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Water Dependency of Energy Production and Power Generation Systems

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Summary

Water and energy systems constitute the foundation for modern infrastructures around the world. Water and energy infrastructure are interdependent. In the U.S., energy production and power generation systems are major users of freshwater resources besides agriculture. The major goal of this report is to show dependency of energy production and power generation systems on water availability. The data for this study is extracted from publically available governmental and scientific documents. In estimating water use, water loss (e.g. evaporation losses) is considered water consumed. Water is not considered consumed if the withdrawn water is returned to the source and can be used again for other purposes such as recreation, fisheries and water supplies.

Energy production systems considered in this study include primary fuels sources (coal, natural gas and petroleum oil), biofuels (ethanol and diesel) and synthetic fuels (coal gasification, tar sands and oil shale). Power generation technologies considered include hydroelectric, fossil fueled thermoelectric, nuclear, geothermal, solar thermoelectric and hydrogen. For comparison purposes, all energy units are converted to a standardized unit, i.e., British Thermal Unit (BTU). Water use efficiency of various energy/power technologies is expressed in gallons of water used per BTU generated. Results of this study show that natural gas is the most water efficient energy source while biofuels are the least water efficient. Synthetic fuel production processes are also water efficient but these technologies mostly depend on hydrocarbon feedstock such as coal and natural gas. In terms of power generation, hydroelectric power is the most water efficient while nuclear power is the least water efficient.

The water use processes for energy production and power generation technologies are not well documented in the literature. Thus findings of this report are based on approximate water use volume. Furthermore, this report is solely focused on water use. Adverse impacts of energy production and power generation systems on environment such as water and air contamination are not considered in this report.

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Introduction

Water and energy systems constitute the foundation for modern infrastructures around the world. Water and energy infrastructure are interdependent. While energy is needed for water withdrawal, treatment and distribution, water availability is a detrimental factor for energy production and power generation systems (Caruso et al., 2001). This fact is clearly demonstrated during periodic water shortages and droughts. For example, power plants in the Susquehanna River Basin faced difficulty securing adequate water for power generation during the 1994 drought and the Washington State to spent one million dollars in 2001 to offset the loss of revenues to the Bonneville Power Administration due to water shortage (GAO 2003). If current trends hold, it is projected that in the next twenty five years the U.S. electricity demand will jump by approximately fifty percent (EIA 2006; USDOE 2006). This trend will exert additional pressure on water demand to meet increased electricity demand. Unfortunately, it is also projected that in the next ten years, at least 36 states will face water shortages (GAO 2003; USDOE 2006). The goal of this article is to illustrate the dependency of various energy and power generation systems on water availability.

Study Approach

The data for this study is extracted from publically available governmental and scientific documents. In estimating water use, water loss (e.g. evaporation losses) is considered water consumed. Water is not considered consumed if the withdrawn water is returned to the source and can be used again for other purposes such as recreation, fisheries and water supplies.

Available documents express energy/power in different units. To facilitate comparison between various technologies, in this article all energy/power units are expressed in British Thermal Unit (BTU). The BTU is a standard unit used to denote the amount of heat energy in fuels. A BTU is the amount of heat required to increase the temperature of a pint of water (which weighs exactly 16 ounces) by one degree Fahrenheit. The BTU (or

MBTU - one million BTUs), a standard unit can be applied to all energy production and power generation technologies. Basic heat rate conversion factors for fuels are available from the American Physical Society reports (e.g., APS 2009). Unit conversion from Kilowatt-hours to BTU is based on heat rates for specific energy and power generation technologies (EIA 2008). In this paper, water use efficiency of energy production and power generation technologies is expressed in gallons/BTU. Results are documented for primary energy sources (coal, petroleum oil and natural gas), biofuels (ethanol and diesel), synthetic fuels (coal gasification, tar sands and oil shale), and power generation systems (hydroelectric, nuclear, geothermal, solar thermoelectric, fossil fuel thermoelectric and hydrogen).

It should be noted that water use processes for energy production and power generation technologies are not well documented in the literature and heat rate conversion factors for biofuels are rather approximate values. Thus findings of this article are based on approximate water use volume and energy conversion factors reported in published documents. Furthermore, this report is solely focused on water use. Adverse impacts of energy production and power generation systems on environment such as water and air contamination are not considered in this article.

Results and Discussion

Water is used for energy extraction and power generation that uses various forms of energy. This article discusses water use for extracting primary energy sources such as fossil fuels and water use for power/electricity generation that uses various forms of energy such as water, fossil fuels and nuclear .

Water Use for Extracting Primary Energy Sources

Primary energy sources considered in this category include coal, petroleum oil, natural gas and hydrogen fuel. Primary energy sources are considered as energy carriers within the energy supply system. Table 1 shows calculated water use efficiency for three primary energy sources. The processes of where and how water is used for each energy sources are described below.

Table 1. Water Use Efficiency of Primary Energy Sources (Gallons/MBTU)

Fuel Source	Low Range Efficiency Gallons/MBTU	High Range Efficiency Gallons/MBTU	Sources
Coal	41	164	USDOE 2006; Gleick 1994; EIA 2008
Natural Gas	3		USDOE, 2006; Gleick 1994; EIA 2008
Petroleum/Oil	1200	2420	USDOE 2006; Gleick 1994

Coal

In 2007, coal accounted for 50% of the U.S. total net generation of electric energy (EIA 2008). Water use is a major component of coal production. It is used during coal mining operation (surface mining and deep mining), coal transport and storage, and coal refining process. In addition, water is used to cool or lubricate the drilling equipment, dust suppression, and fuel processing. Water is also used during post-mining activities such as land reclamation and revegetation. Details of water use for coal production are documented by Shannon (1982) and USDOE (2006).

Natural gas

Natural gas provides about 25% of the U.S. total energy use (EIA 2008). About 85-90% of natural gas used in the U.S. is produced domestically and the balance is imported from Canada (USDOE and NARUC 2005). Gas wells are drilled to bring up to the surface the raw natural gas from underground gas fields. Minimal water is used during drilling of gas wells however large volume of water is withdrawn with the extracted gas. Natural gas production is rather water efficient because the withdrawn groundwater is mostly re-injected back into the aquifer (USDOE 2006; Gleick 1994). The raw natural gas is processed to produce pure gas mostly methane. Water is used during the gas purification process, i.e., gas is dehydrated (of water vapor) to prevent formation of methane hydrates in the gas purification plant.

Petroleum/oil

Similar to natural gas extraction, the drilling process for petroleum extraction requires minimal amounts of water but large amounts water called produced water is withdrawn with the extracted oil. The withdrawn water is usually re-injected into the wells (USDOE 2006; Gleick 1994). Water is also used during the petroleum refining process such as desalting and alkylation (uses a caustic/water wash) (Alva-Argaez et al., 2007).

Water Use for Producing Biofuels

Various feedstocks can be used to produce biofuels. Potential feedstocks to produce ethanol are sorghum, cane sugar and cellulose. Potential feedstocks to produce biodiesel are soybean, vegetable oils and grease. Current biofuel production in the U.S. mostly depends on irrigated corn and soybean. Therefore, the discussion here in terms of water use is limited to corn-ethanol and soy-biodiesel production. The crop irrigation water demand depends on its geographic location, climate, and type of feedstock (Dominguez-Faus 2009). Soybean usually uses less water than corn in the Northern and Southern Plains, but in the Pacific and Mountain regions soybean uses more water than corn (Hagens 2007). Table 2 shows water use efficiency for ethanol and biodiesel production.

Ethanol

Ethanol is produced by fermentation process either in dry mills or wet mills. In dry mills, the corn kernel is grinded and subjected to fermentation (Kwiatkowski et al. 2006).
In wet mills, corn kernel is separated into starch, protein, germ and fiber in an aqueous medium prior to fermentation. About 75% of ethanol in the U.S. is produced in dry mills which are less water efficient; uses 4.7 gallons of water to produce 1 gallon of ethanol as

compared to 2.7 gallons of water per gallon of ethanol in wet mills (Shapouri and Gallegher 2005; USDOE 2006). However, major water use for ethanol production is for irrigation demand. Water use for corn irrigation ranges from 500 gallons to 6,000 gallons of water per bushel with an average of 2,200 gallons per bushel depending on climate and region (USDA 2004; USDOE 2006).

Table 2. Water Use Efficiency of Biofuel Energy Sources (Gallons/MBTU)

Fuel Source	Low Range Efficiency Gallons/MBTU	High Range Efficiency Gallons/MBTU	Sources
Corn-Ethanol	2510	29100	USDOE 2006; USDA 2004
Soy-Biodiesel	14000	75000	USDOE 2006; USDA 2004

Biodiesel

Biodiesel fuel is produced through a process called transesterfication. This process involves removing the glycerin from the soybean oil. Similar to ethanol, irrigation water demand for soybean production range from 1,600 to 9,000 gallons per bushel with an average of 6,200 gallons of water use per bushel depending on climate and region (USDOE 2006). To amount of water use to convert soy to biodiesel ranges from 14,000 to 75,000 gallons per MMBTU (USDOE 2006). Details of biodiesel processing from soy are provided by Marchetti et al. (2007) and Gerpen (2005).

Water Use for Producing Synthetic Fuels

Synthetic fuel (synfuel) is a liquid fuel obtained from coal, natural gas, oil shale, tar sand and other biomass. Liquid fuels facilitate easy transportation of energy from source to point of use. Water needs and processes for three common synfuels are described below. Table 3 shows calculated water use efficiency for three synthetic fuel sources described above. The processes of how water is used in synthetic fuel production are described below.

Coal gasification

In this process, hydrocarbon feedstock is converted to a mixture of carbon monoxide (CO) and hydrogen (H_2) gas (syngas) in a gasifier under pressure in the presence of steam (Beychock 1975). Water is also used in Integrated Gasification Combined-Cycle (IGCC) process. This is a combined gasification and combustion process with higher power generation efficiency where the syngas produced during the gasification process is burned as a fuel in the combustion turbine. The exhaust heat from the combustion turbine is recovered and used to produce steam that powers the turbine generator (USDOE 2008).

Table 3. Water Use Efficiency of Synthetic Fuel Sources (Gallons/MBTU)

Synfuel- Coal Gasification	11	26	USDOE 2006;Gleick 1994; EIA 2008
Synfuel - Tar Sands	15	38	USDOE 2006; Gleick 1994
Synfuel - Oil Shale	20	50	USDOE 2006

Tar Sands

Tar Sands, also known as oil sands, contain heavy crude oil that is found in bitumen deposits. A variety of methods, depending on the physical characteristics of oil sands, are used to remove the bitumen from the oil sands. Bitumen can efficiently be removed by hot-water extraction process that uses an alkaline solution near boiling temperature (Hupka et al. 2004).

Oil Shale

Oil shale, an organic-rich fine-grained sedimentary rock, contains significant amounts of kerogen (a solid mixture of organic chemical compounds). Liquid hydrocarbons can be extracted from kerogen using chemical processes such as pyrolysis. The chemical process converts kerogen to synthetic crude oil. Water is used during the surface mining of oil shale as well as post-mining land reclamation and oil shale treatment or retorting process (BML 2007; Bunger et al. 2004).

Water Use for Power Generation

Power or electricity is mostly generated at a power plant using various forms of energy. Various types of electric generators include electromechanical fueled by chemical combustion of fossil fuels or nuclear fission, and kinetic energy such as flowing water and steam. Power generation technologies considered in this article include hydroelectric, fossil fuel thermoelectric, nuclear, geothermal and solar thermoelectric. Table 4 shows calculated water use efficiency for power generation systems. The processes how water is used are described below.

Hydroelectric Power

Hydroelectricity is electricity generated by from energy extracted from water through use of the gravitational force of falling or flowing water and a water turbine. Hydroelectric power plant uses water that turns the turbines which operate the electric generator. Hydroelectric power generation systems are highly water efficient because used water is mostly returned to the river or lake with marginal losses through the turbines. Water evaporation loss through the system is mostly attributed to natural processes and other water uses such as recreation (Gleick 1994; USDOE 2006).

Fossil Fuel Thermoelectric Power

Fossil fuel thermoelectric generation represents the largest segment of the U.S. electricity production with coal power plants alone generating about half of the nation’s electric supply (Feely 2007). A fossil-fuel power plant burns fossil fuels such as coal, natural gas or petroleum oil through combustion. Amount of water use vary for various fossil fuel types (Yang and Dziegielewski 2007). In a fossil fuel thermoelectric power plant, heat is converted to mechanical energy by means of a steam turbine that operates an electrical generator. Water is used in many different steps within thermoelectric plants. In plants that use a steam turbine, water is used not only to drive the steam but to also cool and condense the turbine exhaust (USDOE 2006). Thermoelectric power generation plants use most water in the condensers and in reactor cooling (Inhaber 2004). Water is also used in the emissions scrubbing process (USDOE 2006).

Table 4. Water Use Efficiency of Power Generation Systems (Gallons/MBTU)

Power Generation Method	**Low Range Efficiency Gallons/MBTU**	**High Range Efficiency Gallons/MMBTU**	**Sources**
Hydroelectric	20	N/A	USDOE 2006 Gleick 1994; EIA 2008
Fossil Fuel Thermoelectric	1100	2200	USDOE 2006; Hutson et. Al 2004
Geothermal	130	N/A	USDOE 2006; EIA 2008
Nuclear	2400	5800	USDOE 2006; EPRI 2002a; EPPRI 2002b
Solar Thermoelectric	230	270	USDOE 2006
Hydrogen	143	243	USDOE 2006

Nuclear Power

Water is used during of uranium mining and processing (Gleick 1994). Nuclear power plants convert the energy released from the nucleus of an atom via nuclear fission inside a nuclear reactor. The generated energy heats water (steam) to turn that turbine that operates the electricity generator. This steam is then cooled so that the water can be recycled through the system (Sackett 2001). The amount water a nuclear power station uses depends on the cooling technology. Pressurized-light water reactors and boiling water reactors are two types of commercial reactors used for power generation (USNRC 2007). Most of the water is consumed within the nuclear reactors (USDOE 2006).

Geothermal Power

Geothermal power is energy extracted from the natural heat stored beneath the earth surface by harnessing the steam (Nakamura et al. 2002; Lund and Freeston 2000). Three different approaches - dry steam, flash, and binary cycle - are used to generate electricity. Dry steam and flash steam use geothermal steam directly to turn the turbine/generator while in the binary cycle geothermal steam is first vaporized and then used to turn the turbine/generator. In all cases the condensed steam and remaining geothermal fluid is injected back into the ground to pick up more heat.

Solar Thermoelectric Power

This is a renewable energy source since the sun continually transmits large quantities of radiation on earth's surface (Vatcharasathien et al. 2005). Solar thermoelectric power is generated by conversion of solar radiation to electricity after it is collected on a solar collector or a solar pond (Trieb et al. 1997). Solar thermoelectric power generation uses water for steam generation, as a coolant and cleaning purposes (Trieb et al. 1997). In solar ponds water is used for storage and energy absorption.

Hydrogen

Hydrogen is not an energy source but an energy carrier similar to electricity. But unlike electricity, generated energy can be stored. Hydrogen does not exist as a free gas and should be extracted from water (electrolysis) or from other primary energy feedstock such as natural gas (Ogden 2002; Rajashekara 2005; USDOE 2006). About 95% of hydrogen in the U.S. is produced through natural gas reforming, a process known as steam methane reforming (SMR). The SMR process involves methane reacting with steam at high temperature to produce a synthetic gas, a mixture of primarily hydrogen and carbon monoxide (CO). In the next step the mixture is converted to carbon dioxide and hydrogen. Water is used in reaction processes, plant operations and is often lost as steam (USDOE 2006).

Conclusion

Energy extraction technologies are very diverse with a wide range of water use efficiencies. Natural gas production is the most water efficient. Synthetic fuels can be considered water efficient as well, however, synfuel production mostly relies on hydrocarbon feedstock such as coal and natural gas. Corn and soy-based biofuel production technologies are the most water intensive. Water use for biodiesel and ethanol production crosses over into the agricultural realm where irrigated crop production is the biggest consumer of water (USDOE 2006). Significant amounts of water input into biodiesel and ethanol production occurs is during crop growth and assumed as consumed water. Crop selection, tillage methods, and location are under human control and can benefit biodiesel and ethanol production by decreasing water use (Dominguez-Faus, 2009).

From a power generation perspective, hydroelectric power generation is the most water efficient as most used water is returned to the source. Geothermal power generation is also water efficient. Geothermal plants do utilize less water, however the availability of geothermal energy is localized and the capacity of a geothermal power plant to generate power is much lower than nuclear and fossil fuel thermoelectric power plants (Nakumura 2002). Nuclear power generation is the most water intensive. The low water use efficiency of nuclear power generation is mostly attributed to low efficiency of steam turbine systems (USDOE 2006). Fossil fuel thermoelectric is the second most water intensive power generation method. Significant volume of water is required during the fuel production and purification processes. It is important to note that heat rate values for hydroelectric and solar thermoelectric technologies are not available and therefore, water use efficiency comparison to other technologies may not be very reliable.

Fossil fuel thermoelectric generation represents the largest segment of the U.S. electricity production and for the foreseeable future will continue to require large quantities of water. Water use efficiency in thermoelectric power generation plants can be enhanced by upgrading these plants, for example replacing evaporative cooling towers with dry cooling system within a closed-loop (USDOE 2006). Dry cooling systems use high flow rates of ambient air for exhaust steam cooling thus reducing evaporative losses (Feely 2008). Another water saving option is combined cycle power plants. In these plants, steam produced from generators is used to power another turbine making the system more water efficient. For example, natural-gas-fired combined-cycle gas turbines use half as much water as typical coal-fired plants and are becoming more popular in recent years (USDOE 2006).

Although certain fuel sources and power generation methods discussed in this article are more water efficient than others, water availability remains a problem to meet future energy demands. In the U.S., population growth rates and energy consumption patterns are projected to increase in coming decades and thus will continue to put pressure on water availability for competing interests. There is a critical need for the type of energy production systems that are less water intensive. Also, the climate change and the need for reduced carbon emission dictate the need of developing alternative renewable energy technologies such as wind, solar photovoltaics that consume minimum freshwater and are carbon free.

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