Energy Technology Innovation Policy Research Group

Water Consumption of Energy Resource Extraction, Processing, and Conversion

By Erik Mielke, Laura Diaz Anadon, and Venkatesh Narayanamurti

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Belfer Center for Science and International Affairs
Harvard Kennedy School
79 JFK Street
Cambridge, MA 02138
Fax: (617) 495-8963
Email: belfer_center@harvard.edu
Website: http://belfercenter.org

Harvard Kennedy School

WATER CONSUMPTION OF ENERGY RESOURCE EXTRACTION, PROCESSING, AND CONVERSION

A review of the literature for estimates of water intensity of energy-resource extraction, processing to fuels, and conversion to electricity

Erik Mielke*, Laura Diaz Anadon†, and Venkatesh Narayanamurti§

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* Corresponding author. Research Fellow, Energy Technology Innovation Policy research group, at the Harvard Kennedy School. E-mail: erik_mielke@hks.harvard.edu

† Associate Director, Science, Technology, and Public Policy Program; Director, Energy Technology Innovation Policy research group; Project Manager, Energy Research, Development, Demonstration & Deployment Policy Project, at the Harvard Kennedy School.

§ Benjamin Peirce Professor of Tech- nology and Public Policy and Professor of Physics at Harvard University and Director of the Science, Technology and Public Policy Program and Co-Principal Investigator of the Energy Research, Demonstration & Deployment Policy Project at the Harvard Kennedy School.

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EXECUTIVE SUMMARY

Water as a Factor in the Energy Supply Chain

Water and energy are closely linked. The water industry is energy-intensive, consuming electricity for desalination, pumping, and treatment of wastewater. The energy industry is also water-intensive, which is the focus of this report. Water is used for resource extraction (oil, gas, coal, biomass etc.), energy conversion (refining and processing), transportation and power generation. Energy accounts for 27% of all water consumed in the United States outside the agricultural sector (Electric Power Research Institute 2008). Water, like energy, is a commodity but with very different characteristics. Water is almost always local where energy tends to be more of a global sector, linked to fungible commodities.

Constraints on water availability often influence the choice of technology, sites, and types of energy facilities. For instance, water has always been a potential constraint for thermal electricity generation, given the large volumes of water typically required for cooling. Water availability is thus of paramount importance when deciding on a suitable location of a power plant.

This paper provides an overview of water consumption for different sources of energy, including extraction, processing and conversion of resources, fuels, and technologies. The primary focus of is *consumptive use of water* for different sources of energy. Where appropriate, levels of *water withdrawals* are also discussed, especially in the context of cooling of thermoelectric power plants.

The most comprehensive review of water consumption and energy production is a December 2006 report to Congress by the U.S. Department of Energy (DOE), titled "Energy Demands on Water Resources" (U.S. Department of Energy 2006). The DOE report was the starting point for this research effort, with additional sources used to increase the coverage of fuels (notably improved estimates for biofuels and shale gas production), additional processing technologies (coal-to-liquids and gas-to-liquids), and a more extensive review of water use in electricity from renewable sources, and carbon capture and sequestration (CCS). The data compiled in this analysis is based on an extensive review of available literature for the U.S. market, with particular emphasis on capturing recent trends where there may have been significant changes (e.g., biofuels, shale gas, and solar technology) and further studies completed. To the best of the authors' knowledge, there are no individual reports that have integrated information of resource extraction, processing, and conversion since the 2006 DOE report.

U.S. water consumption for energy

Water is becoming increasingly important in several aspects of U.S. energy production, including the expansion of biofuels, some sources of renewable energy, and cooling technologies for large power plants.

Absolute water consumption for energy production has been increasing in the United States, a trend that may continue if reliance on water-intensive fuels continues. Charts ES-1 and ES-2 summarize water consumption for fuel extraction and processing, and electricity production, respectively.

Thermoelectric **power plant cooling** accounts for between 3 and 4% of all U.S. water consumption, and has been increasing its share of total water use. New or modernized steam turbines and combined cycle gas turbine power plants being built predominantly use closed-loop cooling, a technology which has lower water intake but substantially higher net water consumption. Old power stations with once-through cooling are being updated or replaced with closed-loop cooling systems, (Chart ES-2). Consequently, water consumption from electricity production is likely to continue to increase even if production were to stay the same.

Biofuels are by far the most water-intensive source of fuel in the United States because of the extensive use of irrigation for corn production. The current generation of corn-based ethanol is particularly water intensive, consuming in excess of 1,000 gal/MMBtu on average, a water consumption one or two orders of magnitude greater than that of alternative sources of liquid fuels. A mandated move to advanced biofuels (cellulosic ethanol) could bring biofuels water-usage closer to other fuels, but these technologies are unproven on a commercial scale.

The recent shale gas transformation of the U.S. natural gas industry has also focused attention on the water-energy nexus, although the water consumption for the production of shale gas appears to be lower (0.6 to 1.8 gal/MMBtu) than that for other fossil fuels (1 to 8 gal/MMBtu for coal mining and washing, and 1 to 62 gal/MMBtu for U.S. onshore oil production). The increased role of **shale gas** in the U.S. energy sector could result in reduced water consumption (Chart ES-1). The water used for releasing the gas (hydraulic fracturing), however, has to be carefully managed at a local level. Concerns about potential contamination of freshwater supplies with hydrofracking fluids also need to be addressed. Natural gas-fired combined cycle power plants (CCGT) also have some of the lowest consumption of water per unit of electricity generated, helped by the relatively high thermal efficiency of CCGT plants (Chart ES-2).

Increased reliance on **nuclear** power, which has the highest water consumption of the thermoelectric technologies, and the potential for wide-scale **CCS deployment**, could also significantly increase water consumption (Chart ES-2). In contrast, some of the **renewable energy** technologies, in particular wind and solar photovoltaic, which have practically no water consumption (Chart ES-2), could contribute to reducing water consumption for the energy sector.

Finally, it is worth emphasizing that the wide range of water intensity estimates for the different processes investigated shows that, for each process, there are typically **alternative technologies,** which could reduce water consumption, albeit at a higher cost, with lower efficiency and/or reduced reliability.

Chart ES-1: Water consumption of extraction and processing of fuels

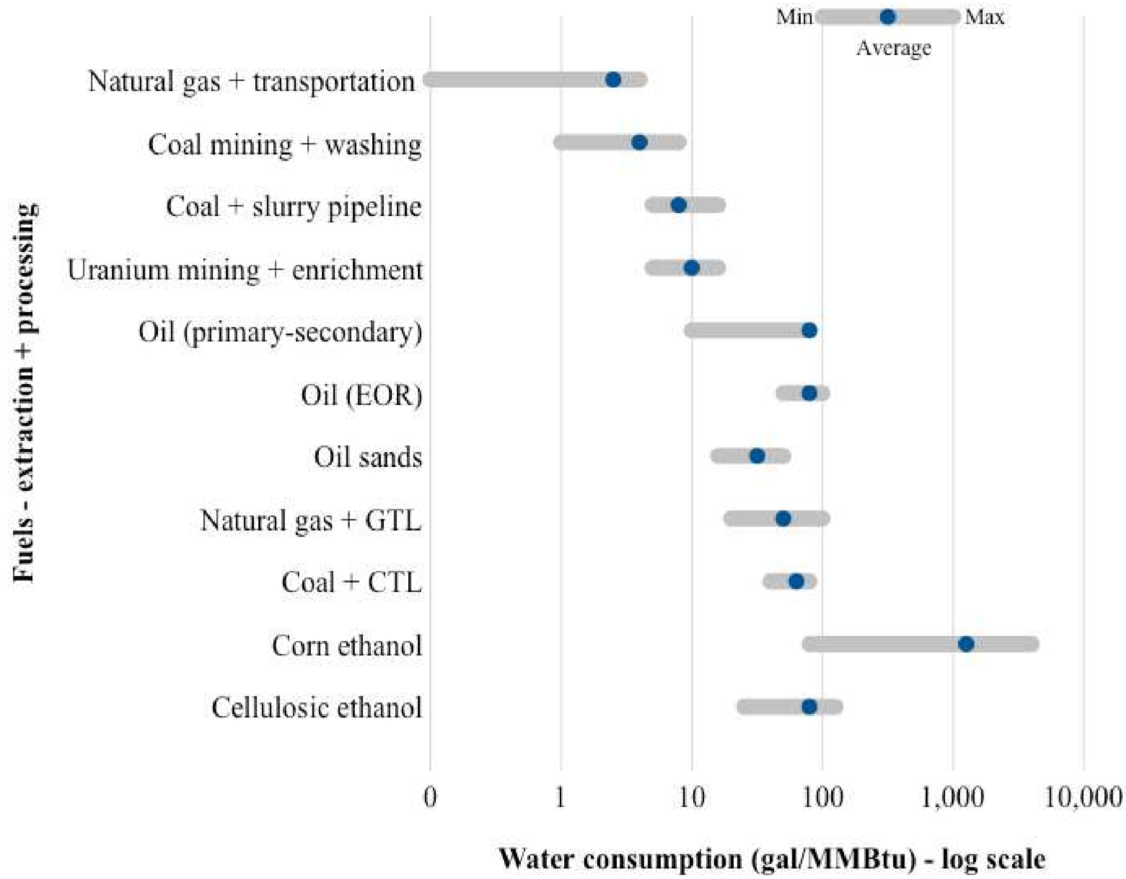
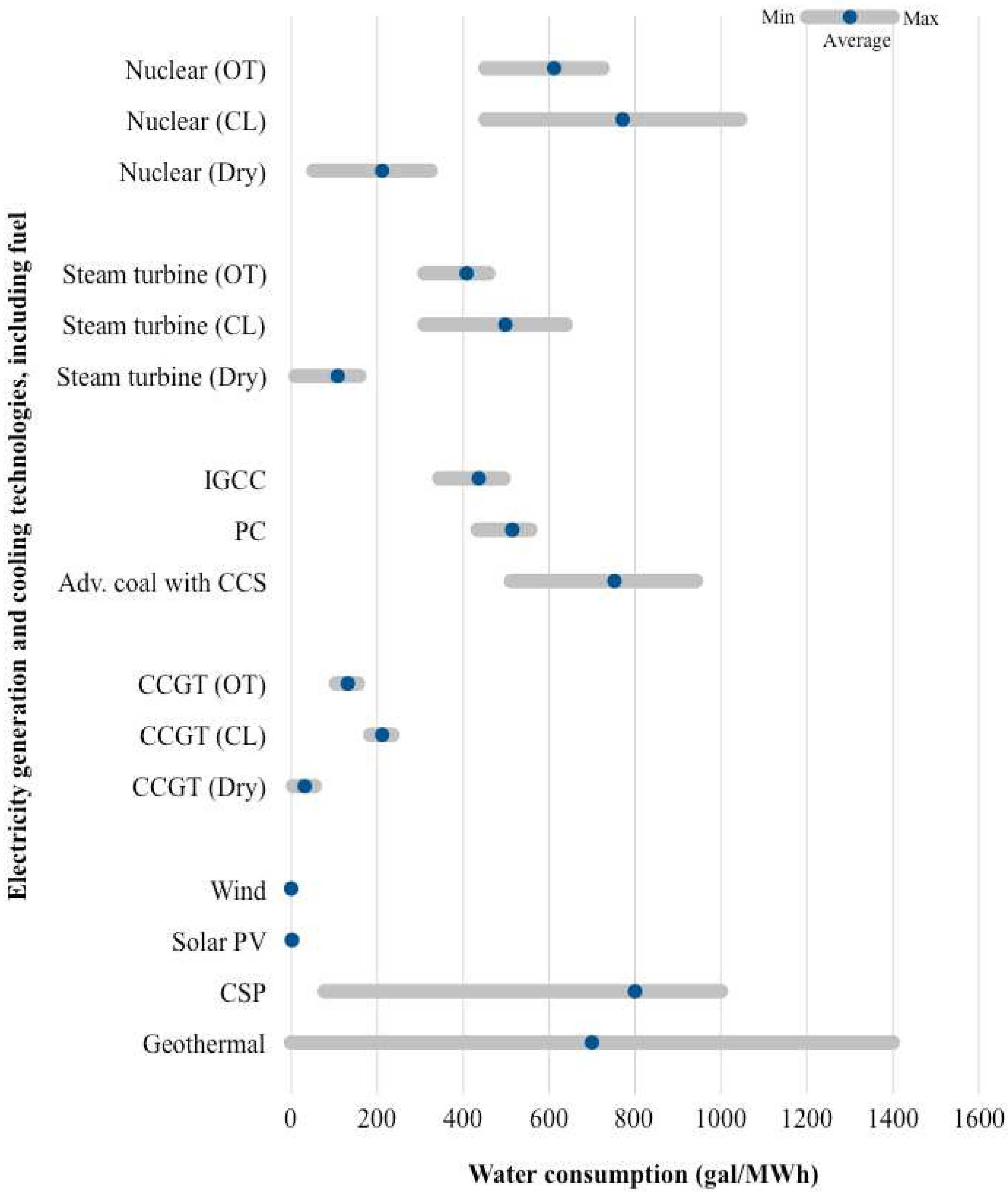


Chart ES-2: Water consumption in electricity generation using different cooling technologies, and including water consumed during fuel extraction and processing



1. INTRODUCTION

1.1. Water and Energy

This paper will provide an overview of the water consumption of different energy technologies, ranging including resource extraction, processing of resources into fuels, and electricity conversion technologies.

Water and energy are closely linked. The water industry is energy-intensive, consuming electricity for desalination, pumping, and treatment of wastewater. The energy industry is water-intensive, which is the focus of this report. Energy accounts for an estimated 27% of all water consumed in the United States outside the agricultural sector (Electric Power Research Institute 2008). Water is used for resource extraction (oil, gas, coal, biomass etc.), energy conversion (refining and processing), transportation and power generation. Constraints on water availability often influence the choice of technology, sites and types of energy facilities.

To illustrate this point, a coal-fired power plant with a once-through cooling system will consume ten times more water than coal (by weight) or many times more for a closed-loop system. This makes it cheaper to transport the coal to the water than the other way around (Gleick 1994, 267-299).

Water has always been a potential constraint for thermal electricity generation, given the large volumes of water required for cooling. Water is also becoming increasingly important in production of fuels, especially with the increased use of biofuels from irrigation-dependent agriculture.

Water, like energy, is a commodity but with very different characteristics. Water is almost always local where energy tends to be more global.

1.2. Methodology

1.2.1. Definition of Water Use

The U.S. Geological Survey separates water use into water withdrawal, *"water removed from the ground or diverted from a surface-water source for use,"* and water consumption, *"the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment."* (U.S. Geological Survey 2009)

The primary focus of this report is *consumptive use of water* for different sources of energy. Where appropriate, levels of water withdrawals will also be discussed, especially in the context of cooling of thermoelectric power plants.

1.2.2. Energy Sources and Technologies to be Reviewed

The technologies surveyed are listed in Table 1-1. They were chosen to cover most of the current and future potential U.S. energy balance.

Table 1-1

Extraction	***Processing***	***Power Generation***
Oil (primary, secondary, tertiary recovery)	Crude oil refining	Fossil fuel/biomass steam turbine
Oil sands	Ethanol dry mill	Combined cycle gas turbine
Oil shale	Biorefinery	Nuclear thermoelectric power plant
Natural gas	Coal-to-liquids	Advanced coal
Shale gas	Gas-to-liquids	Advanced coal with CCS
Coal		Wind power
Corn ethanol (irrigation)		Solar photo voltaic (PV)
Cellulosic ethanol (irrigation)		Concentrating solar power (CSP)
		Geothermal
		Hydropower

1.2.3. Literature Review

The increased focus on the water-energy nexus has led to a significant increase in the available literature, especially from government agencies (notably the U.S. Department of Energy and the U.S. Geological Survey), as well as academic institutions and various industry groups (e.g., EPRI). Most of the literature focuses on one specific area of the water use in energy, e.g., biofuels, but rarely looks at water use across the entire energy spectrum.

The best exception to this rule is a December 2006 report to Congress from the Department of Energy, titled “Energy Demands on Water Resources.” (U.S. Department of Energy 2006)

The DOE 2006 report is the starting point for this research effort, with additional sources used to increase the coverage of fuels (notably improved estimates for biofuels and shale gas production), to provide transparency and consistency of estimates, and to expand the discussion on the estimates provided by the DOE 2006 report.

The data sources used are deliberately, albeit not exclusively, U.S. centric, in line with the focus of the report. This is the case for some sources of crude oil production, oil sands production, and biofuels, non-U.S. sources and estimates have also been used. Coal-to-liquids and gas-to-liquids (CTL and GTL) technologies are currently only deployed internationally on a commercial scale. Non-U.S. estimates are clearly marked throughout the report.

1.2.4. Units and Conventions

The report primarily uses two units for measuring water-intensity of energy: *gal/MMBtu* (gallons of water per million British thermal unit of fuel) for fuel production and processing, and *gal/MWh* (gallons of water per megawatt-hour of electricity) for electricity generation. These units are the most frequently used in North American literature, including the U.S. Department of Energy’s reports (U.S. Department of Energy 2006).

For full-cycle water consumption analysis, the unit is gal/MWh, and includes a range of stated assumptions for fuel efficiency for electricity production.

For fuels, the high heating value (Btu content) has been used consistently.

1.3. Limitations of Study

The study brings together research from various sources, using a range of different methodologies, especially with respect to water consumption for extraction and processing for fuels.

1.3.1. Average vs. Marginal

Some studies focused primarily on arriving at a sensible estimate for average water consumption, potentially ignoring the impact of marginal water consumption being materially lower or higher than the average. Conversely, other studies did not provide typical average usage, making direct comparison and interpretation of the ranges more difficult.

1.3.2. Variability vs. Uncertainty

In most instances, the range of estimates of water consumption for a specific fuel or technology does not represent the true variability. For instance, the estimates of water consumed for corn irrigation (for ethanol production) produced a range reflecting various averages (irrigation, yield, soil, climate) on a regional basis. The ranges are likely incomplete, representing uncertainty around the mean rather than true variability. In contrast, the estimates for water consumption in shale gas developments were based on a range of observations from wells drilled in each of the shale plays where data was available.

The report explains throughout the source of the range but caution should be exercised when making comparisons across datasets, and especially when compounding ranges and averages as indeed this report does.

1.3.3. Technology Efficiencies

The full value-chain water consumption estimates require assumptions about underlying efficiencies of processing of different fuels and electricity generation. For instance, the report assumes that coal-fired steam turbine power plants have thermal efficiency of 33%, pulverized coal 40%, and IGCC 45%, and such simplifications should be borne in mind when comparing data across technologies.

1.3.4. U.S. Data Focus

By design, the study focuses primarily on U.S. data. In some instances, the data should be directly applicable outside the United States, especially for processing and conversion where the estimates are technology driven.

Global extrapolation from the U.S. data for resource extraction is less likely to be accurate as the U.S. water consumption is a function of both physical conditions (e.g., geology for oil and gas; soil and climate for biofuels) and regulatory requirements (e.g., regulations requiring processing and recycling of water), conditions and requirements that can vary greatly from one geography to the next.

1.3.5. Economic Dimension of Technological Analysis

The literature covers a broad range of technological solutions with relative low and high water consumption. However, very few of the studies attempt to analyze the economic incentives for the participants to opt for one technology over another. When analyzing the policy implications of water-consumption of different fuels and technologies, economics should clearly also be an important input.

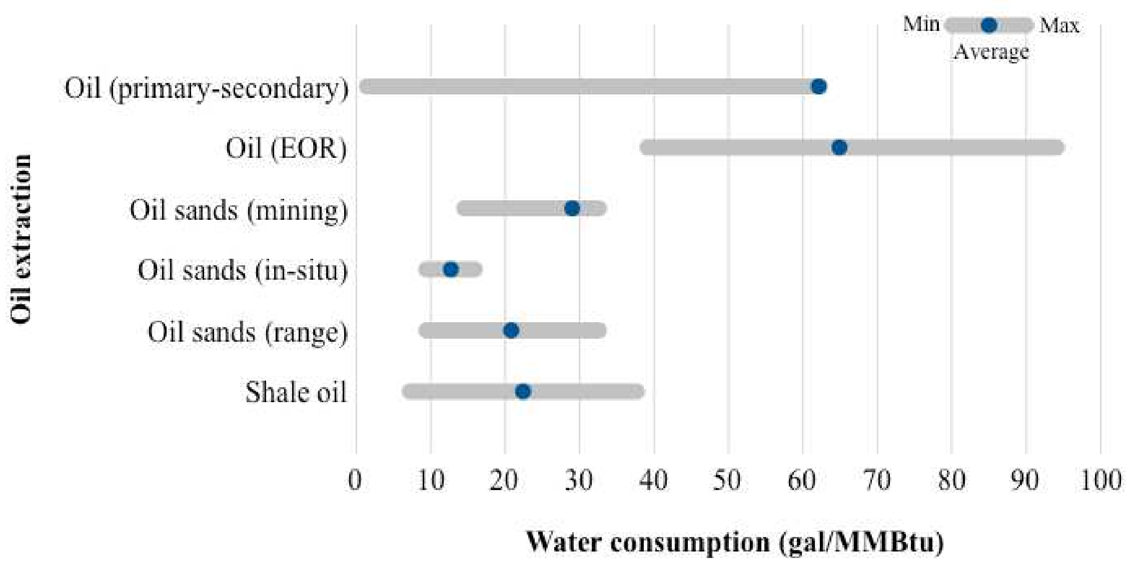
2. WATER CONSUMPTION OF ENERGY RESOURCE EXTRACTION

2.1. Crude Oil Production

This section compares water consumption for different sources of "refinery ready" crude oil, comparing conventional U.S. onshore production and oil produced in Saudi Arabia with less conventional sources of crude oil, namely oil sands and shale oil. The results are shown in Chart 2-1.

The energy content of a barrel of crude oil varies but the standard conversion used by the U.S. Energy Information Administration is 58 MMBtu per barrel, which has been applied through this section.

Chart 2-1: Water consumption during oil extraction



2.1.1. Conventional Crude Oil Production

Water consumption in oil production varies substantially by geography, geology, recovery-technique and reservoir depletion. Water in oil extraction is mainly used for enhanced oil recovery (EOR), where a reservoir is flooded with water or steam to displace or increase the flow of oil to the surface. Oil extraction also generates large volumes of produced water, on average close to seven times the volume of oil produced. After treatment, the produced water can be used for reinjection as part of EOR activities. Consumed water is thus total water injected less produced water used for injection (Wu et al. 2009).

Primary recovery uses only modest volumes of water, but is very uncommon. Most U.S. production uses water flooding early on to stimulate production. Naturally, water flooding is water intensive.

There are multiple technologies used for EOR, not all of which use significant quantities of water. A comprehensive analysis was done by the DOE in 1984 (Royce et al. 1984, 44-53), which was partly updated as part of the 2009 comparison of gasoline (full-cycle) versus ethanol water consumption analysis (Wu et al. 2009).

While the water consumption estimates vary widely, it is possible to summarize the data for the U.S. into two data sets: (i) primary/secondary recovery and (ii) tertiary using common EOR techniques. Primary and secondary production accounts for 0.2% and 79.7% of total U.S. production respectively, with a water-intensity range of 1.4 gal/MMBtu (primary) to 62 gal/MMBtu (secondary). The most common (20%) EOR techniques range between 39 gal/MMBtu (steam injection) and 94 gal/MMBtu (CO_2 injection). The balance is forward combustion/air injection which uses only 14 gal/MMBtu but represents a tiny share of production (0.1%) (Wu et al. 2009). See Table 2-1 below:

Table 2-1: Water consumption for different oil production techniques

	gal/MMBtu	% of U.S. output
Primary	1.4	0.2%
Secondary	62	79.7%
Tertiary		
Steam injection	39	5.5%
CO2 injection	94	11.0%
Caustic injection	28	0.0%
Forward combustion/air injection	14	0.1%
Other	63	3.5%
Micellar polymer injection	2,485	0.0%

Producing, treating, and re-injecting water alongside oil is expensive, using energy for pumping and injection, requiring handling and treatment facilities for volumes many times the oil produced. Similarly, the use of water-intensive secondary and tertiary recovery techniques also tend to increase the cost of extraction progressively. Consequently, economics play an important role in dictating overall water consumption in oil production. All things being equal, higher oil prices should increase water usage, as higher-cost wells and tertiary recovery techniques become economic.

2.1.2. Saudi Arabian Oil Production

The DOE study also includes estimates for Saudi Arabian water consumption in oil production. Saudi Arabia is interesting for multiple reasons, not least its huge resource base, but also the water-scarcity factor is obvious for everyone to see. Saudi Arabia uses mostly desalinated seawater and brackish water for oil recovery (Wu et al. 2009).

The range for Saudi Arabia is estimated between 10 and 33 gal/MMBtu, utilizing primarily water flooding (secondary recovery). The low estimate is for the giant Ghawar oil field and the high estimate is for the North 'Ain Dar field. Contrary to the norm for ageing fields, water consumption has reportedly decline with changes in recovery techniques, e.g., horizontal production wells (Wu et al. 2009).

2.1.3. Oil Sands Production with Upgrading to Synthetic Crude Oil

Imports of crude oil produced from oil sands in Canada are an important part of the U.S. oil balance, representing approximately 1 million barrels per day out total Canadian exports of 1.7 million barrels per day (Wu et al. 2009).

Crude oil is produced from bituminous, predominantly found in Canada. There are two primary technologies for recovering the oil sands: (i) surface *mining* of relatively shallow deposits (typically less than 250 feet below the surface), and (ii) thermal *in-situ* production for exploitation of deeper deposits. Current oil sands production is split almost evenly between the two technologies but the long-term trend favors in-situ production as most of the resources are too deep for mining (Canadian Association of Petroleum Producers 2009; Wu et al. 2009).

Bitumen is a very heavy form of crude oil and requires more intensive processing than most conventional crudes. The bitumen is upgraded (to a synthetic crude oil) by hydrogenation through either *carbon rejection* using thermal cracking (coking) or *hydrogen addition* using hydrocracking technology. Hydrocracking is the most upgrading method for oil sands.

(i) Oil sands mining

Water is primarily consumed during the extraction phase, separating the bitumen from the sands, with consumption levels depending on the choice of solvent. Estimates vary between 14 and 33 gal/MMBtu (Canada National Energy Board 2006, 71) and a reported average of 29 gal/MMBtu (Wu et al. 2009). The estimates for mining include water consumed during upgrading of the bitumen to synthetic crude oil (“syncrude”).

(ii) In-situ production

Two different technologies are used for in-situ production, with the choice depending on the geology of the formation. Cyclic Steam Simulation (CSS) works best in deep, thicker reservoirs, while Steam-Assisted Gravity Drainage (SAGD) is preferred for deposits with thinner reserves. Recovery factors are typically higher for SAGD compared to CCS, ranging from 60-65% and 20-35%, respectively (Wu et al. 2009).

Both CSS and SAGD require large volumes of steam to separate the bitumen from the sand and clay, but re-use of produced water reduces the net consumption to below typical mining operations. Estimates for water consumption for bitumen recovery before upgrading range from 2.2 gal/MMBtu (SAGD) to 8.7 gal/MMBtu (CSS). The lower consumption for SAGD may also be attributable to geology in addition to differences in technology (Wu et al. 2009).

Including upgrading to syncrude increases the water consumption by an estimated 7.2 gal/MMBtu, increasing the range for in-situ water consumption to 9.4 gal/MMBtu to 16 gal/MMBtu for SAGD and CSS, respectively (Wu et al. 2009).

2.1.4. Oil Shale Production

In this report, shale oil is defined as unconventional oil found in sedimentary rock that contains solid bituminous materials which is heated and the resultant liquid is captured, a process known as retorting. Note that this definition of oil shale excludes conventional oil found in shale formations such as the *Bakken* oil field. The United States has significant oil shale resources, with a 2005 study estimating recoverable resources of between 500 and 1,100 million barrels, although these deposits have not been commercially developed in the United States (Bartis 2005).

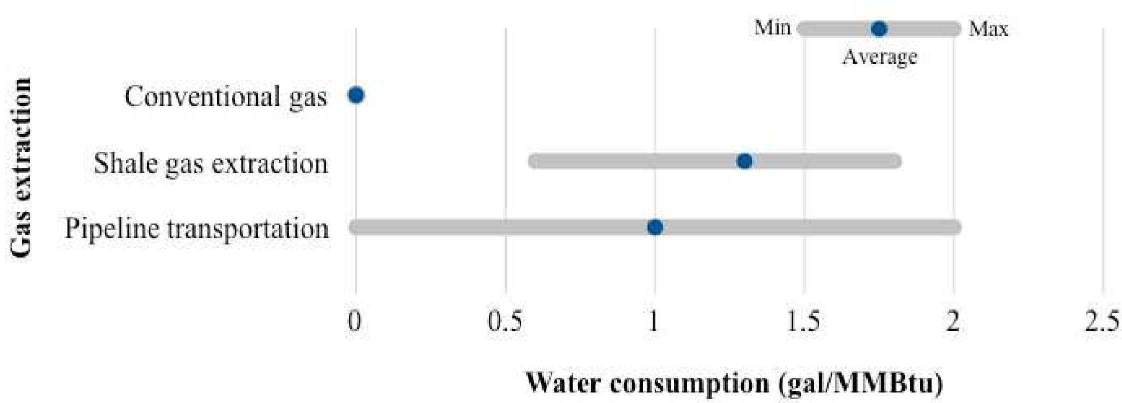
Broadly speaking, there are two development technologies for exploiting oil shale, similar to the commercial technologies that have been developed for exploiting the oil sands in Canada: (i) underground and surface mining with surface retorting, and (ii) in-situ retorting where the oil shale is heated in place and the liquid extracted from the ground (Bartis 2005, 46).

The lack of commercial production of oil shale limits the available data on water consumption. For mining, estimates range between 7.2 to 38 gal/MMBtu (Bartis 2005; U.S. Department of Energy 2006). No estimates were identified of water consumption in oil shale production using the in-situ technology. Note that the average used for shale oil is the simple mean of the low and high estimates.

2.2. Natural Gas Production

This section compares estimates for water consumption of natural gas production in the United States, including estimates for water consumption of extracting shale gas. The results are summarized in Chart 2-2.

Chart 2-2: Water consumption during natural gas extraction and transportation



2.2.1. Conventional Natural Gas

For most conventional natural gas wells, water consumption occurs in small quantities during the drilling phase, as part of the drilling mud, and for drill bit lubrication and cooling. Set against the energy content of the natural gas ultimately recovered from the production well, the net water intensity is effectively close to zero (U.S. Department of Energy 2006).

2.2.2. Shale Gas

The recent growth in unconventional gas, especially shale gas, has brought water to the forefront of the public debate on shale gas. Development of shale and tight gas reservoirs require multi-stage hydraulic fracturing of the wells, a process which uses millions of gallons of water per well.

The most contentious issues relating to water and hydraulic fracturing is not water consumption but rather the risk of contamination of water supplies. This is an important issue that could affect the pace of development of the shale gas industry, but is beyond the scope of this report. However, one possible response to the contamination risk is increased processing and re-use of water at the well, which could ultimately translate into lower *net consumption* of water for hydraulic fracturing.

The shale gas industry is developing rapidly with new production from multiple plays throughout the United States and Canada. Estimates have started to emerge for the water-intensity of shale gas developments, from different gas producers, water regulators, and the USGS. Compared to other fossil fuels, the water-intensity of shale gas appears to be relatively low, at 0.6 to 1.8 gal/MMBtu. But there are fundamental differences with coal and oil, which presents unique challenges for shale gas: the water consumption is front-loaded, during the drilling and completion stage,

The two primary factors determining water-intensity of extraction are (i) water consumed during the development (pre-production) phase, primarily for hydraulic fracturing and, to a lesser extent, drilling, and (ii) expected ultimate recovery of natural gas from the well. These factors vary by well, depending on the geology and the development decisions by the operator.

There are multiple shale plays in the U.S. with heterogeneous geology both across and within the different plays. There are at least 21 shale plays located in the U.S. spread across 20 states. The four most important plays are Barnett (Fort Worth Basin), Fayetteville (Arkoma Basin), Haynesville (East Texas and Louisiana Basin) and Marcellus (Appalachian Basin) (Ground Water Protection Council and ALL Consulting 2009). Data availability on water-intensity of shale gas extraction varies across the different plays and significant caution should be exercised when extrapolating the data.

Water consumption per well can be grouped into four areas: geological (maturity of shale, formation thickness); technological (horizontal vs. vertical wells, water recycling); operational (proximity of fresh-water source); and regulatory. (Bene and Harden 2007).

Chesapeake Energy, the second-largest producer of unconventional natural gas in the U.S., has released data on its own estimates for water consumption in four plays in which it is active, detailing water consumption and reserve estimates for an average well in each play, with average water intensity ranging from 0.8 gal/MMBtu (Haynesville) to 1.7 gal/MMBtu (Fayetteville) (Chesapeake Energy 2010).

The natural gas producer also provides a range of estimates for the company's shale gas drilling as a whole, with water consumption ranging from 3.6 to 4.5 million gal of water per well, and reserve estimates ranging from 2.1 to 6.7 MMBtu (2.0 to 6.5 BCF) per well, giving a company-wide range of 0.6 to 1.8 gal/MMBtu (See Table 2-2). (Chesapeake Energy 2010)

Table 2-2: Estimates of water consumption for different shale plays (Chesapeake Energy 2010)

	Water consumption per well (million gal)			Gas reserves per well		Water intensity
Shale play	Drilling	Hydraulic Fracturing	Total	BCF	MMBtu (million)	gal/MMBtu
Barnett	0.3	3.8	4.1	2.7	2.7	1.5
Fayetteville	0.1	4.0	4.1	2.4	2.5	1.7
Haynesville	0.6	5.0	5.6	6.5	6.7	0.8
Marcellus	0.1	5.5	5.6	4.2	4.3	1.3
Typical min	*1.0*	*3.5*	*4.5*	*6.5*	*6.7*	*0.6*
Typical max	*0.1*	*3.5*	*3.6*	*2.0*	*2.1*	*1.8*
Average						**1.3**

The estimates are specific to one company's operations (i.e. Chesapeake Energy) and reflect typical water-intensity across its asset portfolio, not necessarily a representative range of water-intensity for the industry as a whole. But alternative estimates for Marcellus and Barnett provide comfort that the order of magnitude is appropriate, especially in the context of comparable water-intensity of alternative fossil fuels.

Marcellus data

The U.S. Geological Survey published a factsheet on water issues relating to the Marcellus shale gas developments (Soeder and Kappel 2009), summarized in Table 2-4. The USGS estimates show a similar average water-intensity to the Chesapeake Energy data, at 1.2 and 1.3 gal/MMBtu respectively, albeit with lower water-consumption per well and lower estimated recoverable reserves per well (roughly half the Chesapeake Energy estimates).

Table 2-3: USGS estimates for Marcellus shale (2009)

Reserves per well (BCF)	2.5
Reserves per well (million MMBtu)	2.6
Hydraulic fracturing (million gal)	3.0
Average (gal/MMBtu)	**1.2**

The Susquehanna River Basin Commission (SRBC) regulates water access for a significant portion of the Marcellus shale, covering parts of Pennsylvania, New York, and Maryland. The SRBC estimated in January of 2010 that a typical Marcellus shale stimulation uses between four and seven million gal of water over a two to five-day period, with about 15% of the water flowing back to the surface in the first two months (Susquehanna River Basin Commission 2010), comparable to the Chesapeake estimates. However, based on actual data from approximately 200 wells drilled between June 2008 and March 2009, the SRBC estimates that the average well consumed 2.4 million gal of fresh water with an additional 0.4 million gal of flowback reuse per well (Susquehanna River Basin Commission 2010), very close to the USGS estimates from 2009.

Barnett data

The Barnett shale is much more extensively developed that the other shale plays but water use has received less attention than in the Marcellus, probably because it is closer to existing oil and gas drilling and infrastructure in Texas and therefore is not a new issue.

The available public data on water consumption show a high degree of variation, ranging from 0.25 to 2.75 million gal/well for hydraulic fracturing of vertical wells, and 0.5 to over 6.0 million gal/well for horizontals. The averages were 1.2 and 3.1 million gal/well for vertical and horizontal hydraulic fracturing jobs respectively (Bene and Harden 2007), slightly lower than the average reported by Chesapeake. Given the trend is towards horizontal wells, the vertical data has been excluded from the analysis.

Other water issues

Four issues stand out from the analysis of water-intensity of shale gas production:

1. **Ultimate recovery:** There is substantial *uncertainty about ultimate recovery of natural gas* from each well, the denominator in the water-intensity calculation. The numerator, water consumption per well, is better understood and documented, but should be correlated with the estimates of ultimate recovery. Over time, as more shale gas is produced, the confidence in reserve estimates for different wells should increase.

2. **Timing of water consumption:** The *timing of the water consumption* relative to the energy extraction is very different from other fossil fuels. The hydraulic fracturing is the main source of water consumption, and this takes place (usually over two to five days) during the completion of the well, before the first gas is produced.

3. **Local issues:** According to the Susquehanna River Basin Commission, the issue for the Marcellus shale-gas play is less the absolute volume of water withdrawals, and more the location of the withdrawals (Richenderfer 2010). This would suggest that even though water consumption for shale gas is low compared to other fossil fuels, at a local level, the impact on water supply could be substantial.

4. **Future water consumption:** The analysis assumes that *fracturing only takes place once* for each well. In the industry, it is common to perform additional hydraulic fracturing as part of well workovers to stimulate production from ageing wells. Whether this approach will be also become common for shale gas wells is unclear, as is the impact from additional fracturing jobs on ultimate recovery.

2.2.3. Coal Bed Methane

Another source of unconventional gas of increasing importance in the United States and elsewhere is coal bed methane (CBM), also sometimes referred to coal bed gas or coal seam gas. The production technique used for CBM production can result in substantial volumes of produced water, but the water required per unit of CBM energy is not significant compared to other fossil resources (U.S.Geological Survey 2000).

2.3. Coal Mining

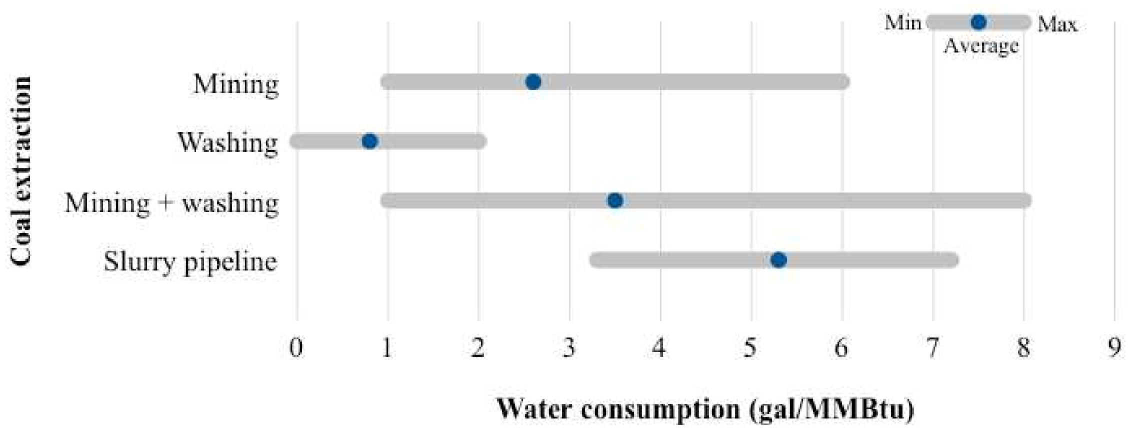
The amount of water used in coal mining depends on whether the mine is an underground or a surface mine. Water is used for coal cutting and dust suppression, with estimates of average water consumption ranging from 1 to 6 gal/MMBtu, representing Appalachian (underground) and Western (surface) mining respectively. An additional 1 to 2 gal/MMBtu is used for washing, mostly Appalachian coal (U.S. Department of Energy 2006).

The calculated weighted average is 2.6 gal/MMBtu for mining and 0.8 gal/MMBtu, which has been applied as the average for the coal range (U.S. Department of Energy 2006).

For coal transported by pipeline as slurry, an additional 11 to 24 gal/MMBtu is withdrawn with 70% recycling taking the net consumption to a 3.3 to 7.2 gal/MMBtu range (U.S. Department of Energy 2006). A simple mean of the low and high estimate for slurry has used been for the average estimate.

The water consumption data for coal is summarized in Chart 2-3.

Chart 2-3: Water consumption during coal extraction and transportation



2.4. Biofuels

2.4.1. Corn Ethanol: Feedstock Production

In a recent study (Wu et al. 2009), the DOE summarized estimates for water intensity of ethanol production. The study shows significant variation in water intensity by geography, reflecting different irrigation requirements due to soil types and climate, as the water consumption estimates exclude precipitation.

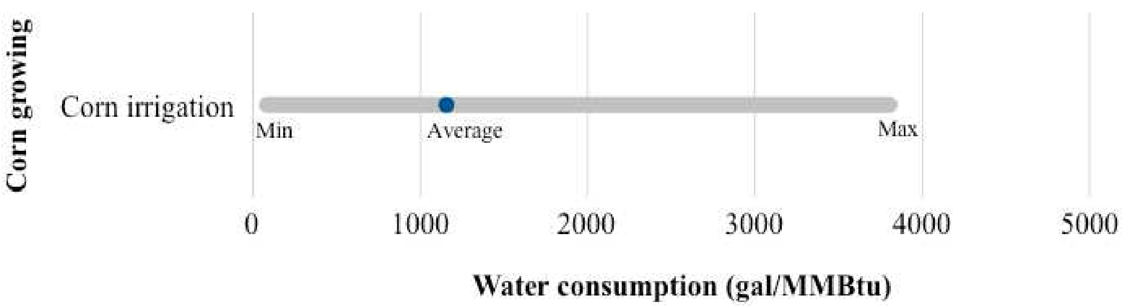
The detailed estimates are shown below in Table 2-4. The estimated water consumption for corn production ranges from 83 gal/MMBtu in USDA Region 5 (Iowa, Indiana, Illinois, Ohio, Missouri) to 3,805 gal/MMBtu in USDA Region 7 (North Dakota, South Dakota, Nebraska, and

Kansas), with a weighted-average of 893 and 1,155 gal/MMBtu when weighted by corn production (region as share of national) and ethanol production capacity (region as share of national) respectively. See Chart 2-4.

Table 2-4: Regional irrigation for corn ethanol feedstock

USDA region	gal/MMBtu	% corn	% of ethanol capacity
Region 5 – Iowa, Indiana, Illinois, Ohio, Missouri	83	51	53
Region 6 – Minnesota, Wisconsin, Michigan	164	17	17
Region 7 – N. Dakota, S. Dakota, Nebraska, Kansas	3,805	27	19
Share of total U.S. production/capacity		**95**	**89**

Chart 2-4: Water consumption for corn irrigation



An estimated 71% of the water input from irrigation is consumed via evapotranspiration with the remaining 29% becoming surface run-off and groundwater recharge, potentially available for reuse as irrigation water. The water consumption estimates in this report do not account for this potential water recovery.

The estimates in the more detailed DOE 2009 study are somewhat lower than an earlier report from the department of energy (U.S. Department of Energy 2006), which had a range of 2,500 gal/MMBtu to 29,000 gal/MMBtu and an average of 11,000 gal/MMBtu. It is likely that this higher average and range is a more appropriate approximation of the irrigation required outside USDA Regions 5, 6, and 7.

2.4.2. Cellulosic Ethanol: Feedstock Production

The second-generation technologies for ethanol from biomass are expected to use very different sources of feedstock, with lower full-cycle CO_2 emissions and reduced competition with food crops (Office of Transportation and Air Quality 2010). Possible sources of feedstock include perennial grasses, forest wood residues, agricultural crop residues, algae, and municipal waste (Wu et al. 2009). Forest wood residues would not require significant incremental irrigation. Likewise, switchgrass can potentially be grown at significant yields without irrigation, if grown where it is native (Wu et al. 2009). Consequently, the DOE 2009 report assumes no incremental irrigation for second-generation biofuels, with water consumption being concentrated in the conversion from feedstock to liquid fuel, although dedicated energy crops for cellulosic ethanol may require additional irrigation (Wu et al. 2009).

2.4.3. Biodiesel

Biodiesel is a smaller part of U.S. biofuels supply and was not covered in the 2009 DOE update of water-intensity. The DOE's 2006 study estimates an average of 50,576 gal/MMBtu (with a from range 13,800 to 60,000 gal/MMBtu) for biodiesel from soy.[1]

In contrast, the estimates for biodiesel from rapeseed (Berndes 2008) show lower water consumption than the comparable estimates for corn ethanol, with a range of 11,518 to 20,281 gal/MMBtu, 24% above and 57% below the low and high-points of the corn ethanol range.

2.4.4. Biofuels Mandate and Water Consumption

Ethanol from corn is an increasingly important part of the U.S. liquids fuel mix, accounting for approximately 11.1 billion gallons or approximately 7% of total transportation fuels in 2009 (Office of Transportation and Air Quality 2010; U.S. Bureau of Transportation Statistics 2010). Biofuels are mandated by statute to represent an increasing share of the U.S. fuel balance, rising to 12.95 billion gal. Further annual increases are mandated, with total biofuels supply rising by an annual average of 9% between 2010 and 2022. By 2015, biofuels are set to make up 20.5 billion gal of total fuel supply nearly double 2009 levels, of which minimum 5.5 billion gallons should be so-called advanced biofuels (e.g., cellulosic ethanol and biodiesel), and the balance (15 billion gallons) coming from other biofuels, principally corn-based ethanol. Increases in the mandate beyond 2015 are entirely in advanced biofuels, increasing to a total 36 billion gallons by 2022 (approximately 2.35 million barrels per day) of which 21 billion gallons should be advanced biofuels (Office of Transportation and Air Quality 2010).

The EPA has set lifecycle CO_2 standards for biofuels (Office of Transportation and Air Quality 2010), but has not made any recommendations on water intensity. The advanced biofuels use different feedstock and are *expected to have significant lower water intensity due to reduced irrigation needs*, although this will depend on *what* type of feedstock and *where* it is grown (Wu et al. 2009). The feedstock for the second-generation fuels is expected to come from perennial plants, with different effects on the water cycle, in particular groundwater use (Meijerink, Langeveld, and Hellegers 2008).

2.5. Uranium Mining

Similar to coal mining, water consumption in uranium mining varies mostly by whether the mine is an underground or a surface mine, with estimates of 1 to 6 gal/MMBtu respectively (Gleick 1994, 267-299; U.S. Department of Energy 2006). Water is required for dust control, ore beneficiation and re-vegetation of mined surfaces (Gleick 1994, 267-299).

[1] The soy-based biodiesel estimates for water consumption seem very high relative to corn ethanol but are repeated throughout the DOE literature.

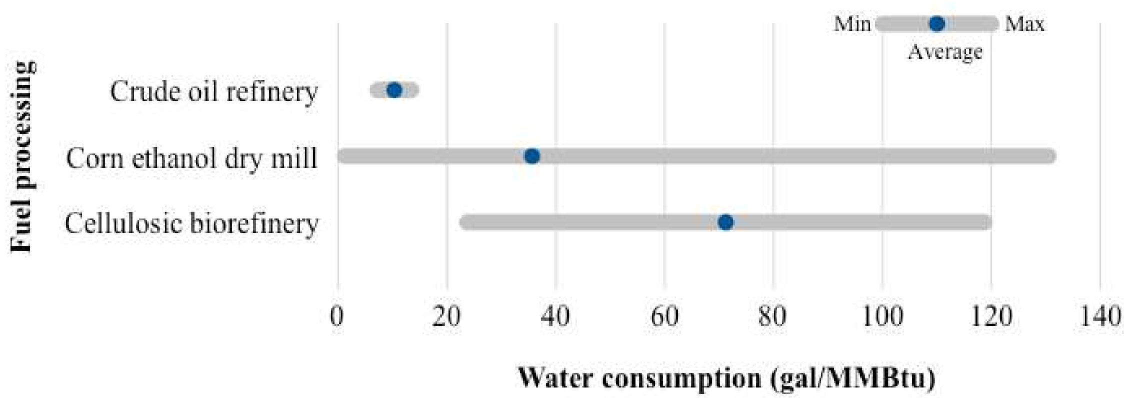
3. FUEL PROCESSING

This section reviews estimates for water consumption in processing of energy feedstock into fuels, for crude oil, biofuels, natural gas, CTL/GTL ,and uranium. The results are summarized in (missing text)

3.1. Oil Refining

Water consumption in a refinery depends on its configuration. Crude distillation (all refineries) and FCC units (most U.S. refineries) account for most of the water withdrawal and consumption for steam and cooling water use. Typical U.S. refineries consume between 7.2 and 13 gal of water per MMBtu of crude oil (see Chart 3-1). The output fuel water-intensity is lower by approximately 6% on average due to the volumetric gain during the refining process (i.e., typical yield of 1.06 barrel of petroleum product per barrel of crude oil), although the exact water-intensity will vary by petroleum product and its energy content (Wu et al. 2009).

Chart 3-1: Water consumption during fuel processing



3.2. Biofuels Processing

The estimates for biofuels processing are for direct water usage only and exclude any water consumption related to the energy inputs, such as upstream water consumption related to natural gas or electricity used for processing purposes. All of the studies reviewed for this report attribute the water consumption to the fuel process, ignoring any possible attribution to co- and by-products. Chart 3-1 compares biofuels processing water consumption with crude oil refining, and Chart 3-2 summarizes total water consumption for the corn ethanol cycle and cellulosic ethanol (note log scale).

3.2.1. Ethanol Production: Processing Corn to Ethanol

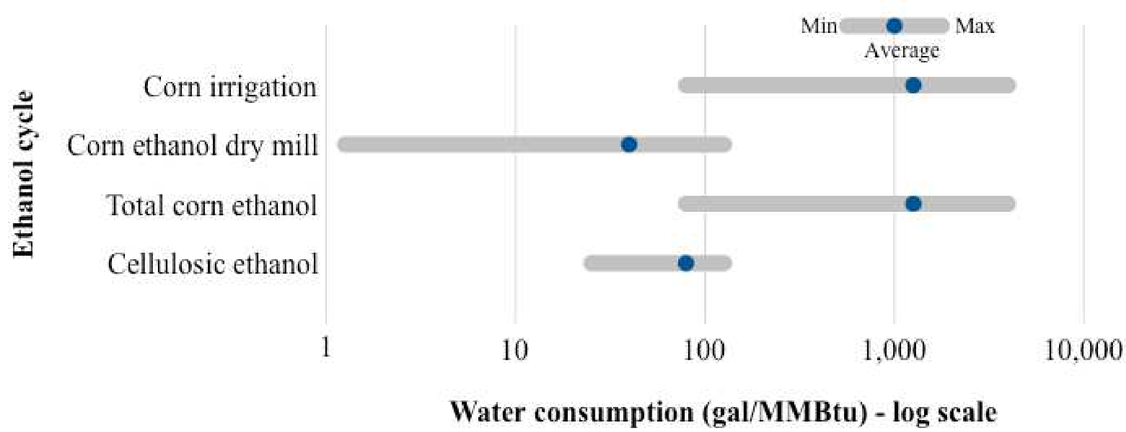
Producing ethanol from corn requires water for grinding, liquefaction, fermentation, separation, and drying (Wu et al. 2009). The average water used in dry mills varies substantially depending on the technology (often determined by age) of the plant, with a clear downward trend. Some older facilities consume as much as 131 gal/MMBtu while in theory the net consumption from the process could be zero. As the industry has expanded and newer facilities have lower water-intensity, the average water consumption has halved from 71 to 31 gal/MMBtu between 1998 and 2008.

Weighted by output, the grain ethanol processing plant is estimated to consume 36 gal/MMBtu (Wu et al. 2009), with a mean of 62 gal/MMBtu and range of 13 to 145 gal/MMBtu (U.S. Department of Energy 2006).

3.2.2. Cellulosic Ethanol: Processing to Ethanol

Conversion estimates vary depending on the technology. Using current technology for biochemical conversion, average water consumption is estimated at 119 gal/MMBtu. Expected yield (efficiency) improvements could lower the water consumption to 71 gal/MMBtu while using more advanced thermochemical conversion via gasification and catalytic synthesis would consume 24 gal/MMBtu, according to the DOE estimates (Wu et al. 2009).

Chart 3-2: Water consumption during corn and cellulosic ethanol production cycles (log scale)



3.3. Gas processing and Transportation

Water consumption in natural gas processing and transportation varies between 0 to 2 gal/MMBtu according to estimates by one energy company (Chesapeake Energy 2010). This is consistent with an old (1994) approximation of water consumption in natural gas processing and pipeline operations of close to 2 gal/MMBtu (Gleick 1994, 267-299).

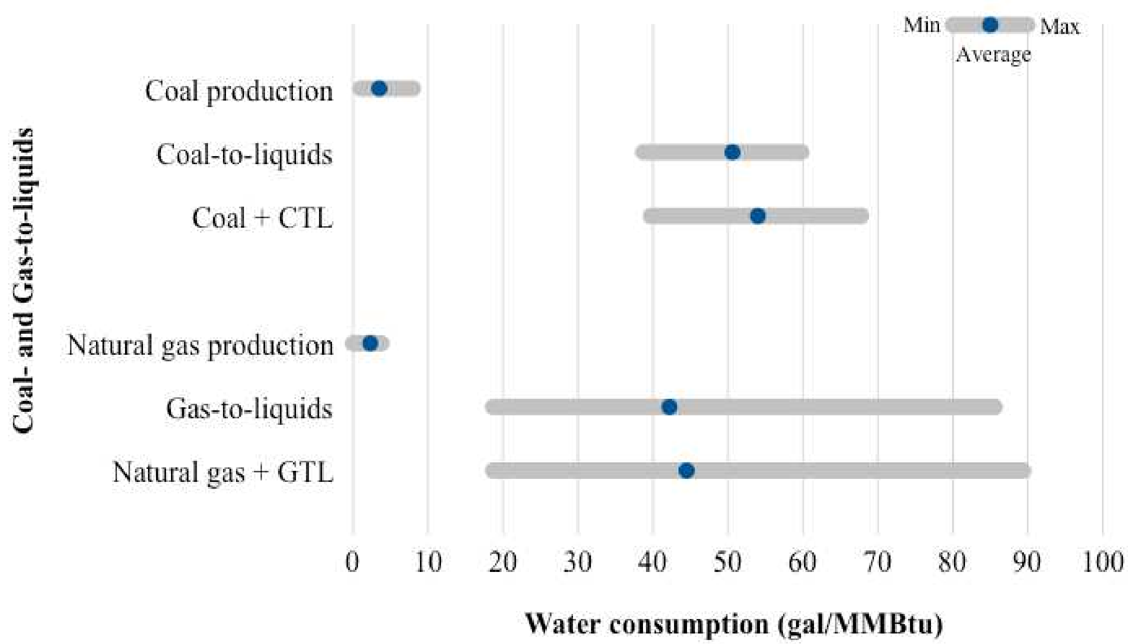
3.4. Coal- and Gas-to-Liquids (Fischer-Tropsch)

Coal-to-liquids (CTL) and Gas-to-liquids (GTL) Fischer-Tropsch (FT) processing plants use less expensive coal and natural gas as the major feedstock for producing more valuable liquid fuels, including gasoline/naphtha, middle distillates, and petroleum gasses for petrochemicals. These projects are of potential interest in countries that have large coal or natural gas endowments but limited oil resources. However, high complexity and high capital costs have limited the actual number commercial-scale plants built around the world to less than a handful.

Commercial CTL plants only exist in South Africa (Sasol) but China's Shenhua has plans to construct multiple facilities in China. Commercial GTL plants operate in Qatar since 2007, demonstration-scale plants in Malaysia and South Africa, and additional commercial GTL plants under construction in Qatar and Nigeria (Cochener 2007).

The source of estimates for water intensity of FT CTL and GTL fuels is a 2001 study comparing four different CTL designs, three GTL options and one Biomass-to-liquids (BTL) plant design, with all eight options assuming a U.S. location (Marano and Ciferno 2001). Chart 3-3 summarizes the estimated water consumption in the coal and CTL cycle as well as the natural gas and GTL cycle.

Chart 3-3: Water consumption during coal-to-liquids and gas-to-liquids fuel cycle



3.4.1. Gas-to-Liquids (GTL)

The water-intensity estimates range from 19 to 86 gal/MMBtu for GTL-derived liquid fuels, with an average of 42 gal/MMBtu (Marano and Ciferno 2001). The high-estimate is for the most efficient design, maximizing total product yield and in particular distillate. The lower water-intensity estimates assume significantly lower efficiency (feedstock-to-fuel conversion).

3.4.2. Coal-to-Liquids (CTL)

For CTL, the water-intensity estimates range from 39 to 60 gal/MMBtu, and an average of 51 gal/MMBtu (Marano and Ciferno 2001; U.S. Department of Energy 2006). The analysis "is based on earlier FT plant designs, and no effort has been made to improve on these conceptual designs." (Marano and Ciferno 2001).

Water consumption varies with design configuration (distillate, gasoline, or chemicals optimization), with greater complexity leading requiring higher water consumption.

3.4.3. Biomass-to-Liquids (BTL)

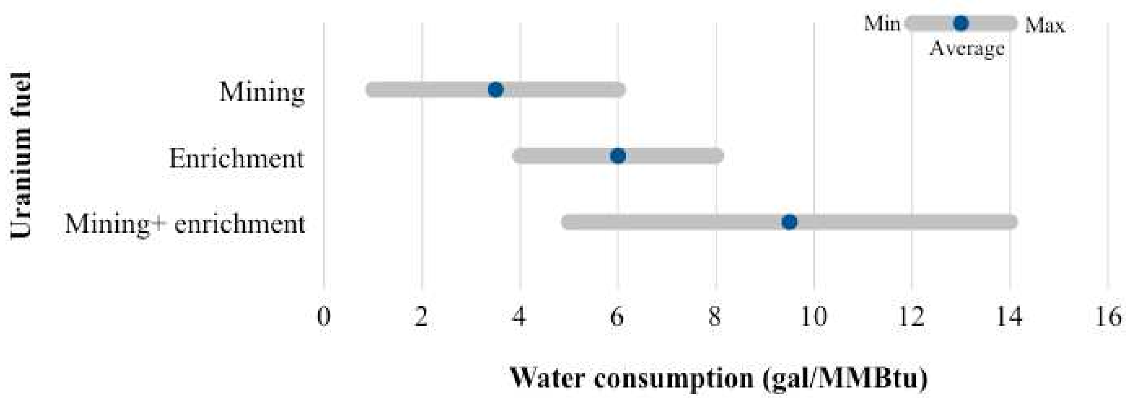
An alternative source of feedstock is biomass. Depending on how the feedstock is sourced (the 2001 study assuming Maplewood), BTL has potential CO_2 advantage over CTL and GTL, but a large catchment area is required to source biomass material on a commercial scale, and BTL plants are approximately 2x and 3x more expensive than CTL and GTL plants (Cochener 2007). Water consumption is also significantly higher than for CTL and GTL, with the 2001 study estimating 314 gal/MMBtu for a 1,000 barrels per day BTL facility (Marano and Ciferno 2001).

3.5. Uranium Processing

Milling, refining and enriching uranium also consumes water, with most of the water loss coming from evaporation from tailing ponds. Consumption is estimated at 4 to 5 gal/MMBtu if enrichment with centrifuge, and 7 to 8 gal/MMBtu if enrichment by gaseous diffusion (Gleick 1994, 267-299; U.S. Department of Energy 2006). See Chart 3-4 for a summary of water consumption throughout the uranium cycle, from mining to enrichment.

Note that the shown averages are the simple mean of the low and high estimates.

Chart 3-4: Water consumption during uranium mining and enrichment



4. FULL-CYCLE WATER CONSUMPTION OF FUEL PRODUCTION

This section combines the estimates for water consumption during extraction/production from Section 2 with the processing estimates from Section 3.

Chart 4-1 summarizes the full-cycle water consumption for various fuels, including extraction, transportation, and processing. Note the use of log scale, due to corn ethanol being so much higher than the other fuels.

Natural gas has the lowest water consumption of the fuels covered in this report (shale gas is shown, conventional natural gas would be close to zero).

Chart 4-1: Water consumption for extraction and processing of fuels (log scale)

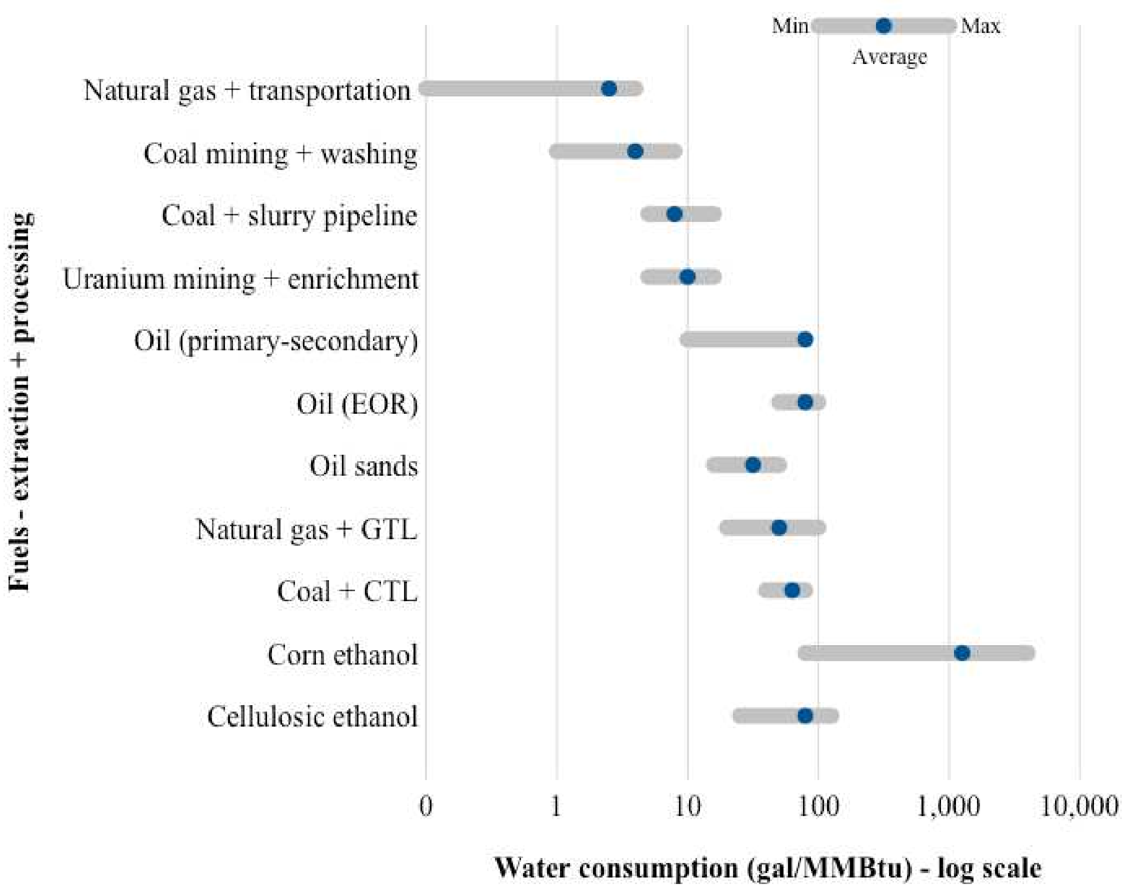
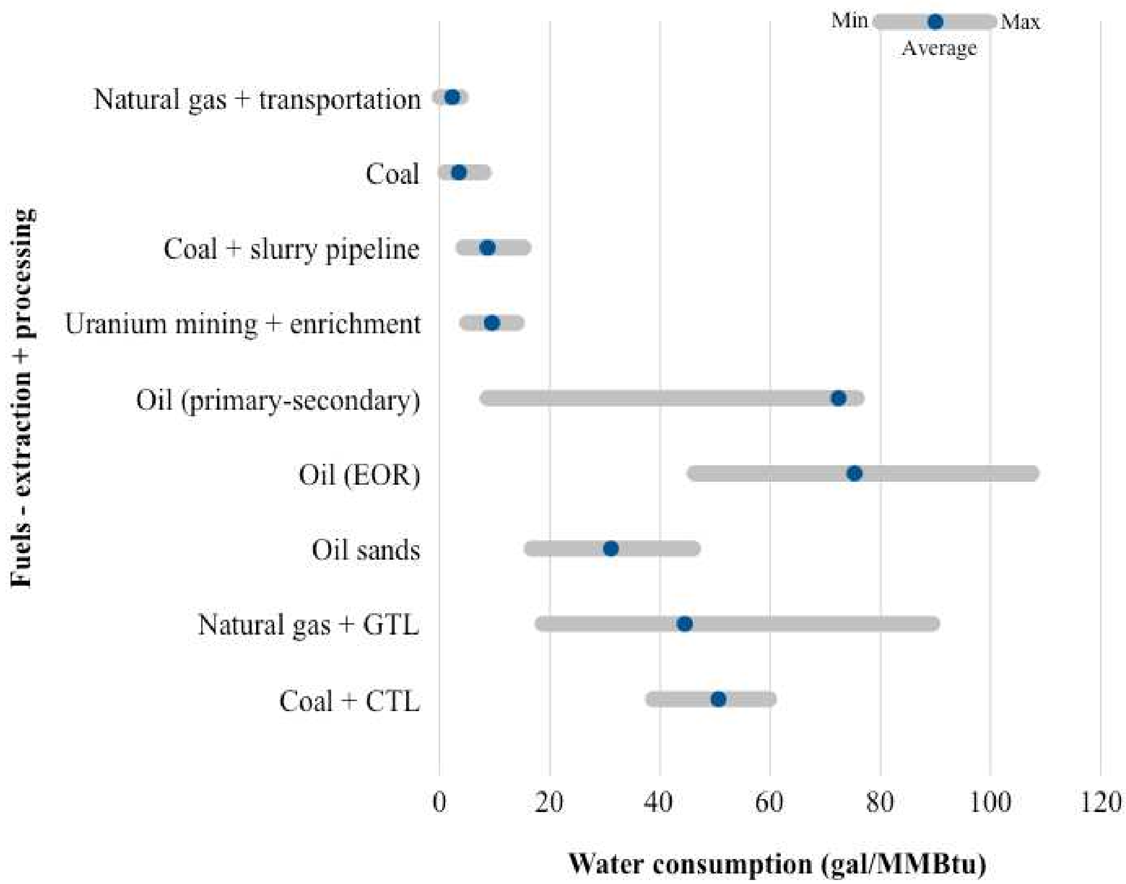


Chart 4-2 shows the same data but excluding ethanol and on a normal scale. Natural gas has the lowest water consumption per unit of energy (note the gas data is for shale gas, water consumption for conventional natural gas is negligible).

Water consumption in the oil cycle is relatively high, reflecting the extensive use of water flooding to boost production and recovery factors onshore U.S. A surprising conclusion is that the oil sands import from Canada, on average, probably has lower water consumption associated with extraction and processing than domestic oil.

Chart 4-2: Water consumption for extraction and processing of fuels



5. ELECTRICITY CONVERSION

5.1. Thermoelectric Power Generation

Water is used extensively in the electric power sector, for cooling and scrubbing. Thermoelectric power plants account for 45% of total U.S. water withdrawals in 2005 (U.S. Geological Survey 2009), the highest share of any category; irrigation for agriculture was second with 31%. However, much of the water withdrawn for cooling is returned to the water system, and net consumption is substantially lower, around 3% to 4% (Electric Power Research Institute 2003; Hightower 2008).

Water availability is a critical issue for power plant operators and for planning new capacity. Utilities have also come under increased pressure to reduce water consumption, due to droughts, competing demand for water, public pressure and the public in general (Electric Power Research Institute 2008).

This report does not distinguish between the different possible sources of the water being consumed – fresh, waste, and seawater – as it is beyond the scope of the study. It is an important distinction at the local level, however. For instance, a power plant sited next to the ocean that is technically able to utilize seawater for cooling, is unlikely to face water constraints, subject to meeting other environmental requirements (aquatic life, discharge, etc).

5.1.1. Cooling Technologies

The vast majority of water consumption in thermoelectric power generation relates to cooling. There are three basic cooling technologies for thermoelectric plants, with a few variations on the theme: (i) once-through (OT), (ii) closed-loop (CL) or wet cooling, and (iii) dry cooling (Dry). Hybrid cooling (iv) is also deployed in some facilities, incorporating elements of CL and Dry (Gerdes and Nichols 2009) (Figure 5-1).

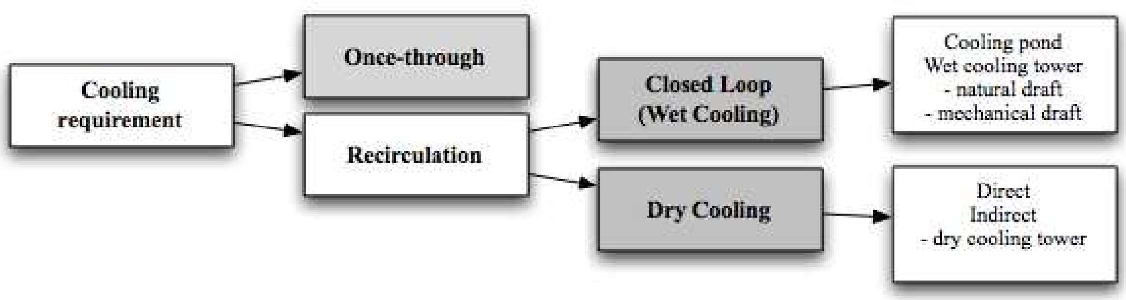


Figure 5-1: Cooling options for thermoelectric power plants (Gerdes and Nichols 2009)

(i) Once-through cooling

Once-through cooling was the conventional technology up until the early 1970s. Water is run through the system and used to condense the steam from the turbine. The water is then returned to the original source (e.g., the river), about 20F warmer. The advantages of this technology are two-fold: the relatively low capital and operating cost and low net water consumption. The disadvantages are environmental due to the impact on aquatic life at the water intake and due to thermal discharge downstream. Another disadvantage is that – although net consumption is low – the high throughput volumes required for the plant to operate, could be a constraint in drought conditions (Electric Power Research Institute 2007, 26). Once-through cooling is now uncommon for new power plants due to section 316(a) of the Clean Water Act, which regulates water intake structures and thermal pollution discharges. Figures 5-2 to 5-5 give a schematic overview of each cooling technology.

Once-through cooling

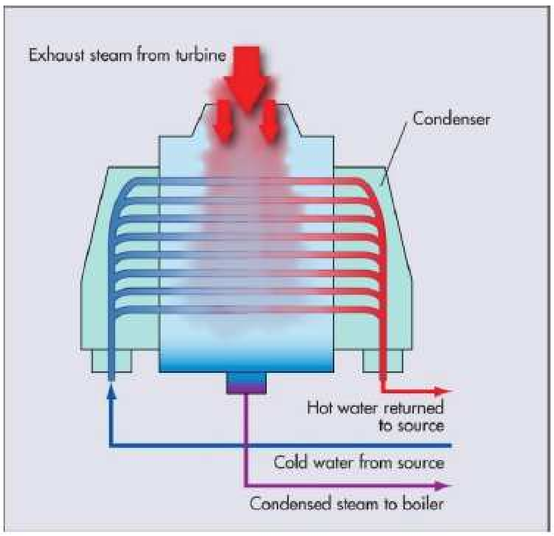


Figure 5-2: Once-through cooling schematic (Electric Power Research Institute 2007).

Closed-loop cooling

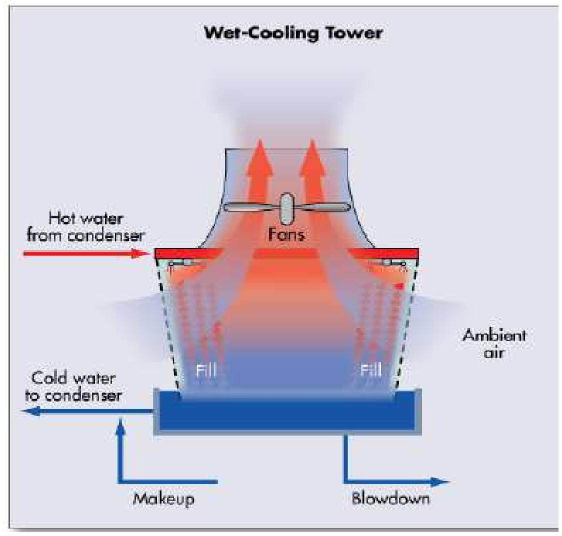


Figure 5-3: Closed-loop (wet) cooling schematic (Electric Power Research Institute 2007).

(ii) Closed-loop cooling (wet cooling)

Closed-loop cooling has become the technology of choice for most power stations since the early 1970s. Relative to a once-through configuration, closed-loop cooling has relatively low water withdrawal, but water consumption at the power plant is significantly higher. Cooling water exits the condenser, goes through cooling tower, and is then returned to the condenser.

(iii) Dry cooling (air cooling)

Dry cooling systems are similar to wet closed-loop but the evaporative cooling tower is replaced with dry cooling towers cooled only by air, effectively eliminating water consumption.

One significant downside of dry cooling is a negative impact on plant efficiency, as ambient temperatures and humidity affect the effectiveness of dry cooling. The net result is that plant efficiency is higher for plants using wet cooling than for plants using dry cooling, especially in a hot, arid climate. The average loss of output is approximately 2% on an annual basis. But at the peak of summer, when demand is at its highest, the efficiency penalty can be as high as 25% (U.S. Department of Energy 2006).

Dry cooling

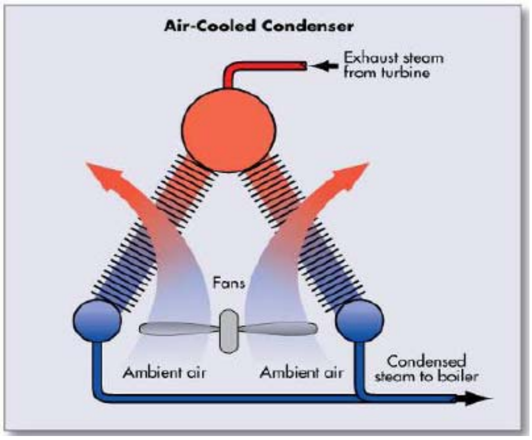


Figure 5-4: Dry cooling schematic (Electric Power Research Institute 2007).

Hybrid cooling

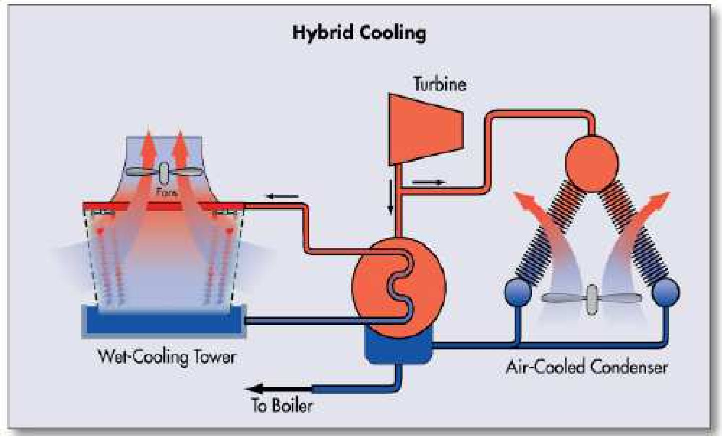


Figure 5-5: Hybrid cooling schematic (Electric Power Research Institute 2007).

5.1.2. Cooling Cost and Performance Comparison

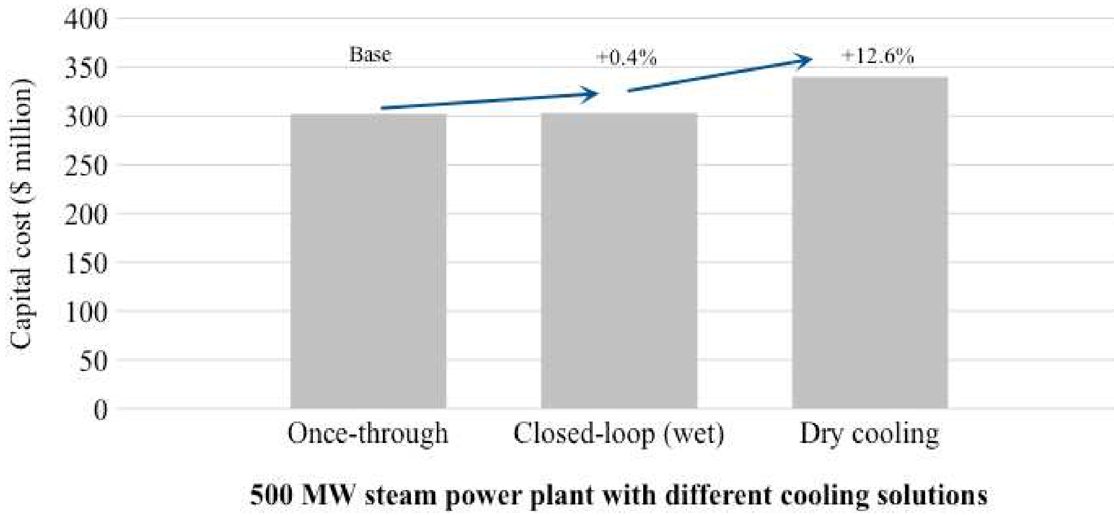
Table 5-1 shows industry estimates for the capital cost of different cooling technologies on a unit of capacity basis. Dry cooling is nearly ten times more expensive than one-through (Electric Power Research Institute 2007, 26).

Table 5-1: Capital cost of cooling technologies

	$/kW	***Relative to once-through***
Once-through	19	-
Closed-loop/cooling pond	28	+47%
Others including dry cooling	182	+858%

Chart 5-1 takes the same analysis a step further by incorporating other costs into the power plant. The overall increase in the cost of the power plant (an illustrative 500 MW steam power plant) increases by nearly 13% by going from once-through to dry-cooling. The increase from once-through to closed-loop (wet) is small, at less than 1%.

Chart 5-1: Illustrative impact on capital cost for a hypothetical 500 MW steam power plant of different cooling technologies



Capital costs are only part of the equation. Other important factors are (in addition to water consumption) plant efficiency, efficiency variability, operational integrity, and power consumption. Some of the most important factors have been summarized in Table 5-2.

Table 5-2: Cooling technologies – advantages and disadvantages (O'Hagan and Maulbetsch 2009)

Cooling technology	*Advantages*	*Disadvantages*
Once-through (OT)	Lower consumptive use of water High cooling efficiency Mature technology Lower capital cost	Clean Water Act 316(b) rules for fish protection Thermal discharge limits [CWA 316(b)]
Closed-loop (CL)/wet	Significantly lower water *withdrawal* than OT Standard choice for most new plants Mature technology	Higher *consumptive* use of water than OT Higher parasitic load Lower plant efficiency Higher capital cost than OT
Dry	No or very low water consumption	Higher capital cost Higher power consumption Lower plant efficiency, especially in hot weather Large area requirements
Hybrid	Lower capital cost than all-dry cooling Significant reduction in water consumption vs. CL Elimination of hot day penalty Flexibility: energy vs. water	Higher capital cost than CL Still uses water Limited experience Similar issues to CL and Dry

5.1.3. Water Use in Power Generation

Table 5-3 summarizes the estimates for water withdrawals and net water consumption for different types of power generating facilities, with different types of cooling technologies. (U.S. Department of Energy 2006; Gerdes and Nichols 2009).

Table 5-3: Water intensity of electricity generation – withdrawal and consumption

All units in gal/MWh	Steam condensing				Other use				Total			
	Withdrawal		Consumption		Withdrawal		Consumption		Withdrawal		Consumption	
	Low	High	*Low*	*High*	Low	High	*Low*	*High*	Low	High	Low	High
Steam turbine (coal, gas, biomass)												
Once-through	20,000	50,000	***300***	***300***	30	30	***0***	***30***	20,030	50,030	300	330
Closed-loop	300	600	***300***	***480***	30	30	***0***	***30***	330	630	300	510
Dry	0	0	***0***	***0***	30	30	***0***	***30***	30	30	0	30
Steam turbine (nuclear)												
Once-through	25,000	60,000	***400***	***400***	30	30	***0***	***30***	25,030	60,030	400	430
Closed-loop	500	1,100	***400***	***720***	30	30	***0***	***30***	530	1,130	400	750
Dry	0	0	***0***	***0***	30	30	***0***	***30***	30	30	0	30
Combined-cycle gas turbine												
Once-through	7,500	20,000	***100***	***100***	30	30	***0***	***30***	7,530	20,030	100	130
Closed-loop	230	230	***180***	***180***	30	30	***0***	***30***	260	260	180	210
Dry	0	0	***0***	***0***	30	30	***0***	***30***	30	30	0	30
IGCC (coal)												
Closed-loop	250	250	***200***	***260***	137	140	***137***	***140***	387	390	337	400

Charts 5-2, 5-3, and 5-4 show water consumption for steam turbine, nuclear, and CCGT power plants respectively, utilizing once-through (OT), closed-loop (CL), and dry cooling technologies. CCGT have the lowest consumption rates of the three plant-types, with steam turbine second and nuclear the highest. For dry cooling, the three plant types all have water consumption rates between 0 and 30 gal/MWh. The averages used are the simple mean of the low and high estimates.

Chart 5-2: Water consumption in steam turbine power generation with different cooling technologies

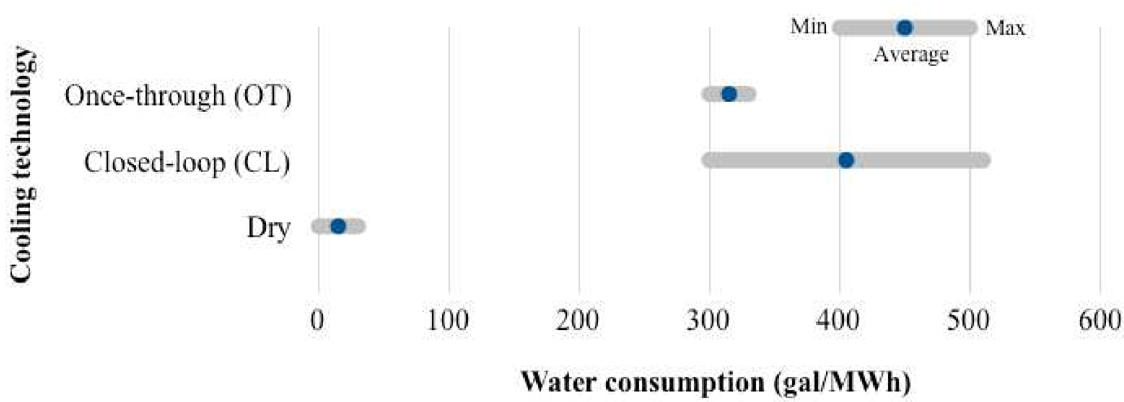


Chart 5-3: Water consumption in nuclear power generation with different cooling technologies

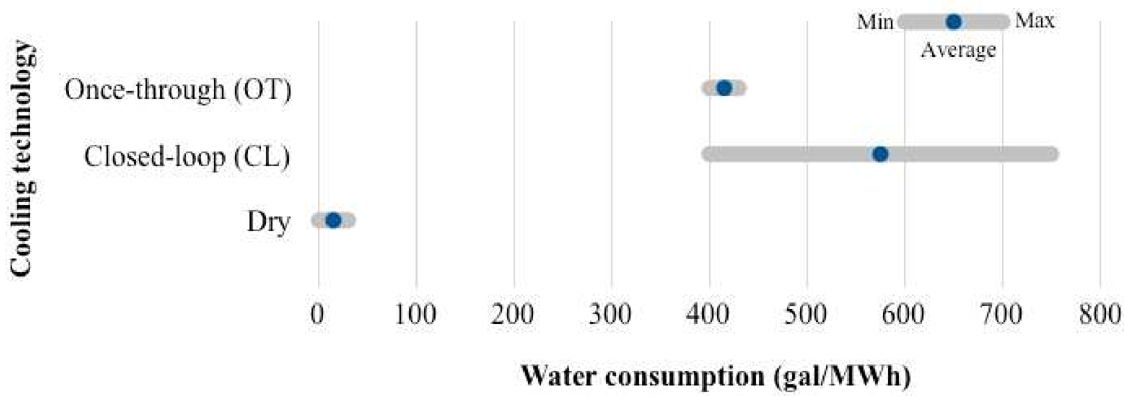
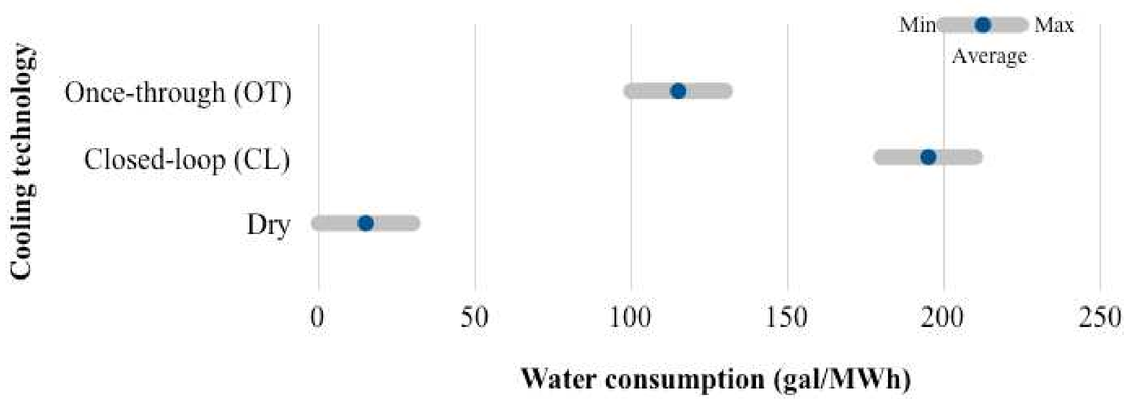


Chart 5-4: Water consumption in combined-cycle gas turbine (CCGT) power generation with different cooling technologies



5.1.4. Advanced Coal and CCS

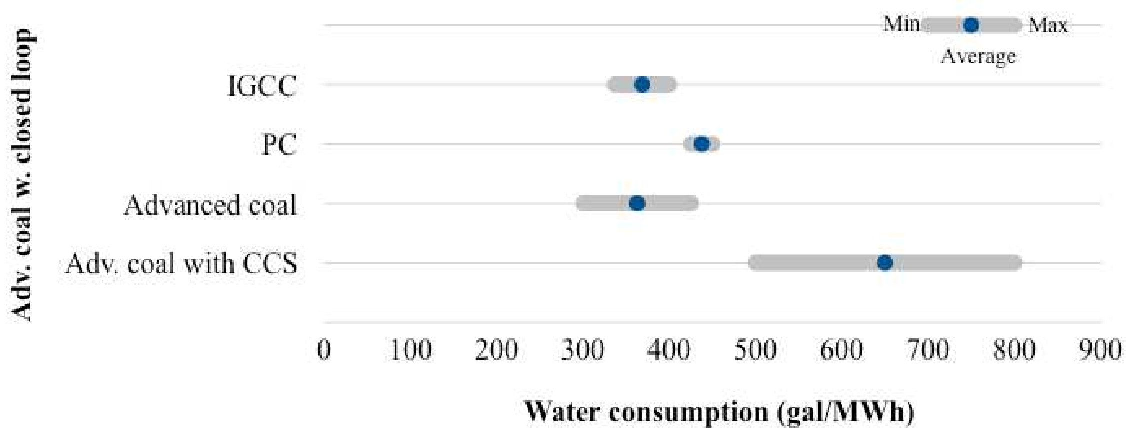
Advanced coal-fired power technologies have water consumption rates comparable to coal steam turbine plants, assuming closed-loop cooling technologies for all. New advanced coal facilities may also include carbon-capture and sequestration (CCS) technologies. CCS would substantially increase water consumption if applied to power generation. The water increase comes partly from water used in the capture process but also from the parasitic effect of CCS (a reduction in overall efficiency).

A recent study from late 2009 estimates that water withdrawal and consumption levels increase by two-thirds or almost double (National Energy Technology Laboratory 2009), summarized in Table 5-4 and Chart 4. These estimates are for greenfield plants (retrofit CCS would be higher still on a net energy output basis). The averages used are the simple mean of the low and high estimates.

Table 5-4: Advanced coal with CCS

(gal/MWh)	No CCS	CCS
Subcritical PC	450	900
Supercritical PC	425	800
IGCC	300	500

Chart 5-5: Water consumption in advanced coal power generation using closed-loop cooling

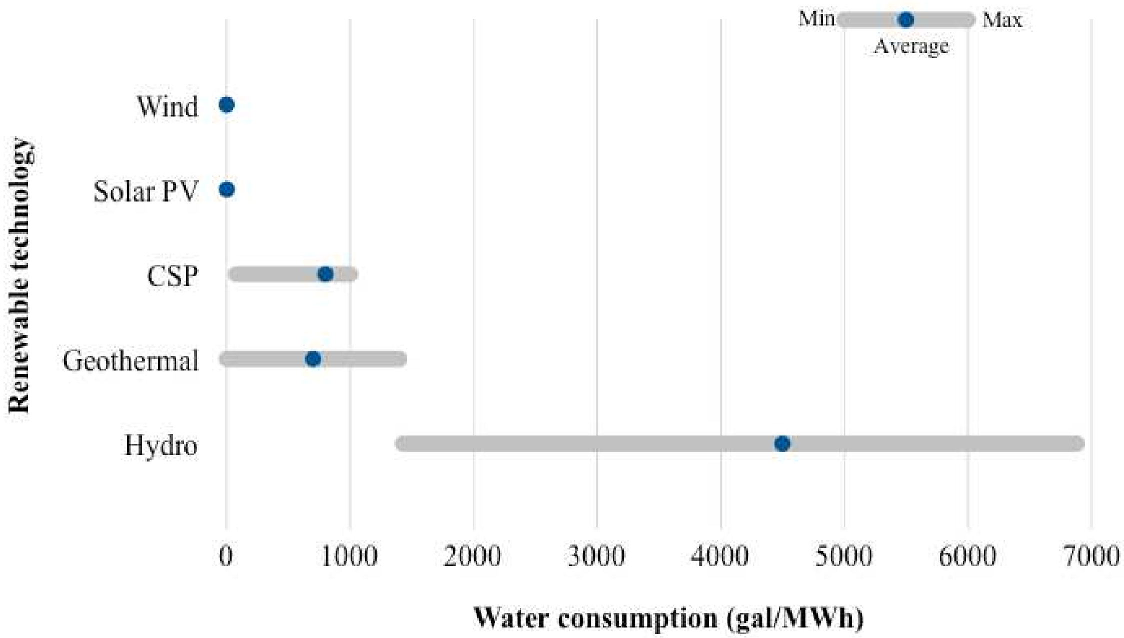


5.2. Renewable Energy

Renewable sources for electricity have very diverse water consumption issues. Wind and solar PV use practically no water, while concentrating solar power uses steam turbines and therefore has water consumption patterns comparable to or higher than conventional power plants.

The odd ones out are geothermal and hydropower, which are both very large users of water, but both have definitional issues that make it difficult to compare directly with other sources of electricity. The following chart summarizes the range of estimates for water consumption for each technology.

Chart 5-6: Water consumption for renewable sources of electricity



5.2.1. Concentrating Solar Power (Thermal)

Large-scale Concentrating Solar Power (CSP) facilities require space and sun, making desert application a natural fit. However, current CSP technologies typically have water consumption levels comparable to the highest thermal power plants, including nuclear, potentially limiting the appeal in a desert environment, given the potential for severe water constraints and competition with irrigation from farming.

Water consumption for CSP is primarily related to cooling with a small amount (~10%) related to mirror washing. A NREL report to Congress on CSP (U.S. Department of Energy 2008) reviewed four CSP technologies with water consumption range of 20 to 1,000 gal/MWh.

The technologies reviewed were (i) parabolic troughs, (ii) linear Fresnel, (iii) power towers, and (iv) dish/engine. Parabolic troughs are the most commercially available technology and have an estimated consumption of 800 gal/MWh for recirculating cooling, although this can be lowered to 78 gal/MWh by air cooling or to somewhere in between by using a hybrid approach (U.S. Department of Energy 2008). Water cooling is the most economic; air cooling reduces water consumption by 90% but increases the levelized cost of electricity by 2-10% (Kutscher 2008).

In common with parabolic troughs, Fresnel (1,000 gal/MWh), and power tower (90 gal/MWh for air cooling, 500 gal/MWh for recirculating) use the heat collected from the sun to power conventional Rankine steam cycles, similar to those in conventional power plants. The Stirling cycle used for dish/engine systems use sunlight to power a small engine using hydrogen as the working fluid. These are air-cooled and only require water for mirror washing (20 gal/MWh) (U.S. Department of Energy 2008).

The mean is assumed to be close to 800 gal/MWh given the current prevalence of parabolic troughs with recirculating cooling.

5.2.2. Solar Photovoltaic and Concentrating Solar Photovoltaic

Solar photovoltaic (PV) does not require significant quantities of water during normal operation (U.S. Department of Energy 2006).

A more efficient application of PV, but less mature technology, is solar concentrating photovoltaic (CPV). CPV is being deployed on an increasingly large scale but the studies reviewed for this report do not include estimates for CPV. However, two of the leading manufacturers, SolFocus and Amonix, both report water consumption close to 4 gal/MWh for cleaning the CPV system (Amonix 2010; SolFocus 2010), and these estimates have been included in the summary.

5.2.3. Wind

Like solar PV, wind power does not require significant water during normal operation (U.S. Department of Energy 2006).

5.2.4. Geothermal

Estimates for water consumption in geothermal vary substantially, depending on the definition of which type of water should be included in the consumption figure. For instance, the DOE (EERE) Geothermal Technologies Program's FAQ section estimates between 2,700 and 4,500 gal/MWh for evaporative cooling (Geothermal Technologies Program 2010), while the DOE's 2006 report to Congress estimated 1,400 gal/MWh net consumption out of 2,000 gal/MWh withdrawal.

The Geothermal Energy Association (GEA) challenges the fairness of the above estimates (Jennejohn, Blodgett, and Gawell 2009). GEA points out that the estimates include geothermal fluid (i.e., not drawn from freshwater sources), the validity of the above estimates, as the "geothermal reservoir fluids are not fresh or potable and cannot be used for other purposes due to their temperature and mineral content." The GEA estimates freshwater requirements of 5 gal/MWh for a binary, water-cooled plant, and no water consumption for binary, air-cooled facilities (Jennejohn 2009, 31).

However, the 5 gal/MWh estimate relates to a specific 1997 project called *Telephone Flat* proposed by Calpine Corporation (Kagel, Bates, and Gawell 2007). There is no indication of whether the project went ahead and/or if the estimate was appropriate. It is also unclear that this project is representative of other geothermal projects.

As a result, a range of 0 gal/MWh (closed-loop, air-cooled system, (Jennejohn, Blodgett, and Gawell 2009) to 1,400 gal/MWh (U.S. Department of Energy 2006) has been used, but it is reasonable to conclude that the mean consumption of freshwater is likely to be closer to the lower end of that range.

5.2.5. Hydropower

Hydropower evidently uses water in vast quantities but the majority of this is passed straight through with negligible losses at the turbine level. Hydropower plants with reservoirs incur evaporative water loss, with an estimated average for the United States of 4,500 gal/MWh (Gleick 1994, 267-299; U.S. Department of Energy 2006). A range of estimates is not available although Gleick gives a range for California, which has been used in this report to bound the average estimate.

However, the reservoir is typically also used for other purposes than hydropower (such as water supply, leisure, irrigation) raising a question whether it is reasonable to allocate this entire consumption to the electricity production.

5.3. Electricity Summary

Charts 5-7 and 5-8 summarize the analysis from Sections 5.1 and 5.2, showing first the water consumption data for electricity generation from non-renewable sources, then incorporating renewable energy. Note that Chart 5-8 excludes hydropower.

The inclusion of electricity from renewable sources shows the importance of considering water consumption as part of energy, especially if the *new* energy sources rely on *old* steam turbine solutions, as is the case for CSP and geothermal.

Chart 5-7: Water consumption in electricity generation using different cooling technologies

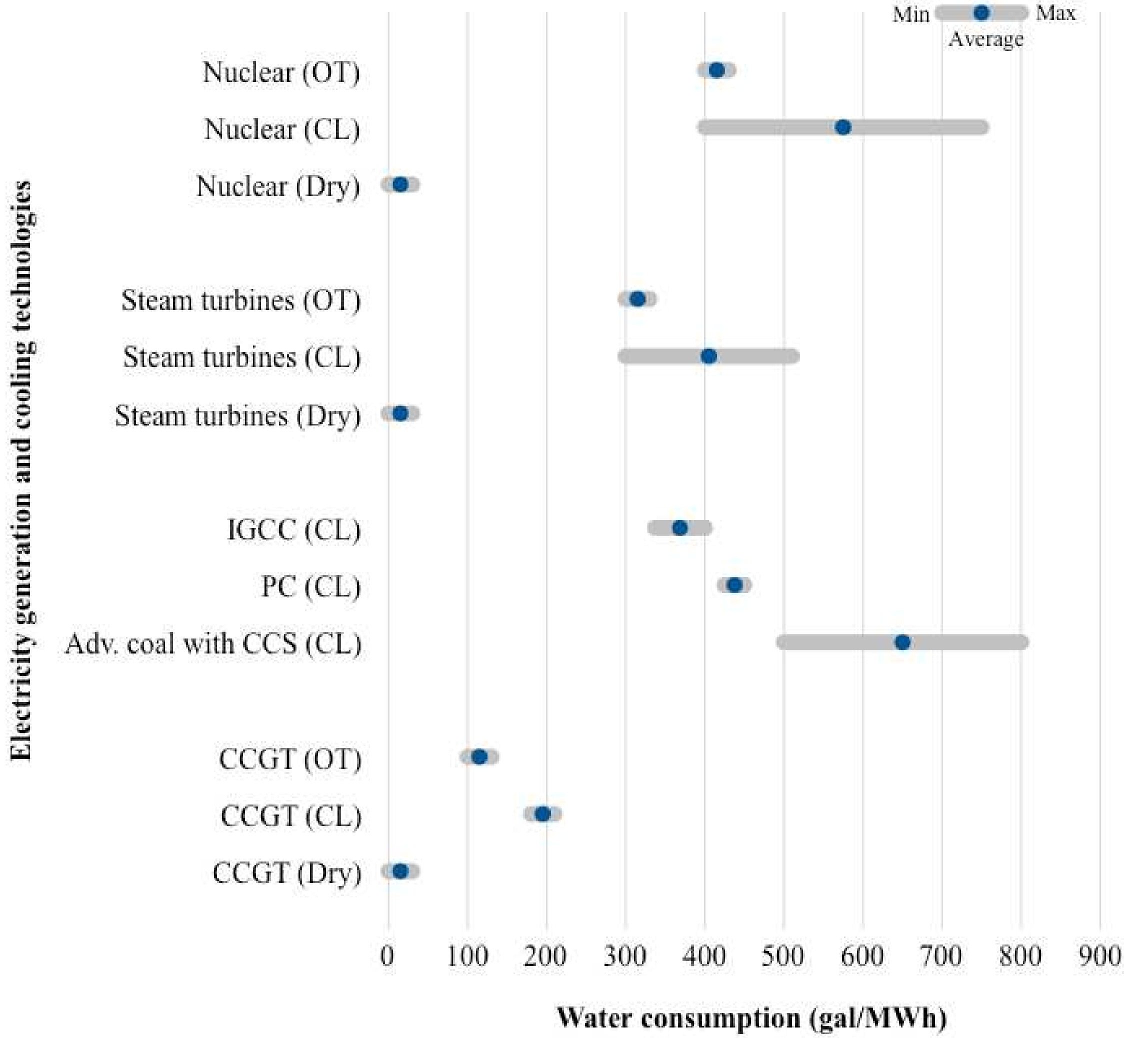
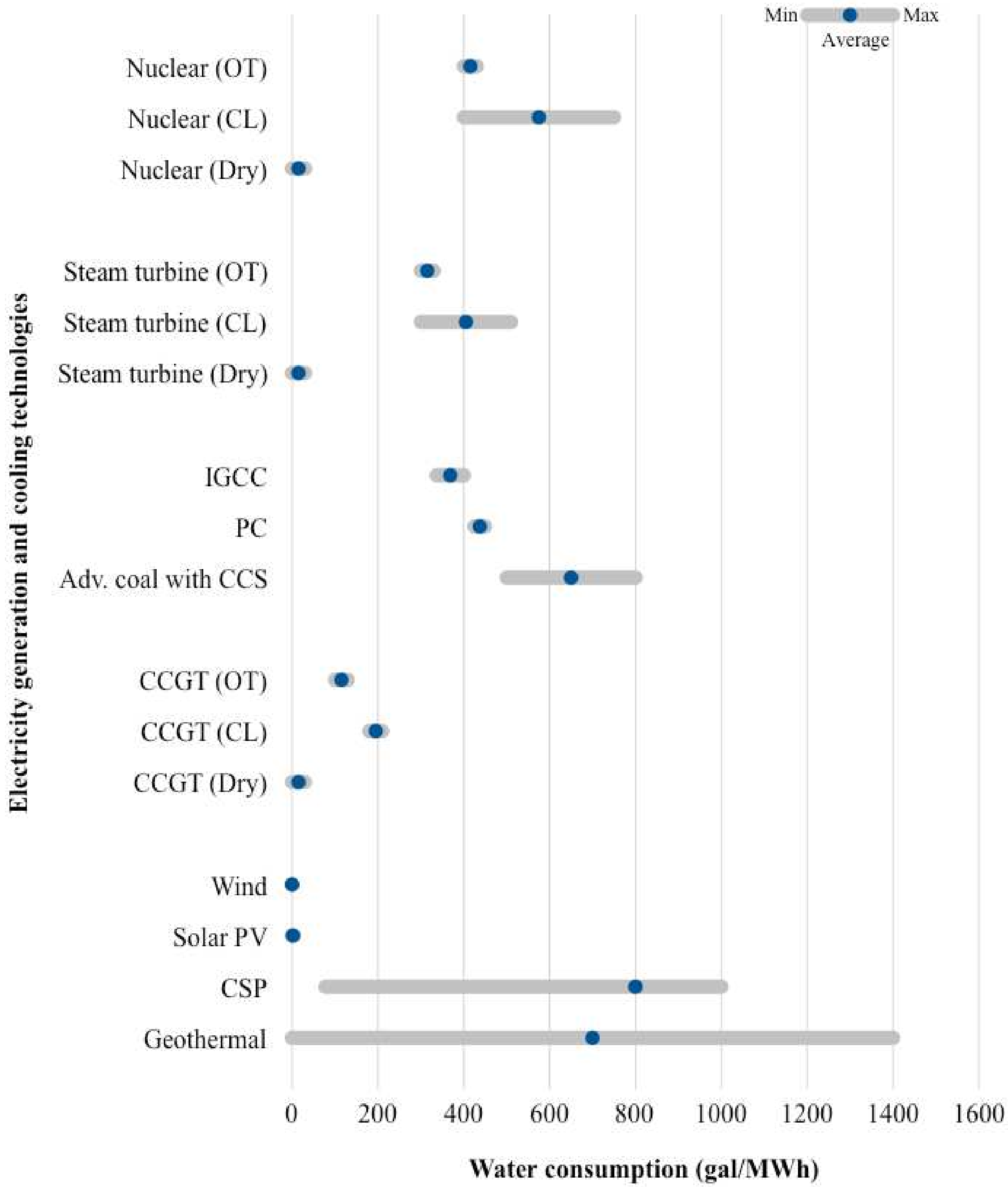


Chart 5-8: Water consumption in electricity generation using different cooling technologies



6. FULL-CYCLE WATER-CONSUMPTION OF ELECTRICITY PRODUCTION

This section incorporates the water consumption relating to the fuel used for electricity generation, as summarized in Section 4. Chart 6-1 shows the full-cycle water consumption per unit of electricity for fossil fuels and nuclear power, and Chart 6-2 adds renewable energy.

Chart 6-1: Water consumption in electricity generation using different cooling technologies, and including water consumed during fuel extraction and processing

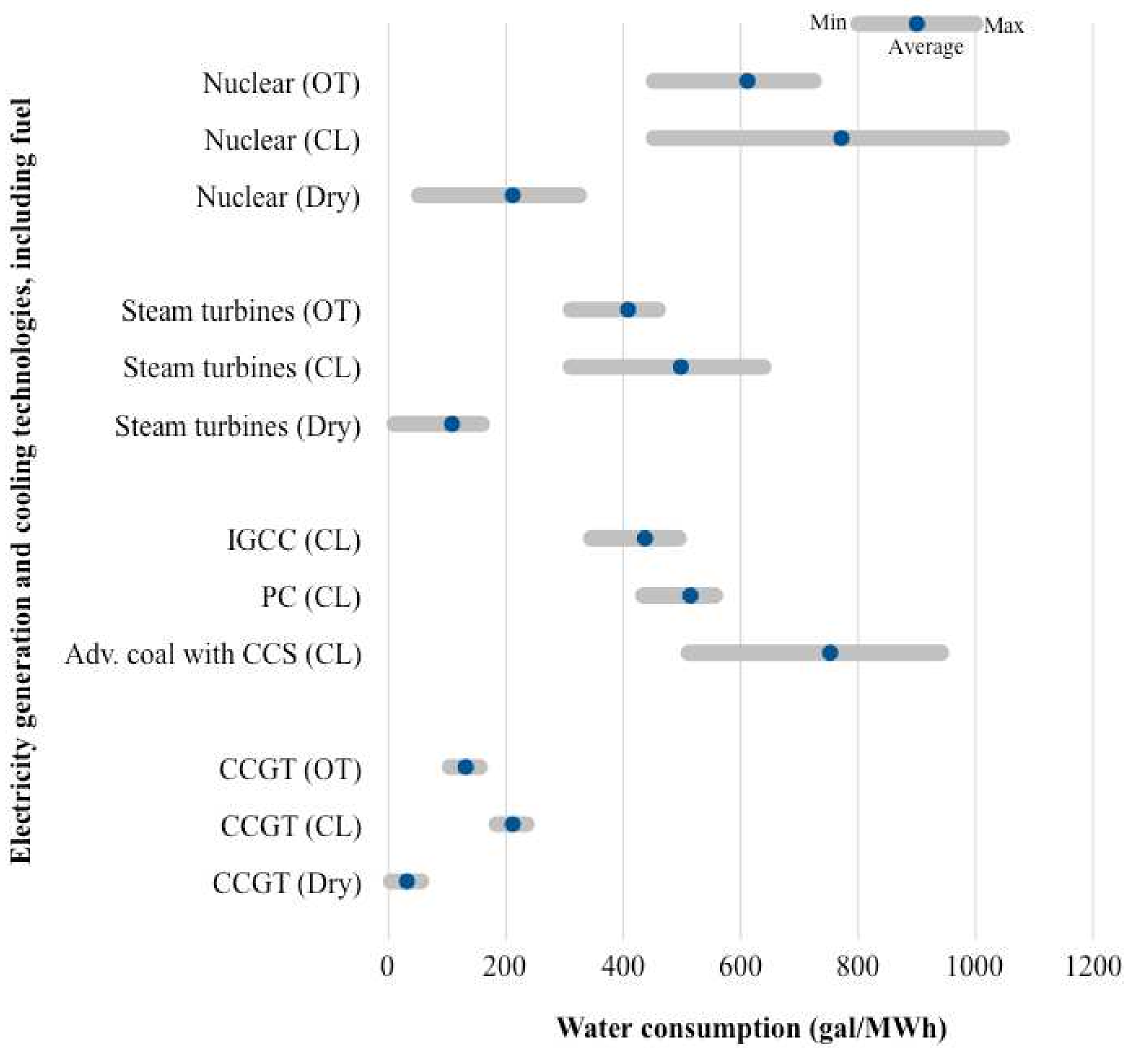
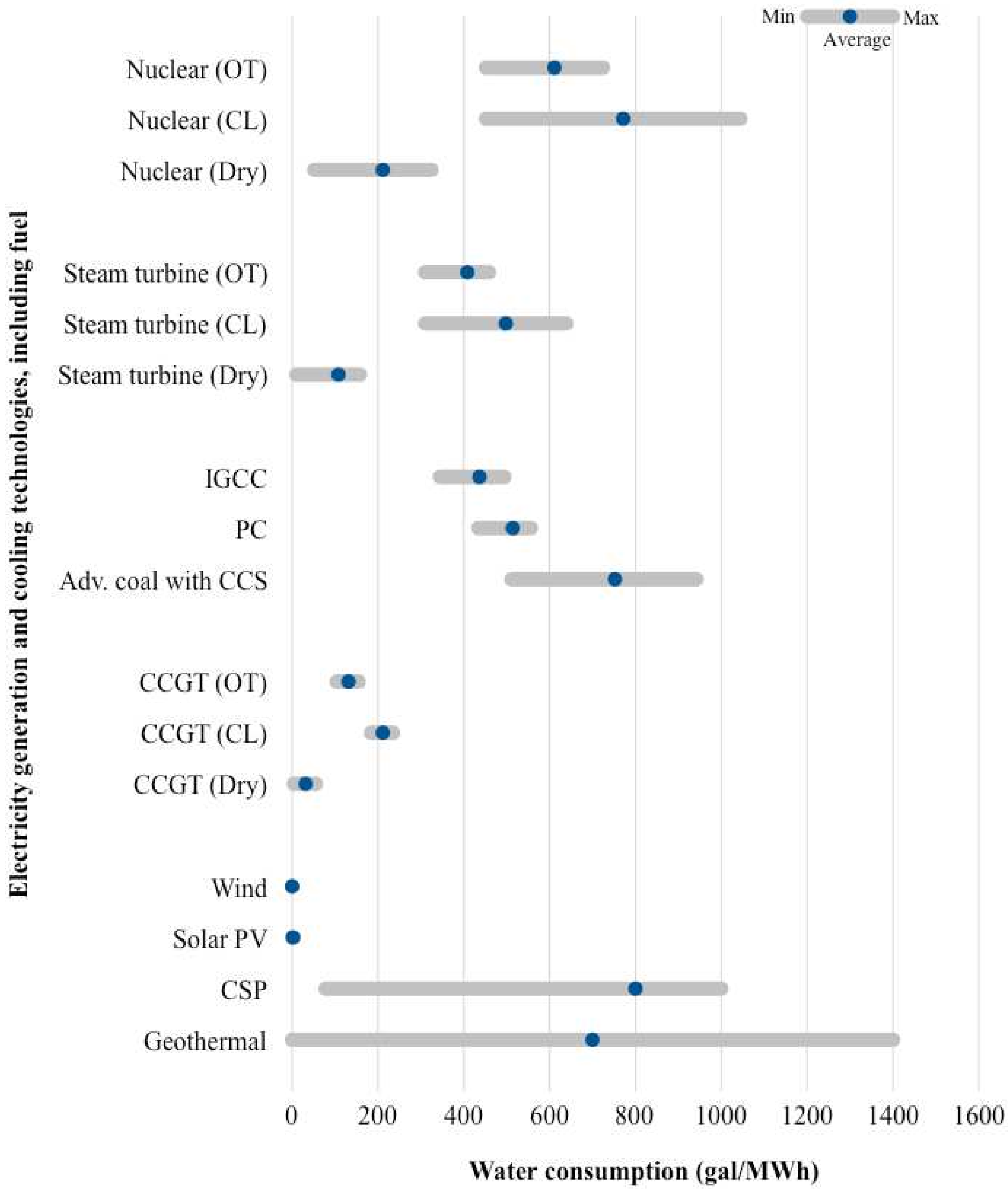


Chart 6-2: Water consumption in electricity generation using different cooling technologies, and including water consumed during fuel extraction and processing



7. CONCLUSIONS

Water used in energy extraction, processing and conversion is a significant share of overall demand for water demand in the United States. It is likely to rise as we increase reliance on water-intensive fuels.

Some of the fuels that have been promoted by government policies have larger-than-average water consumption, especially **biofuels** for transportation fuels. Corn ethanol has by far the highest water consumption of any fuel analyzed, largely due to irrigation during the corn-growing stage. A mandated move to advanced biofuels (cellulosic ethanol) could bring biofuels water-usage closer to that of other fuels—these technologies are currently unproven on a commercial scale.

Thermoelectric **power station cooling** accounts for between 3 and 4% of all U.S. water consumption, and has been increasing its share. The trend of higher water consumption from new or modernized steam turbine and CCGT power plants is likely to continue. Old power stations with once-through cooling are being upgraded with closed-loop cooling systems, a technology which has lower water intake but substantially higher net water consumption.

Increased reliance on **nuclear** power inland, which has the highest water consumption of the thermoelectric technologies, and the potential for wide-scale **CCS deployment**, could also significantly increase water consumption.

Some of the **renewable energy** technologies could offset these negative water-consumption trends, in particular wind and solar photovoltaic installations, which have practically no water consumption, although not all renewable energy technologies have low water consumption, e.g., CSP.

Another beneficial trend could be the increased role of **shale gas**, which has lower water consumption than other fossil fuels. The water used for releasing the gas (hydraulic fracturing), however, has to be carefully managed at a local level as there is a large upfront use of water over a few days or weeks, after which the natural gas is produced over many months or years. Concerns about potential contamination of freshwater supplies with hydrofracking fluids also need to be addressed. Natural gas-fired power plants (CCGT) also have some of the lowest consumption of water per unit of electricity generated, helped by the relatively high thermal efficiency of CCGT plants.

Finally, it is worth emphasizing that the wide range of water intensity estimates for the different processes investigated shows that, for each process, there are typically **alternative technologies,** which could reduce water consumption, albeit at a higher cost, with lower efficiency and/or reduced reliability.

8. IDEAS FOR FUTURE RESEARCH

Research on the policy implication of interdependencies of water and energy systems is relatively new and many areas would benefit from further research. Some ideas for future research avenues are:

- Analysis of the potential for increasing substitution of waste water for freshwater in the processes investigated.
- Study of the impact of water and electricity price and regulation on technology choice, especially in power generation.
- Comparison of estimates of the water intensity of energy processes in the United States with those of other regions.
- Quantification of the potential of technology innovation to reduce water consumption in the energy sector as a whole, e.g., new cooling technologies or different crops for biofuels.

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http://www.chk.com/Media/HaynesvilleMediaKits/Haynesville_Water_Use_Fact_Sheet.pdf,
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ABOUT THE ENERGY TECHNOLOGY INNOVATION POLICY (ETIP) RESEARCH GROUP

The overarching objective of the Energy Technology Innovation Policy (ETIP) research group is to determine and then seek to promote adoption of effective strategies for developing and deploying cleaner and more efficient energy technologies, primarily in three of the biggest energy-consuming nations in the world: the United States, China, and India. These three countries have enormous influence on local, regional, and global environmental conditions through their energy production and consumption.

ETIP researchers seek to identify and promote strategies that these countries can pursue, separately and collaboratively, for accelerating the development and deployment of advanced energy options that can reduce conventional air pollution, minimize future greenhouse-gas emissions, reduce dependence on oil, facilitate poverty alleviation, and promote economic development. ETIP's focus on three crucial countries rather than only one not only multiplies directly our leverage on the world scale and facilitates the pursuit of cooperative efforts, but also allows for the development of new insights from comparisons and contrasts among conditions and strategies in the three cases.

Belfer Center for Science and International Affairs
Harvard Kennedy School
79 JFK Street
Cambridge, MA 02138
Fax: (617) 495-8963
Email: belfer_center@harvard.edu
Website: http://belfercenter.org