation. Fresh water consumption for the most common sources of electricity generation is shown

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[5] NPC, Prudent Development – Realizing the Potential of North America's Abundant Natural Gas and Oil Resources, Sep. 2011.

[6] Marano and Ciferno, Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels, 2001.

[7] Spath, P. and M. Mann, Life Cycle Assessment of Hydrogen Production via Natural Gas Reforming, NREL, 2001.

[8] King, C. and M. Webber (2008). "Water Intensity of Transportation." Environmental Science & Technology 42(21)

[9] Pate, 2007

Figure 4. The upstream component reflects water volumes required in the extraction and transportation of fuel to a power generation facility. The downstream component describes water used within the generation facility.

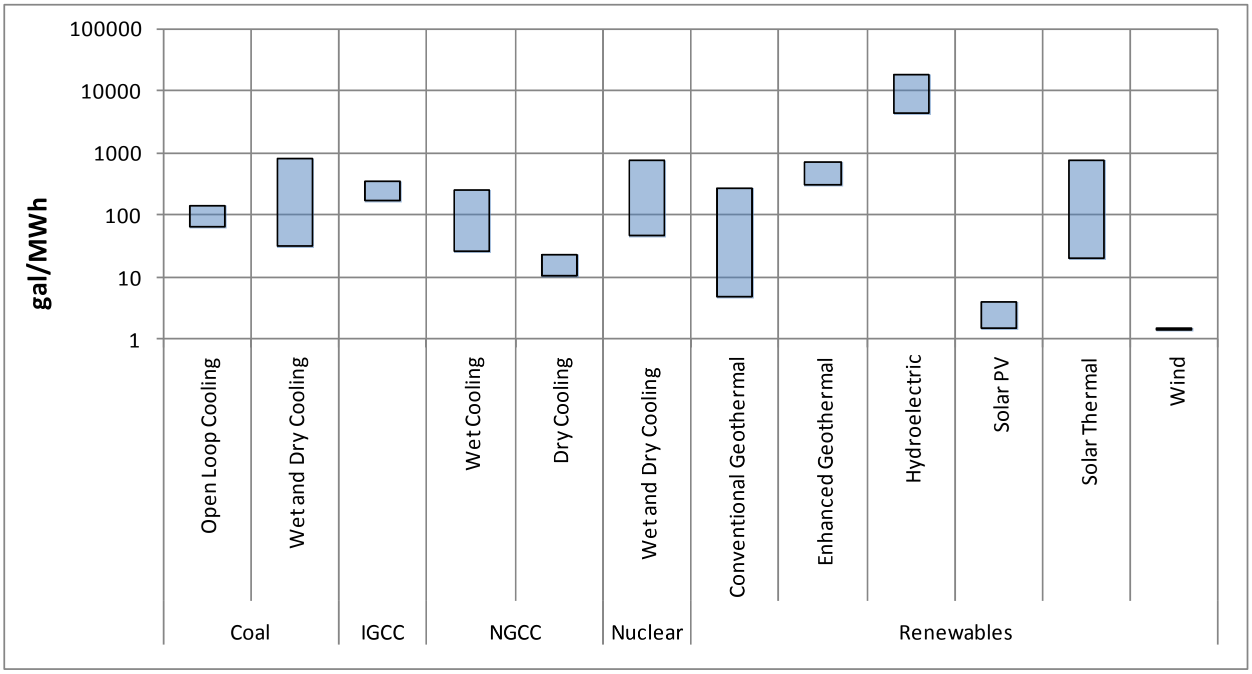

Figure 4. Power Generation Pathways – Life Cycle Water Consumption (gal/MWh)

Thermo-electric power generation uses the chemical energy in fuel to heat water, which is expanded through steam to mobilize turbines to drive an electrical generator. Waste heat recovery processes (such as combined cycle power generation) extract as much energy from the combustion process as is economically viable for the plant. The main consumption of fresh water for thermo-electric generation is in cooling. Primary methods of cooling are wet and dry cooling. Wet cooling uses water as a heat transfer medium and may be either a once-through “open loop” or circulating “closed loop” system. Open loop cooling uses an artificial lake or natural waterway to extract water and pump it through the cooling heat exchangers of the plant. The water is only pumped through one time, and the heat (or temperature) gain to the water is generally small. The water is then discharged back into the waterway. This method consumes the smallest volume of water. A closed loop system uses cooling towers to cool water that is confined within heat exchange loops in the plant. Cooling is caused by water evaporating in a cooling tower. Water used in circulating systems is often exchanged with new make-up water to prevent mineral build up. The removed water is called blowdown, and it is generally treated and discharged back to a waterway.

Dry cooling technologies, where air is used as the heat transfer medium across a fin-fan heat exchanger, can be utilized to minimize water consumption. Plants with dry cooling systems have higher capital costs than plants with wet cooling systems and are less thermally efficient due to the parasitic load of dry cooling. The comparison of operating costs for wet and dry systems depends on the price of water and the price of power. Moreover, there are significant power production capacity limitations on very hot days due to cooling capacity constraints with dry cooling systems (caused by steam turbine backpressure increases), resulting in potentially lower generation capacity. Dry cooling is best suited to wet, cool climates (not the hot and arid climates where water scarcity is typically greatest). The Electric Power Research Institute has written a comprehensive report showing the performance and cost characteristics for various types of power plant cooling technologies.[10]

Natural gas combined cycle (NGCC) plants are some of the most thermally- and water-efficient power plants. The primary power output comes from the expansion of hot combustion gasses turning a turbine which drives the generator. The cooling load and water requirements for gas turbines are minimal. The secondary power output comes from the steam cycle of an NGCC plant. Waste heat is recovered from the combustion flue gas to heat water and convert it to steam to turn a steam turbine which generates power. The steam cycle generally accounts for a third of the total output of the NGCC plant. An NGCC plant may more efficiently utilize dry cooling than a nuclear or coal plant, where all of the power is produced by the steam cycle.

Nuclear facilities often use once-through cooling systems, but it is not expected that such systems will be utilized for new facilities. The range shown in Figure 4 is for dry cooling and closed-loop wet cooling; however, no existing nuclear plants utilize dry cooling. Uranium fuel supplies require water for mining, milling, conversion to uranium hexafluoride, enrichment and fuel reprocessing (if applicable).[11]

Power plants that use heated water as the expansion medium also require highly processed water for steam generation. This water is softened and de-ionized to prevent mineral buildup in the steam generators or power turbines. A portion of this water (blowdown) is removed from the system to prevent mineral buildup. The blowdown water is generally treated and discharged to a waterway.

Water consumption for pulverized coal plants depends mainly on the type of cooling technology, the boiler operating temperature (subcritical, supercritical and ultra-supercritical) and the type of emissions control (e.g., flue gas desulfurization, wet or dry). The integrated gasification combined cycle (IGCC) coal technology uses less water than pulverized coal plants with wet cooling, primarily because a large fraction of the power is produced by a combustion turbine which requires minimal water. Water is used in the gasification reaction and in cooling for the steam cycle.

Renewable electricity sources made up 11% of total U.S. power production in 2009, according to the EPA statistics,[12] with hydroelectric power contributing 7% of the total power production. Hydroelectric power also represents most of the fresh water consumption for the renewable generation category due to evaporation from reservoirs. However, these reservoirs and dams serve other functions in addition to power production, so water losses may not solely be attributed to power production. Evaporation rates are highly dependent on the climatic conditions at the reservoir site. Solar photovoltaic and wind generation use little water. Solar tower and parabolic trough systems use a

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[10] EPRI, Comparison of Alternate Cooling Technologies for U.S. Power Plants, 2004

[11] Gleick, P. (1994). "Water and Energy." Annu. Rev. Energy Environ. **19**: 267-299

[12] http://www.eia.gov/cneaf/electricity/epa/epates.html

steam cycle, similar to other thermal generation technologies. When installed with wet cooling systems, these solar plants consume water in similar magnitude to their fossil fuel counterparts. Electricity generation from biomass combustion also uses a steam cycle, and may be combined with a coal fired plant to reduce the coal plant's carbon footprint.

In open loop, or once-through cooling, water withdrawals are very large since the cooling relies on changes in sensible heat, not the larger latent heat of evaporation. Water consumption is much smaller in open loop cooling, but there is decreased acceptance of such systems due to thermal pollution and impacts on aquatic/marine life and water quality. Environmental regulations (EPA 316a and 316b) make it difficult to permit new once-through plants. For coal and nuclear plants, where once-through cooling is most common, water withdrawals may be 35,000-40,000 gal/MWh, much higher than the water consumption values shown in Figure 4. In once-through cooling, the demand for very large water volumes can be problematic in areas with water shortages/stresses. There can also be limits on cooling water temperature, resulting in curtailed power production or mandated shutdowns because of inadequate cooling capacity.

Carbon capture and sequestration (CCS) applied to coal and natural gas fired generation will have a significant impact on water demands for power production. This is due to the reduced efficiency of the plant and additional cooling and process water used in the CO_2 removal process. Carbon capture can raise water consumption by 50-90% per MWh produced, depending on the process technology.[13]

Water Availability and Water Quality

Water availability is critical to the fuel and power industries. Depending on the region, climate, local water users, and fuel production pathway, the availability of water could be a limiting factor to resource extraction and energy production. This constraint will become even more important as population growth leads to increased energy and water demands. At the same time, petroleum fuels will be increasingly derived from unconventional resources and enhanced oil recovery processes that may have larger water footprints than conventional hydrocarbons.

While the availability of water is a key issue to the energy industry, the industry's impact on water quality has important environmental and societal impacts as well. Groundwater and surface water quality can be impacted by many processes in the fuel and power industries. A concise summary of water quality issues is given by the USDOE report to Congress on the energy-water nexus.[14]

The availability of water varies greatly from region to region, and water resources are typically managed at a local and state level. Fuel production options can be constrained by regional water resource availability.

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[13] USDOE/NETL, Water Requirements for Existing and Emerging Thermoelectric Plant Technologies, 2009

[14] USDOE, 2006

Summary and Emerging Issues

While water consumption for fossil fuel and electric power production is a relatively small portion of total fresh water consumed in the U.S., it is often a matter of political and public concern. There are a number of challenges facing water management for energy production. A major issue is the growth of electric power generation in water-stressed areas, especially the Western U.S. Another issue is diminished water resource availability due to potential changes in climate. For unconventional natural gas and oil production, there is concern over the volumes of water needed for hydraulic fracturing. The increasing production of unconventional hydrocarbon resources and renewable energy technologies such as solar thermal will place greater demands on water resources in parts of the country that have not historically been a major part of the energy supply. Additionally, use of CCS to control greenhouse gas emissions may place increasing demands on water resources in regions that have been part of the historical energy supply.

Thermo-electric power generation consumes large amounts of water, mainly for cooling. Once-through, or open loop cooling processes consume less water than closed-loop evaporative cooling, but require large water withdrawals and are not favorable environmentally. Water consumption can be drastically reduced by utilizing air cooled systems, but with higher capital costs and efficiency/capacity penalties.

Advances in water treatment technologies and increasing water scarcity are driving the development of water reuse projects in oil and gas production facilities, power plants and refineries. For example, use of treated effluent from industrial or municipal wastewater treatment plants in industrial facilities is a way to displace freshwater use at these facilities. Produced water from oil and gas production can be a new water resource if it can be cleaned up economically, instead of being disposed of as a waste stream. Hydraulic fracturing companies increasingly are re-using more of the flow back and produced water to displace fresh water supplies. Advances in desalination technologies are enabling the economical development of brackish water and seawater resources for process water in energy and fuels production. Increased water scarcity, water pricing escalation and advances in water treatment technology will drive the development of alternative water resources and recycling programs.

Biofuels

The biofuel pathways listed in **Table 1** have been evaluated for consumptive water use in feedstock production and conversion to fuels in the biofuel value chain. Estimates for water consumption are from published literature, and a brief description of the issues surrounding water use, water quality, and water availability is provided.

Table 1. Select Biofuel Pathways

Fuel	Feedstock	Conversion Process
Ethanol	Corn	Fermentation - Dry Mill
		Fermentation - Wet Mill

Fuel	Feedstock	Conversion Process
	Sugarcane	Fermentation
	Switchgrass	Cellulosic Fermentation
	Corn Stover	Cellulosic Fermentation
Biodiesel	Soybean	FAME
Biogasoline	Forest Residue	Pyrolysis
FT Diesel	Forest Residue	Fischer Tropsch
Renewable Diesel	Soybean	Hydroprocessing

Water use related to biofuel production has been well described by numerous works.[15,16,17,18,19] This section will give a brief overview of water use and related issues as they apply to the selected biofuel pathways.

The United States' Renewable Fuels Standard (RFS) mandates significantly increased production and use of first-generation and advanced biofuels. Water is intimately tied to the major components of the biofuel production chain –used directly during feedstock production and conversion, and impacted by erosion, runoff, and industrial discharges. Existing demands and impacts on fresh water resources will be increased by the biofuel production mandated by the RFS.

The location of feedstock production, the type of feedstock produced, and the location and type of conversion facilities is dependent, in part, on the availability of adequate and balanced water resources. Adequate water supplies in agriculture and industry are those that allow production to occur at prescribed scale. Balanced water supplies are those that are able to replenish consumed water with precipitation or groundwater recharge. Feedstock production or conversion processes that require water from unbalanced water sources do not demonstrate long-term sustainability. Irrigation and biorefinery water use have acute impacts on local water resources.

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[15] NRC 2011. Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Polity. Committee on Economic and Environmental Impacts of Increasing Biofuels Production; National Research Council. ISBN 978-0-309-18751-0

[16] NRC 2008. Water implications of biofuels production in the United States. Water science and technology board. Division of Earth and Life Studies. National Research Council of the National Academies. The National Academies Press, Washington, DC. ISBN 13: 978-0-309-11361-8

[17] Tidwell, V., A. Cha-tein Sun, L. Malczynski. 2011. Biofuel Impacts on Water. Prepared by Sandia National Laboratories. SANDIA REPORT SAND2011-0168

[18] Elcock, D. 2008. Baseline and projected water demand data for energy and competing water use sectors. Argonne National Laboratory. ANL/EVS/TM/08-8

[19] Wu, 2009

The projected increase in production of biofuel feedstocks between 2006 and 2030 is expected to result in an additional 6.4 billion gallons per day of water withdrawals in the United States. Associated with this withdrawal will be an increase of 5.2 billion gallons per day of water consumption, an increase of over 5% from current total U.S. water consumption (see Figure 1). Compared to the water needed to grow the feedstock, water withdrawals and consumption related to feedstock processing are minor, as they increase from 0.09 to 0.5 and from 0.07 to 0.4 billion gallons per day, respectively.[20] Water consumption increases will vary by region and may represent a significant impact on water supplies in areas that are already water-supply stressed.

Biofuel Consumptive Water Use

Water consumption in the biofuel value chain is caused by evaporated and transpired[21] irrigation water, pollution, and water lost during industrial processes within biorefineries. Evaporation during cooling is the primary source of water consumption in biorefining. Water use in biorefineries may also include feedstock cleaning, fermentation, and other processes. A typical biofuel water balance is shown in Figure 5.

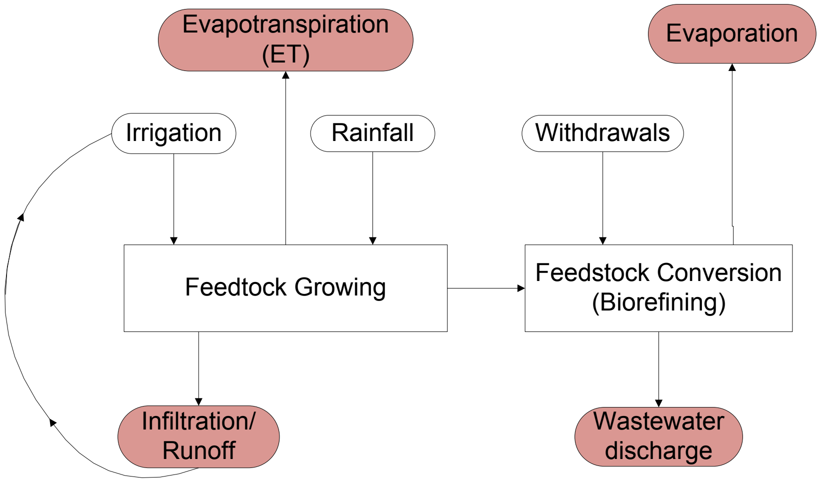

Figure 5. Biofuel Water Balance

Feedstock Production

With the complete implementation of RFS2 in 2022, cellulosic feedstock and corn production for biofuel is expected to approximately double water use compared with biofuel water use in 2006. The increase is likely to be caused by the future production and processing of cellulosic feedstocks. Corn ethanol production is not likely to contribute to the increased water demands as most corn acreage that would be brought into production for ethanol is already irrigated for other uses.[22] Any feedstock (cellulosic

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[20] Tidwell, 2011

[21] Transpiration is the process by which plants excrete water vapor via actively opening stomata (pores on leaf surfaces).

[22] Tidwell, 2011

biomass or corn) which is dependent on precipitation rather than irrigation will be advantaged from a water resources perspective.[23]

Production of the same feedstock in different climates results in a range of water consumption profile values for each crop. For example, water consumption for corn production in three areas of the Midwest with different water balances is shown in Table 2.[24] In production regions that are more arid, farmers rely more on irrigation. Though precipitation is not the only determining variable, this general relationship between precipitation and irrigation requirements applies to most crops.

Table 2. Precipitation and Irrigation Needs (Wu 2009)

Region	Precipitation (inches)	Irrigation (gal per MMBTU Ethanol)
Lower Midwest (region 5)	37.8	93
Upper Midwest (region 6)	29.5	183
Western Midwest (region 7)	21.7	4,218

Estimates of crop water use can be made for nearly any crop in any region using evapotranspiration models. Such methods account for the water requirements of each plant and the climate of the production region to estimate water requirements for optimal growth. An example of such a model is available from the Food and Agriculture Organization of the United Nations.[25]

Feedstock Conversion

Different conversion processes have very different water withdrawal and consumption requirements. Thermo-chemical and biodiesel conversion pathways have lower water requirements than fermentation pathways. The FAME process of biodiesel production and the hydroprocessing of bio-oils require very small water inputs due to the nature of the conversion processes.

Gasification and pyrolysis processes generally use water for cooling processes, and water re-use can make them water efficient. Fermentation processes utilize water for grinding, liquefaction, fermentation, separation, and drying. Water losses primarily occur through evaporation, drift, blowdown and leaks during these processes. The biochemical conversion process for cellulosic feedstocks requires additional water for the pretreatment processes.

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[23] Wu, 2009

[24] Wu, 2009

[25] FAO 2001. FAO Methodologies on crop water use and crop water productivity. Paper No CWP-M07. Expert meeting on crop water productivity. Rome, December 3-5, 2001

Water Consumption Ranges for Selected Biofuel Pathways

While the amount of water (precipitation and irrigation) needed to grow biomass feedstocks dwarfs the amount of water used during conversion, certain feedstocks do not require irrigation (i.e., forest residues and dedicated feedstocks grown in regions with enough precipitation to meet the demands of growth). In these instances, the biomass conversion component of the value chain will be the dominant factor in determining total water consumption.

The general ranges for water use in feedstock production and conversion are shown in Figure 6. The representative reference values for fresh water consumption are based on reasonable feedstock production scenarios. For example, forest residues will be collected as a byproduct from naturally forested regions requiring no irrigation. Maximum values represent production under conditions where water is supplied via irrigation and then lost through evaporation and transpiration. Pathways for gasoline and diesel are provided for comparison purposes.

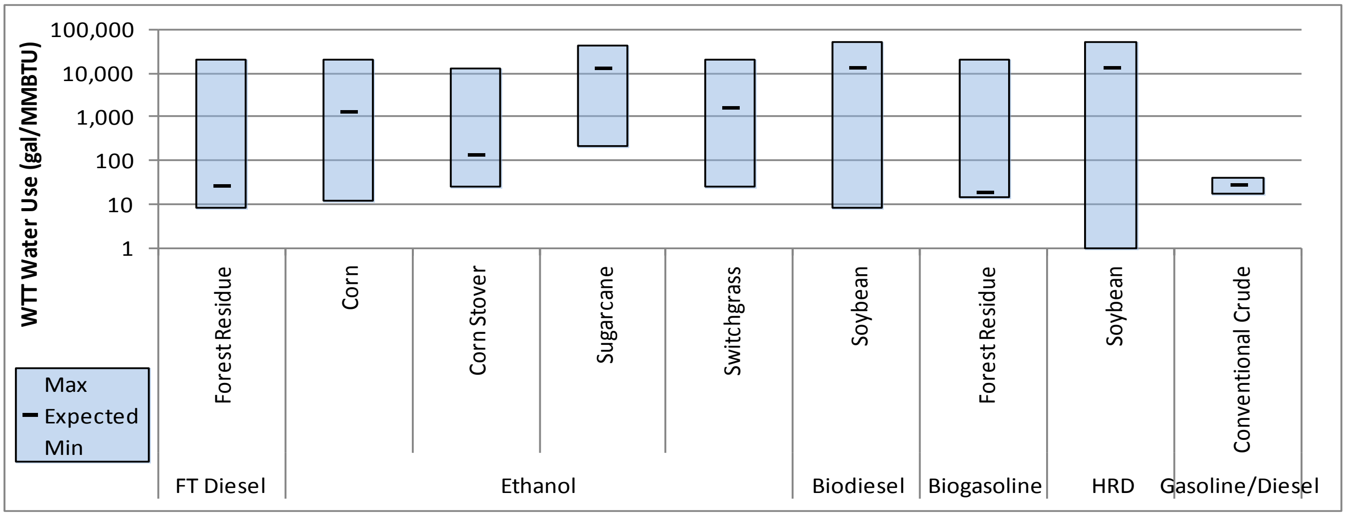

Figure 6. Well-to-Tank (WTT) Water Consumption for Various Biofuel Pathways

Water Quality

Water quality impacts should be considered on the scale of biofuel production required under the RFS; however, no comprehensive life cycle assessment has been undertaken to estimate these impacts. There is general consensus that the RFS regulation will intensify agriculture's impact on water quality and increase industrial water discharges from biorefineries.[26] Unless perennial lignocellulosic feedstocks replace annual row crop feedstocks, there will be more water consumption, soil erosion, and runoff of agrichemicals and fertilizers relative to current rates.[27,28] Intensification of agriculture may

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[26] NRC, 2011

[27] NRC, 2011

negatively impact water quality, leading to increased turbidity[29] and eutrophication[30] of surface waters. Additionally, the majority of land suitable for biofuel feedstock production is within the Mississippi Drainage Basin, and intensification of agriculture may increase the size and impact of the Gulf of Mexico hypoxic zone.[31]

Water Availability

Biofuel production will have to compete with industrial and power generation requirements, municipalities, and other demands for limited water resources. In general, surface and ground water resources experience regional pressure in most areas of intensive agriculture in the U.S.[32] Since annual precipitation and groundwater recharge are finite in all places, increased agricultural consumption associated with feedstock production should be carefully evaluated. Water withdrawals and environmental discharges associated with biorefineries should also be considered. Geographies with stressed water resources can be severely impacted if total water requirements are not thoughtfully considered. Nebraska, Kansas, Colorado, Texas, the Dakotas, eastern Washington and Oregon have stressed or unbalanced water resources (more consumption than recharge) and rely primarily on irrigation for crop production. During periods of drought in any geography, biofuel crops require additional irrigation support to maintain yields. Depleted water resources (Ogallala aquifer, etc.) may not satisfy demand, which will limit the productivity and sustainability of biofuel production.[33]

Water Consumption per Vehicle Mile Traveled

A useful metric for comparing water consumption is to consider it on the basis of gallons used per distance traveled in selected fuel/vehicle systems. The use of biofuels may have a relatively high water requirement if irrigated feedstocks are used. Fuels with relatively low water consumption include diesel, gasoline, natural gas, hydrogen, and certain non-irrigated biofuels. The use of electricity as a transportation fuel may also offer a relatively low water consumption option if electricity is sourced by non-hydroelectric technologies or if the water consumption by hydroelectric installations is allocated across multiple reservoir uses.

Figure 7 shows the Well-to-Wheel (WTW) water consumption ranges (gallons per mile traveled). Water consumption data is used in combination with 2050 fuel economy from the NPC analysis (see the Light Duty Vehicles chapter of the Future Transportation Fuels Study) to estimate ranges for water consumption per vehicle mile traveled. Water requirement data for each fuel option are from publicly

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[28] Georgescu, M., D.B. Lobell, and C.B. Field. 2010. Direct climate effects of perennial bioenergy crops in the United States. Proceedings of the National Academy of Sciences. www.pnas.org/cgi/doi/10.1073/pnas.1008779108

[29] Cloudiness of water due to suspended sediment.

[30] Process by which water becomes enriched in dissolved nutrients that stimulates the growth of aquatic plant life, which in turn usually leads to depletion of dissolved oxygen.

[31] Area of reduced dissolved oxygen along Texas-Louisiana coasts believed to be due primarily to excess nutrients delivered via the Mississippi River combined with seasonal stratification of Gulf waters.

[32] Tidwell, 2011

[33] Tidwell, 2011

available data presented in preceding sections. In cases where projections out to 2050 were not available, the most forward looking projection is used and assumed to remain unchanged to 2050. (For example, if data was only available to 2020 for a fuel option, data projected for 2020 were used in the analysis and assumed to remain unchanged to 2050.) The assumed 2050 electricity generation mix is from the AEO2010 Study Reference Case.

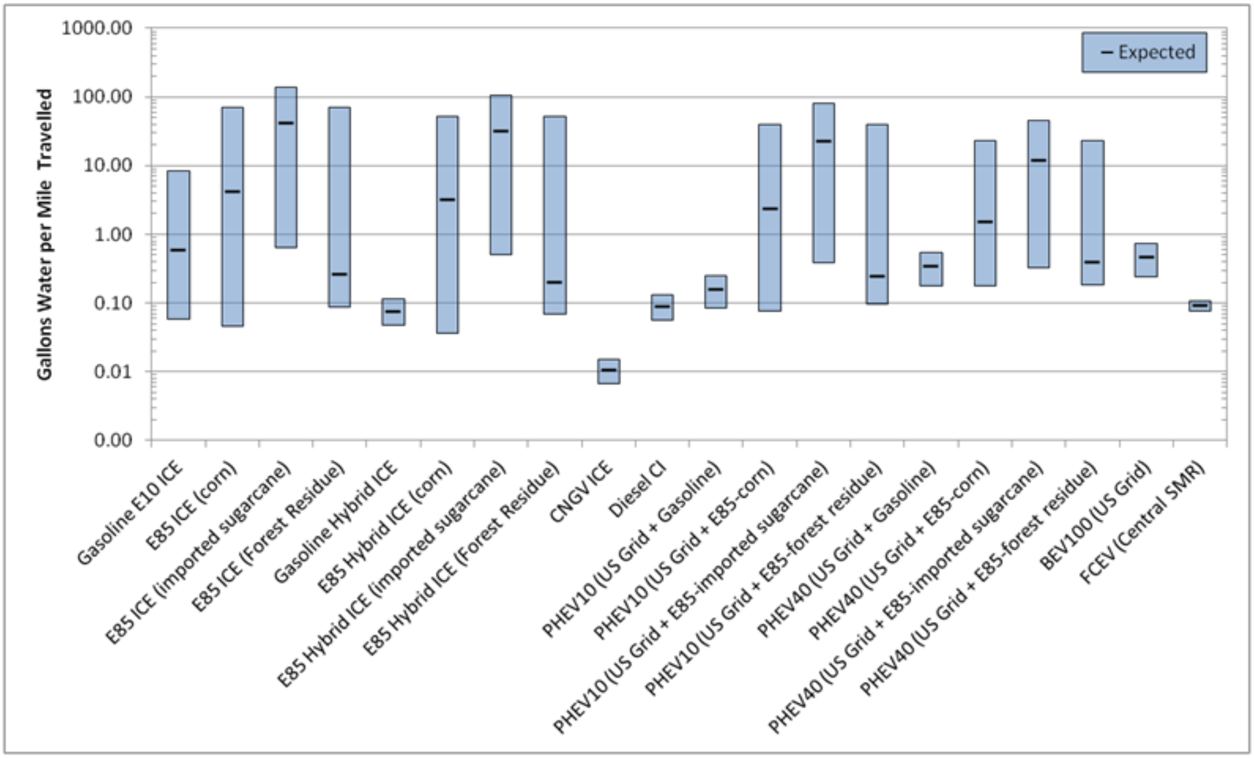

Figure 7. Well-to-Wheels (WTW) Water Consumption for Fuel-Vehicle Systems

Fuel/vehicle systems that rely solely on fossil fuels (diesel, gasoline, and natural gas) have the smallest estimated water consumption ranges. Diesel and natural gas fuels have the lowest WTW water use profiles in this analysis. Diesel has lower water use than the E10 gasoline because it has no biofuel component. The biofuel contribution to E10 gasoline was assumed to be corn ethanol. U.S. grid-based (BEV) has relatively low water use per mile traveled compared to biofuels.

Electricity used for transportation assumes a 2050 U.S. grid mix projection per Argonne National Laboratories' VISION model. The grid water consumption factor was derived from a combination of the reported thermoelectric power water consumption and the range of water consumption for non-thermoelectric technologies. In 2005 NETL reported that 3.7 billion gpd in 2005 was consumed[34] for producing 3.732 million GWh electricity.[35] This gives a non-renewable thermoelectric consumption factor of 362 gal/MWh. Including water consumption for the renewables mix increases this water consumption significantly, to between 700 and 2000 gal/MWh. This is mainly driven by the

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[34] NETL, 2008
[35] EIA energy statistics for 2005

hydroelectric power water consumption, with the associated allocation issues described in the power generation section of this report.

The renewables electricity water consumption is dominated by hydroelectric power. The use of hydroelectric power, and the assumptions regarding fresh water consumption from such installations, also drives the range of water use in the U.S. grid. Literature sources[36] estimate hydroelectric freshwater consumption between 4,500 and 18,000 gallons per MWh, due to evaporation. The sources attribute all evaporation to hydroelectricity production, though they point out that the reservoirs enable other uses, such as recreation, flood control, and irrigation. No allocation of water consumption between the multiple uses was done. As a consequence, the water consumption from hydroelectricity could be significantly less than what is reported here.

Water consumption from the PHEV is lower than that of the BEV when using a combination of U.S. Grid electricity and gasoline. However, when the PHEVs utilize biofuel, the water consumption per mile increases significantly due to the water footprint of most biofuel production scenarios. The PHEV water footprint also increases as PHEVs rely more on grid electricity than gasoline. For example, the PHEV10 will consume less water per mile traveled than the PHEV40.

Though nearly all of the fuel and technology configurations present low water consumption per mile traveled under specific production scenarios, the maximum potential water use for some configurations is significantly higher than others. In general, the use of biofuels will increase water consumption per mile traveled in comparison to fossil fuels and electric vehicles. Water consumption is the highest when irrigation is required to produce biofuel feedstocks. Avoiding irrigated feedstocks puts consumptive water use for all fuel/vehicle systems on a similar order of magnitude; however, most biomass feedstock conversion is expected to consume more freshwater than fossil feedstock conversion. This relationship should be considered as the RFS requirements for biofuel volumes in the U.S. transportation fuel mix increase.

Panel of Expert Reviewers

This paper was reviewed by the following list of expert reviewers:

- **Wil Kirchner, Marathon**
- **Tom Binder, Archer Daniels Midland**

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[36] NREL TP-550-33905, 2003 and Gleick 1994

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