SAND 2007-1349C

# OVERVIEW OF ENERGY-WATER INTERDEPENDENCIES AND THE EMERGING ENERGY DEMANDS ON WATER RESOURCES

**March 2007**

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## Introduction

For the past century, the U.S. has invested significant research, development, and construction funding to develop both fresh surface and groundwater resources. The result is a water infrastructure that allows us to harness the vast resources of the country's rivers and watersheds, controlling floods and storing water during droughts to provide reliable supplies of freshwater for agricultural, industrial, domestic, and energy uses. During this same period, the U.S. developed extensive energy resources such as coal, oil, natural gas, and uranium and created an infrastructure to transport, process and distribute these resources efficiently and cost-effectively to consumers. These two achievements have helped stimulate unprecedented economic growth and development.

However, as population increases, demand for energy and water continues to grow. U.S. efforts to replace imported energy supplies with non-conventional domestic energy sources have the potential to further increase demand for water. At the same time, competing demands for water supply are affecting availability. Operation of some energy facilities has been curtailed, and siting of new facilities is becoming more difficult. Currently, electric power generation is one of largest water withdrawal and use sectors in the U.S. Additionally, future energy development: such as biofuels, hydrogen, or synfuels production; oil shale development; carbon sequestration; and nuclear power development could significantly increase water use and consumption. On the other hand, water resource development - distribution, treatment, and transmission - is one of the largest energy use sectors. As future demands for energy and water continue to increase, competition for water between the energy, domestic, agricultural, and industrial sectors, could significantly impact the reliability and security of future energy production and electric power generation.

To address these growing concerns, Congress directed the Department of Energy (DOE) to develop a Report to Congress identifying current and emerging national issues associated with the interdependencies between energy and water, and to develop an Energy-Water Research and Development Roadmap. This paper provides an overview of the interdependencies of energy and water, outlines the emerging energy demands on water resources identified in the Energy-Water Report to Congress, and summarizes some of the major challenges and research directions identified through the Energy-Water Roadmap process. The Report to Congress (DOE, 2007) has recently been approved for release by DOE and is available at the web site http://www.sandia.gov/energy-water/congress_report.htm. The Energy-Water Research and Development Roadmap is expected to be published later in 2007 or early 2008.

## Emerging Challenges of Water and Energy Development

The availability of adequate water supplies has a profound impact on the availability of energy, while energy production and power generation activities affect the availability and quality of water. In today's economies, energy and water are tightly linked. As illustrated in Figure 1, energy production and power generation require water, and water pumping, treatment, conveyance, and end-use conditioning

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[2] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

require energy. As these two resources see increasing demand and growing limitations on supply, energy and water must be recognized as highly interdependent critical resources that need to be managed together in a more integrated way to provide reliable energy and water supplies and sustain future national growth and economic development while maintaining the health of ecosystems and the environment.

The emerging vulnerability of energy and water supplies and infrastructures is becoming clearer. Low water levels from drought and competing uses have limited the ability of power plants to generate power. Additionally, water levels in aquifers in many regions of the U.S. have declined significantly, increasing energy requirements for pumping, and, in some cases, leading to ground subsidence issues. Lack of water for thermoelectric power plant cooling and for hydropower has the potential to contribute to power shortages like those of recent years that have illustrated the vulnerability of the U.S. electrical grid to unplanned generation outages, especially in hot weather.

Of concern to many water managers is the effects climate variability and changes could have on snow fall and precipitation and the associated impacts on surface water reservoir storage and operations and ground water recharge. Climate variability has caused reductions in snow pack, earlier spring snow melt, and earlier but smaller peak stream flows in some regions. If the trends seen over the past 50 years continue, many regions could see significant reductions in reservoir storage levels, forcing reduced surface water withdrawal rates and decreasing future surface water availability.

At the same time, demand for energy continues to grow. The 2006 Annual Energy Outlook report of the U.S. Department of Energy's Energy Information Administration projects that demand for energy supplies from 2003 to 2030 is on track to increase over current use as follows: petroleum, 38 percent; natural gas, 20 percent; coal, 54 percent; nuclear power, 14 percent; and renewable energy, 58 percent. Demand for electricity from all sources is projected to increase by 53 percent. Providing this energy and electrical power will require access to sufficient water resources.

Unfortunately, freshwater withdrawals already exceed available precipitation in many areas across the country as shown in Figure 2, where the red colors denote water withdrawals exceeding available precipitation by up to a factor of five. The shortfalls are most dramatic in the Southwest, the High Plains, California, and Florida. Population growth in these regions between 2000 and 2025 is estimated to be 30 to 50 percent. This additional population will require more water and more energy. The challenges are not limited to these regions, however. For example, nearly the entire western shoreline of Lake Michigan has water demand above available precipitation, and aquifers in that region have declined as much as 900 feet, and are declining as much as 17 feet per year in some cases, while many areas in the East and Southeast are also becoming short of water.

## Water Availability and Use

For much of the 20th Century, the increasing demands for water in the U.S. were met by extensive development of surface and ground water supplies. This was accomplished through the construction of large dams and reservoirs to harness our vast surface water resources and by extensive development of easily accessible fresh ground water supplies across the country. These efforts increased water supplies to help support growth in industrial, agricultural, energy, and domestic water demands. As our population and economy continue to grow, there may be a need to further increase water supplies or improve water management and availability to support future domestic, agricultural, industrial, and energy growth. Figure 3 provides an overview of the trend in surface and ground water use for different sectors since 1950 (Hutson, 2004).

There have been significant increases in water withdrawals over the past 50 years, especially for irrigation and energy. Since 1980 there has been a decrease in water withdrawals for industrial applications and irrigation, with continued increases in water withdrawals for domestic supplies and energy development. As shown in Figure 3, most water withdrawals are of fresh surface and ground water, with saline water withdrawals predominately used as cooling water for coastal thermoelectric power plants. Since 1980, fresh water withdrawal in the U.S. has been relatively constant at about 265 billion gallons per day (BGD). This is for several reasons that include limitations on the ability to develop new fresh surface and ground water resources, increased withdrawals for the energy and

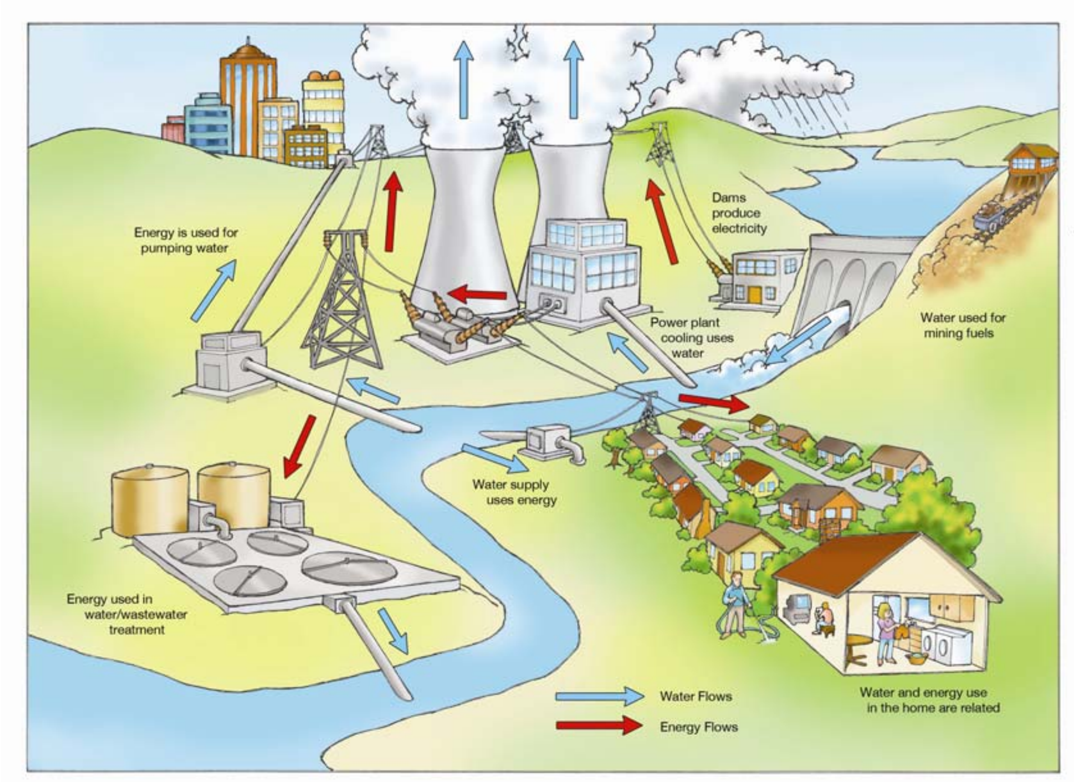


**Figure 1. Examples of Interrelationships Between Water and Energy**

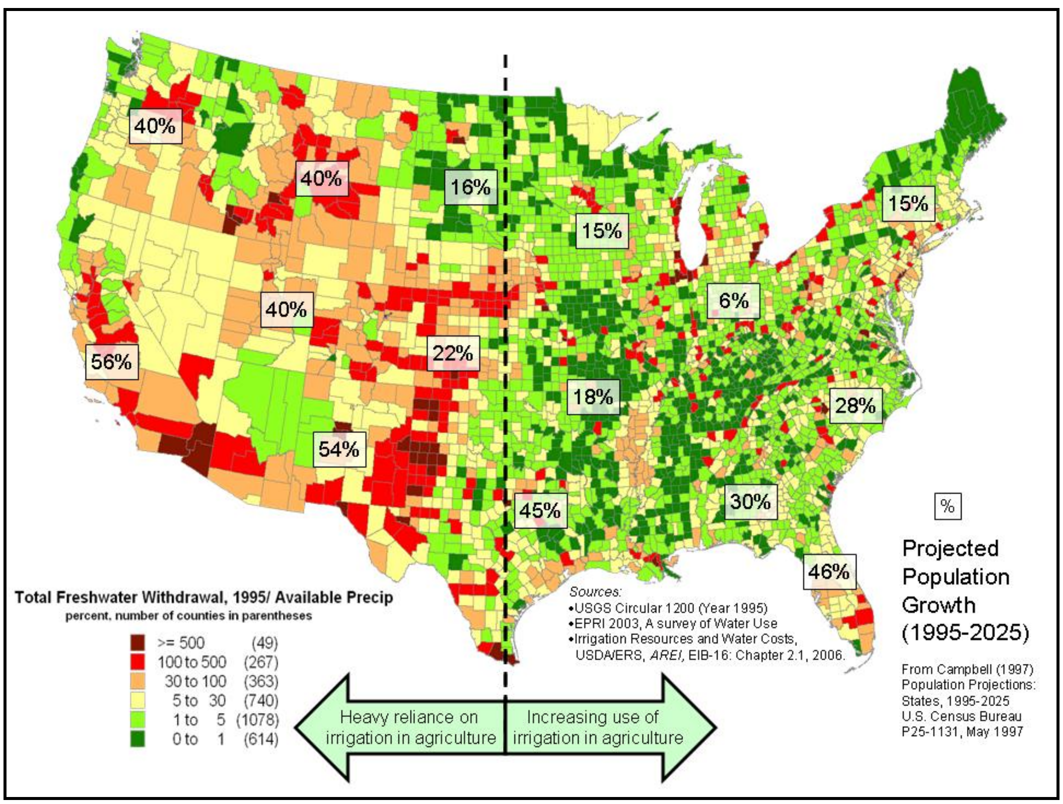


**Figure 2. Emerging Water Stress and Projected Population Growth**

domestic use sectors being offset by reductions in water withdrawals for agriculture and industry, and improved water conservation and increasing waste water reuse. From 1920 to 1980, surface water reservoir storage capacity tripled in the U.S. due to the construction of many large dams across the nation. Since 1980, reservoir storage capacity has increased by only a few per cent and currently only one major dam and reservoir is under construction. Current surface water withdrawal rates are over 96 percent of reservoir withdrawal capacity for a two percent deficiency rate, which is an operational approach to ensure that reservoirs can reliably support the identified water withdrawal rates over a fifty year period. Without the expansion to existing dams or the construction of new dams, fresh surface water withdrawals in the U.S. will continue to be limited to current withdrawal levels. If major dams are retired or removed, future fresh surface water withdrawal rates could actually be reduced.

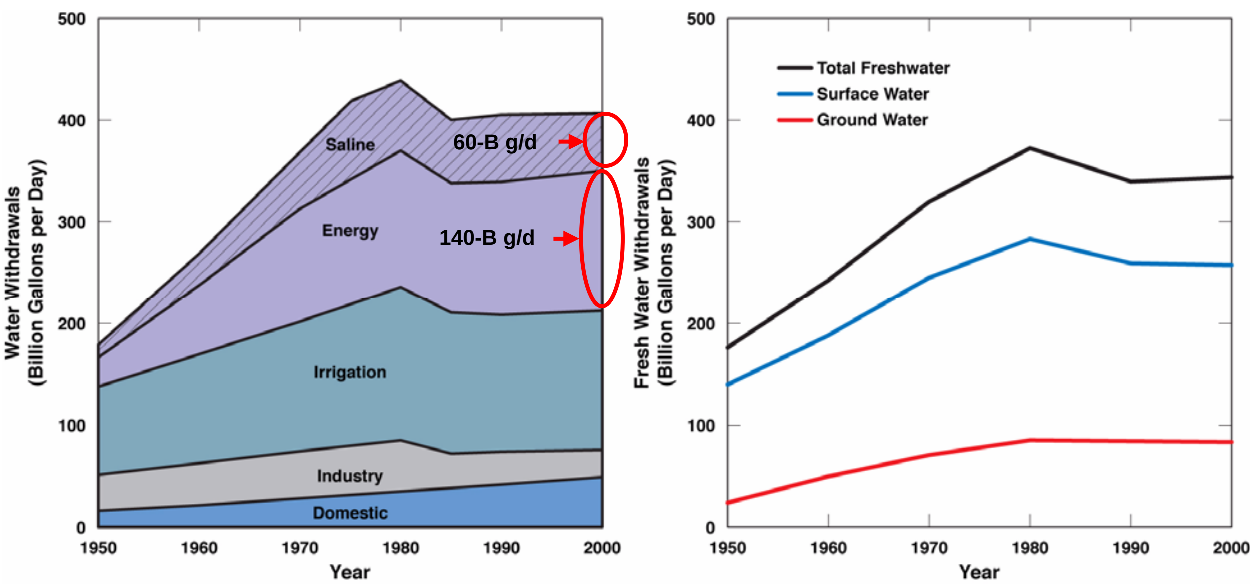


**Figure 3. Trends in Water Withdrawals, 1950–2000 (Hutson et al., 2004)**

## Water Demands for Energy Production, Power Generation, and Refining

Water is an integral element of energy- resource development and utilization. It is used in energy resource extraction, refining, processing, and transportation, as well as in hydroelectric generation, thermoelectric power plant cooling, and emissions scrubbing. In its reference case for 2006, the EIA Annual Energy Outlook projects that the U. S. population will grow by about 70 million people by 2030. This growth, along with the economic and industrial development needed to support this growth, is expected to significantly increase energy demands for electric power generation and transportation fuel production. The growth in energy demand could significantly increase the water needs and water consumption for energy development. As noted in Figure 3, in 2000 the energy sector accounted for almost 50%, or 197 billion gallons per day, of all U.S. fresh and saline water withdrawals. Fresh water withdrawals for 2000 were dominated by irrigated agriculture and thermoelectric power, as noted in Figure 4. Most of the energy sector water withdrawals were for thermoelectric power generation, but over one billion gallons per day are withdrawn for petroleum refining. Almost all of the saline water withdrawals, about 60 billion gallons per day and thirty-nine percent of all freshwater withdrawals of 134 billion gallons per day in 2000, were for thermoelectric power plant cooling (Hutson, 2004). These values do not include the water used for hydroelectric power generation.

Thermoelectric generating technologies, including fossil fuel, nuclear, biomass, solar thermal, and geothermal steam plants, require cooling to condense the steam at the turbine exhaust. Prior to 1970, most thermoelectric power plants were built adjacent to surface waters and used open-loop cooling. These plants withdraw large volumes of water that are discharged to the source at a higher temperature

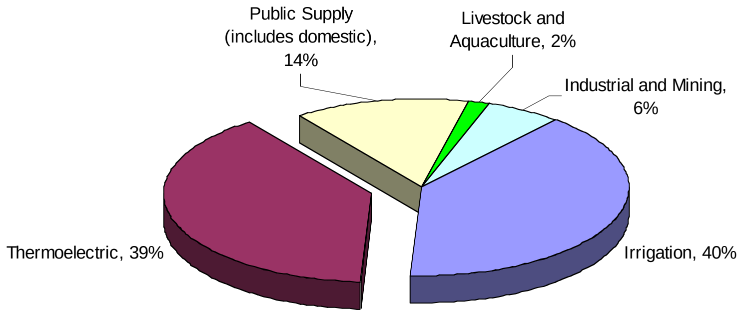


**Figure 4. Fresh Water Withdrawals by Sector, 2000 (Hutson, 2004)**

and with other changes in quality, but otherwise available for further use. Due to changes in environmental law as well as increasing demand for electric power in arid areas, most thermoelectric plants installed since the mid-1970s are cooled by evaporation of the cooling water using cooling towers or cooling ponds. These systems withdraw less than 5 percent of the water withdrawn by open-loop systems, but most of the water withdrawn is lost to evaporation. The thermoelectric water withdrawal data is currently dominated by plants that return most of the water back to the source, with total freshwater consumption for the thermoelectric power sector reported to be 3.3 BGD in 1995 (Solley et al., 1998) as shown in Figure 5. While that was only 3.3 percent of total U.S. fresh water consumption of about 100 BGD, it was 20 percent of nonagricultural water consumption in 1995.

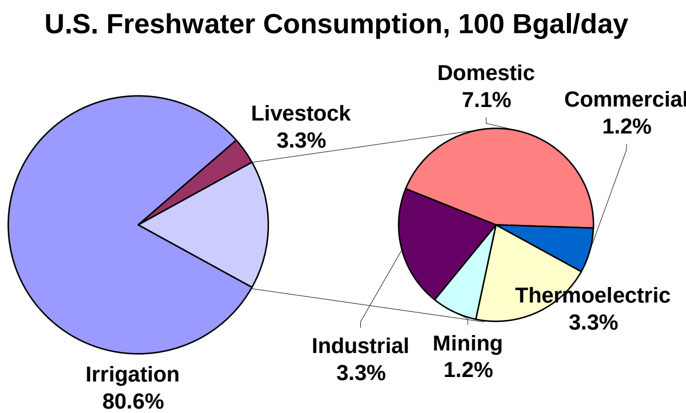


**Figure 5. Estimated freshwater consumption by sector, 1995 (Solley et al., 1998)**

## Projected Growth in Electric Power Generation

U.S. electric power demand is expected to grow from 3700 billion kilowatt hours (kWh) in 2005 to 5500 billion kWh by 2030, an increase of almost 50 percent as shown in Figure 6. In its reference case for 2006, the EIA projects major growth in electric power generation from coal-fired thermoelectric power plants, increasing by 1300 billion kWh per year by 2030. The EIA projects modest growth by 2030 for several other types of electric power generation including an increase in generation of 200 billion kWh per year from both natural gas and renewable energy power plants, and an increase in generation of 100 billion kWh per year from nuclear power plants. This equates to approximately 350 new 400 Megawatt (Mw) coal-fired power plants, about 150 new 100Mw gas turbine power plants, 5 new 1000 Mw nuclear plants, and about 125 new 200 Mw or equivalent wind and solar power plants. The projections do not include major increases in hydroelectric power development or generation.

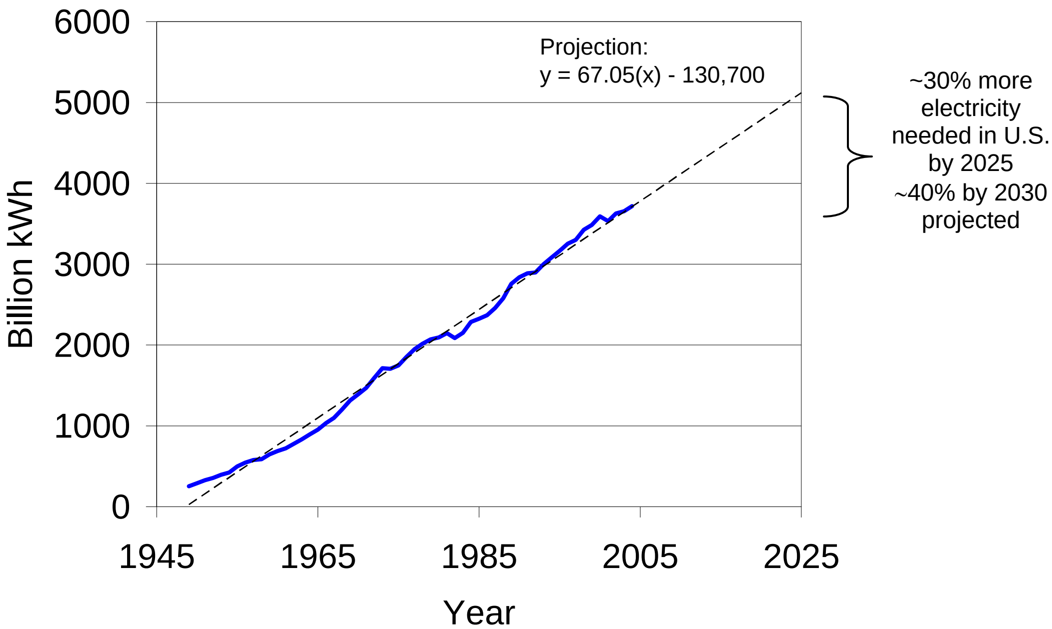


**Figure 6. Projected Growth in Electric Power Demand (EIA, 2006)**

The impact of new electric power generation on future water demands will depend on the number and type of power plants built, the rate at which existing plants are retired, the type of cooling installed, and the type of air emissions controls required. Alternative approaches to evaporative closed-loop cooling systems are being developed in an effort to significantly reduce future demand for cooling water, but many technical and economic issues have limited their introduction. Emerging alternatives include dry cooling, which currently has significant cost penalties and performance issues in hot, dry weather, and hybrid cooling, which mitigates the performance penalty of dry cooling, but is currently more expensive and more complex to operate. Wet surface air cooling to enhance use of impaired waters to reduce fresh water use and consumption is also being considered. Different electric power generation approaches require different amounts of water and have different operational issues and benefits. The major electric power generation approaches include thermoelectric plants (coal, natural gas, biomass, and nuclear), and renewable energy plants (hydropower, geothermal, wind, and solar). The water demands for coal, natural gas, biomass, and nuclear thermoelectric power plants vary and are illustrated in Table 1.

Hydroelectric power also uses water, but since the water remains in the river, U.S.Geological Survey does not include hydropower use in water withdrawal statistics. Hydroelectric power is an important, but drought-sensitive, component of U.S. electricity generation, supplying 5 to 10 percent of generated power from 1990 to 2003, but also stabilizing the electrical transmission grid by meeting peak loads, reserve requirements, and other ancillary electrical energy needs. Beyond conventional hydroelectric power, other renewable energy sources, including wind, solar, and geothermal energy systems, currently contribute a very small additional percentage of the nation's electricity generation. Solar photovoltaic, solar dish-engine, wind, and air-cooled geothermal hot water (binary) power systems offer a single significant advantage over other electricity generation technologies — they consume almost no water while producing electricity, as noted in Table 2.

**]Table 1. Water Use for Thermoelectric Power Generation**

| | | Water intensity (gal/MWh$_e$) | | | |
|---|---|---|---|---|---|
| **Plant-type** | **Cooling Process** | **Steam Condensing[a]** | | **Other Use[b]** | |
| | | **Withdrawal** | **Consumption** | **Withdrawal** | **Consumption** |
| Fossil / biomass-steam turbine | Open-loop | 20,000–50,000 | ~300 | ~30 | |
| | Closed-loop | 300–600 | 300–480 | | |
| | Dry | 0 | 0 | | |
| Nuclear steam turbine | Open-loop | 25,000–60,000 | ~400 | ~30 | |
| | Closed-loop | 500–1,100 | 400–720 | | |
| | Dry | 0 | 0 | | |
| Natural Gas Combined-Cycle | Open-loop | 7,500–20,000 | 100 | 7–10 | |
| | Closed-loop | ~230 | ~180 | | |
| | Dry | 0 | 0 | | |
| Integrated Gasification Combined-Cycle | Closed-loop | 200 | 170 | 150 | |
| | Dry cooling | 0 | 0 | 150 | |
| **Carbon sequestration for fossil energy generation** | | | | | |
| Fossil or biomass | All | ~20% increase in water withdrawal and consumption | | | |

[a] Values are included for a range of plant designs, cooling water temperatures, and locations
[b] Includes water for equipment washing, emission treatment, restrooms, and other water uses, but references did not always specify whether values are for withdrawal or consumption

Some renewable energy applications, such as some geothermal and concentrating solar systems that use evaporative cooling for steam condensing, do have high water consumption. Interestingly, solar, wind, and geothermal energy resources are most abundant in regions most strongly associated with increasing water demand or water scarcity, such as the intermountain West and Southwest and the Northern Plains. Non-hydroelectric renewable power systems have limitations that have limited their wider use in many cases. Although the costs of these technologies are declining, the electricity they generate remains more expensive than from conventional generating sources in many cases. While geothermal, solar thermal power with integrated storage, and biomass systems can provide dispatchable power, other renewable energy technologies, such as wind, solar photovoltaics, and kinetic hydropower (run-of-river, wave) currently produce electricity only when the resource is present. Connecting modest amounts of

**Table 2. Water Use for Renewable Electric Power Generation**

| **Generation Process** | **Cooling Process** | **Average Water Use Intensity (gal water/MWh$_e$)** | | |
|---|---|---|---|---|
| | | **Water Withdrawal** | **Cooling Water Consumption** | **Total Water Consumption** |
| Geothermal Steam | Closed-loop | 2000 | 1350 | 1400 |
| Concentrating Solar | Closed-loop | 750 | 740 | 750 |
| | Dry cooling | 10 | 0 | 10 |
| Solar Photovoltaic (PV) | N/A | ~1-2 | 0 | ~1-2 |
| Wind Turbines | N/A | ~1-2 | 0 | ~1-2 |

intermittent renewable sources to the grid has not been shown to undermine grid stability, but currently there are issues and concerns associated with potential large-scale deployment of renewable electric power generation on overall grid stability and energy reliability. In some cases, renewable sources, such as solar, may have the potential to improve grid operations by providing power when it is most needed, during the hottest part of the day. Also significant transmission improvements may be needed to fully realize the potential water savings of intermittent renewable energy resources.

## Water Use for Energy Extraction and Conventional Fuel Production

Coal and uranium mining uses water to cool or lubricate cutting and drilling equipment, for dust suppression, for fuel processing, and for re-vegetation when mining and extraction are complete. Depending on the source of the coal, 1 to 6 gallons of water are required per million British Thermal Units (MMBTU) of coal extracted, with total water use for coal mining in the U.S. estimated at 70–260 million gallons per day. For comparison purposes, 1-MMBTU is approximately the energy content of one hundred pounds of coal or eight gallons of gasoline.

Initial extraction of oil and gas requires minimal consumption of water, but, as oil wells age, enhanced oil recovery (EOR) techniques are used to extract additional oil. Many of these EOR techniques involve injection of water or steam into the well, with water consumption ranging from of 2 to 350 gallons of water per gallon of oil extracted. Much of these water needs are met by recycling produced water. In 1995, the American Petroleum Institute (API) estimated that oil and gas operations generated 18 billion barrels of produced water, compared to total petroleum production of 6.7 billion barrels of oil equivalent (BOE). Produced water varies in quality from fresh to hypersaline brine, with most as saline as sea water. API indicates that about 71 percent of produced water was recycled and used for EOR in 1995. Coal-bed natural gas (methane) extraction also yields produced water per well at rates varying from 7 barrels of water per barrel of oil equivalent (BOE) in the San Juan Basin to approximately 900 barrels per BOE in the Powder River Basin. Water production is high initially, but declines relatively rapidly over the life of the well.

Conventional petroleum refineries use water for processing and cooling. Currently about two gallons of water are used and one gallon consumed for each gallon of oil refined. Current U.S. oil refining is about 20.8 million barrels per day (approximately 880 million gallons per day). Natural gas processing and pipeline operations consume an additional 0.4 BGD. Therefore, over 1 BGD of fresh water is consumed for oil and gas refining. When added to the fresh water consumption for thermoelectric power generation, the energy sector currently accounts for about 25 percent of daily fresh water consumption in the U.S.

## Growth in Transportation Fuel Demands

In 2004, the U.S. consumed 20.8 million barrels of crude oil and refined products per day, approximately 58 percent of which were imported from other countries. About half of these imports came from non-OPEC nations, such as Canada and Mexico, while the other half came from OPEC nations, mainly Saudi Arabia, Venezuela, Nigeria, and Iraq. Crude oil is used to produce a wide array of petroleum products, including gasoline, diesel and jet fuels, heating oil, lubricants, asphalt, plastics, and many other petrochemicals. The transportation sector receives nearly all of its energy from petroleum products and accounts for two-thirds of U.S. petroleum use, mainly in the form of gasoline and diesel fuel. Current U.S. fuel use is 140 billion gallons of gasoline blends and over 60 billion gallons of distillate fuel per year. Based on EIA projections, imported oil and refined products could account for as much as 67 percent of total U.S. petroleum supplies by 2030 (EIA, 2006).

To reduce America's vulnerability to oil supply disruptions, and the associated economic concerns, President Bush recently introduced the Advanced Energy Initiative to help reduce U.S. dependence on foreign sources of oil. This new initiative includes support for increased domestic production of oil and gas and expanding refining capacity, accelerated deployment of hybrid and clean diesel vehicles, development of advanced battery and hydrogen fuel-cell technologies to reduce oil demands, and developing domestic renewable alternatives to gasoline and diesel fuels while fostering the commercialization of technologies to make lignocellulose-based ethanol competitive with corn-based ethanol. Part of this Initiative is to meet 30 percent of our current gasoline needs with domestically grown and refined biofuels by 2030. This will require production of about 60 billion gallons of ethanol per year by 2030, with over two-thirds needing to come from lignocellulosic-based feedstocks. Current U.S. biofuel production is dominated by ethanol from starch grains, primarily corn and sorghum. Grain-based ethanol production reached about 5 billion gallons per year in 2006, and is expected to reach between 6 and 7 billion gallons per year in 2007 (RFA, 2007). Other domestic fuel alternatives include biodiesel and other emerging forms of biofuel production, expansion of oil shale exploration and production; coal-to-liquid fuel production, and expansion of hydrogen production through steam reforming of natural gas or the use of renewable energy sources, such as concentrating solar and wind, for electrolysis of water, or implementation of a new generation of high temperature nuclear reactor to create both electric power and hydrogen.

Like the growth trends for domestic electric power generation capacity, the growth in the production and use of non-conventional fuels will tend to be regionally distributed near feedstock supplies, especially in the case of biofuel and oil shale production, and therefore regionally intensive in terms of water use and consumption. For example, the expanding cultivation and refining of energy crops such as corn, soybeans, sunflowers, poplars, and switchgrass is expected to occur predominately in areas of high rainfall, including the Midwest, Southeast, and temperate coastal areas, in order to reduce irrigation water demands and production costs for energy crops. Oil shale development is expected to occur primarily in the Rocky Mountain West - Wyoming, Colorado, and Utah - where oil shale reserves are most concentrated. As with new electric power production, the siting and development of these energy facilities will be guided by the availability of feedstock supplies, water resources, and transmission and transportation infrastructure factors. These factors must all be considered in assessing the regional intensity of the growth in developing reliable domestic transportation fuel alternatives.

The impact of alternative transportation fuel production and use on future water supplies will depend on the approaches taken, and the mix of fuels needed. Different alternative transportation fuel production and refining approaches require different amounts and qualities of water and have different operational issues and benefits. The available resources and associated water demands and water consumption for the different type of alternative fuels production and refining are discussed below.

## Water use for Non-Conventional Transportation Fuel Production

Non-conventional transportation fuels include renewable biofuels derived from biomass, non-renewable crude oils derived from oil shale and oil sand deposits, non-renewable synthetic liquid fuels derived from coal and natural gas, and hydrogen derived from fossil or biomass sources, or from the electrolysis of water using wind or nuclear power. Hydrogen is important as an essential reactant for the production and refining of other synthesized fuels. However, hydrogen for direct use as a transportation fuel has numerous technical, economic, and infrastructure barriers that push it relatively far into the future. Table 3 provides a summarized overview of the connection of water with the production of selected alternative transportation fuels. Estimated ranges of water use are given both in terms of the relative per-unit-energy content of the fuel, and in terms of the gallons of water consumed per gallon of liquid fuel produced. Coal, gas, and oil shale based alternatives are in the range of three to five times more water-intensive than conventional fuels. They are not yet being used for commercial transportation fuel production in the U.S. because of environmental and economic barriers, and are currently projected to lag well behind biofuels in production volume growth over the next several decades. Hydrogen production from natural gas reforming is very water intensive, while production from wind or nuclear power uses a factor of two less water. Water quantity and quality issues are tied to both the energy feedstock production and fuel processing for all of the alternative non-conventional fuels.

**Oil Shale.** The U.S. is estimated to have 500 billion to 1.1 trillion barrels of oil in the form of oil shale deposits, which is more than triple the proven oil resources of Saudi Arabia. Initial recovery work focused on mining and above-ground processing (retorting) that consumed 2–5 gallons of water per gallon of refinery-ready oil. Providing 25 percent of U.S. oil demand by this means would require 400–1000 million gallons of water per day. Because oil shale resources are predominantly located in areas where water availability is already constrained, oil shale development could have significant regional impacts. In addition, runoff could wash salt from shale residue into surface waters. More recently, an electrically driven underground oil shale retorting process is being prototyped, as shown in Figure 7, that does not directly use water and can potentially reduce overall water demand. However, generation of the required electricity would consume about one-third of the energy produced. If that energy were provided by evaporatively-cooled CCGTs, consumptive requirements would be about 250 million gallons of water per day. In either case, the energy consumed to produce fuel could increase U.S. emissions of carbon dioxide by up to 50 percent per unit energy. Further development and assessment is needed to validate both water quantity and quality impacts.

**Table 3. Non-Conventional transportation fuel connections to water**

| Fuel Type and Process | Relationship to Water Quantity | Relationship to Water Quality | Water Consumption: Water consumed per-unit-energy [ gal / MMBTU ] † | Water Consumption: Average gal water consumed per gal fuel |
|---|---|---|---|---|
| **Conventional Oil & Gas** | Water needed to extract and refine; Water produced from extraction | Produced water generated from extraction; Wastewater generated from processing; | | |
| - Oil Refining | | | 7 – 20 | ~ 1.5 |
| - NG extraction/Processing | | | 2 – 3 | ~ 1.5 |
| **Biofuels** | Water needed for growing feedstock and for fuel processing; | Wastewater generated from processing; Agricultural irrigation runoff and infiltration contaminated with fertilizer, herbicide, and pesticide compounds | | |
| - Grain Ethanol Processing | | | 12 - 160 | ~ 4 |
| - Corn Irrigation for EtOH | | | 2500 - 31600 | ~ 980* |
| - Biodiesel Processing | | | 4 – 5 | ~ 1 |
| - Soy Irrigation for Biodiesel | | | 13800 – 60000 | ~ 6500* |
| - Lignocellulosic Ethanol and other synthesized Biomass to Liquid (BTL) fuels | Water for processing; Energy crop impacts on hydrologic flows | Wastewater generated; Water quality benefits of perennial energy crops | 24 – 150 ‡§ (ethanol)<br>14 – 90 ‡§ (diesel) | ~ 2 - 6 ‡§<br>~ 2 - 6 ‡§ |
| **Oil Shale** | Water needed to Extract / Refine | Wastewater generated; In-situ impact uncertain; Surface leachate runoff | | |
| - In situ retort | | | 1 – 9 ‡ | ~ 2 ‡ |
| - Ex situ retort | | | 15 - 40 ‡ | ~ 3 ‡ |
| **Oil Sands** | Water needed to Extract / Refine | Wastewater generated; Leachate runoff | 20 - 50 | ~ 4 - 6 |
| **Synthetic Fuels** | Water needed for synthesis and/or steam reforming of natural gas (NG) | | | |
| - Coal to Liquid (CTL) | | Wastewater generated from coal mining and CTL processing | 35 - 70 | ~ 4.5- 9.0 |
| - Hydrogen RE Electrolysis | | | 20 – 24 ‡ | ~ 3 ‡ |
| - Hydrogen (NG Reforming) | | | 40 – 50 ‡ | ~ 7 ‡ |

† Ranges of water use per unit energy largely based on data taken from the Energy-Water Report to Congress (DOE, 2007)
* Conservative estimates of water use intensity for irrigated feedstock production based on per-acre crop water demand and fuel yield
‡ Estimates based on unvalidated projections for commercial processing; § Assuming rain-fed biomass feedstock production


(a) (b)

**Figure 7.** (a) Oil shale resources in Colorado, Utah, and Wyoming represent 1-2 trillion barrels of potentially recoverable crude oil (EIA, 2006); (b) Shell Oil Company's in-situ retort research and testing field site in Colorado (Shell, 2006)

**Synthesized fuels.** Liquid fuels based on the conversion of coal or natural gas, or hydrogen from methane, also require water, at up to triple the requirements for water consumption in petroleum refining. Reforming hydrogen from methane is quite water-intensive. Even production of hydrogen by electrolysis using a water-independent source of energy such as wind requires water as the feedstock. In summary, virtually every alternative will require as much water as refineries consume now, if not substantially more. To be able to increase domestic supplies of transportation fuels will require significant water resources using current approaches and options.

## Biomass and Biofuels Development Trends

In recent years biomass has overtaken hydropower as the largest domestic source of renewable energy. Biomass currently supplies over 3 percent of the nation's total energy consumption, and represents nearly half of all U.S. renewable energy use. Biomass-based energy feedstocks come primarily from agriculture (energy crops, residual crop stover/straw, manure) and from forestry (logging residues, forest management thinnings). Secondary sources are waste streams from the food and fiber industries, the wood products, pulp and paper industries, and municipal wastes (landfills, sewage treatment). Conversion processes can transform this biomass into useful products and services, as illustrated in Figure 8. A 2005 joint DOE-USDA study concluded that the U.S. could potentially produce over one billion dry tons of biomass each year, enough to generate more than 60-billion gallons of fuel ethanol and other biorefinery products that can displace petroleum-based products (ORNL, 2005). Figure 9 provides an illustration of the national distribution of projected biomass resources by county. This figure highlights agricutural crop residue, forest, and municipal resources, and points out the regional nature of the projected major biomass resource areas.

Liquid biofuels for transportation, primarily in the form of ethanol from starch and sugar crops and biodiesel from oil crops, are experiencing a major increase in interest nationally and globally. Government regulations, such the Clean Air Act Amendments of 1990, the Energy Policy Act of 1992, and the Energy Conservation Reauthorization Act of 1998, significantly increased the demand for ethanol during the 1990's.

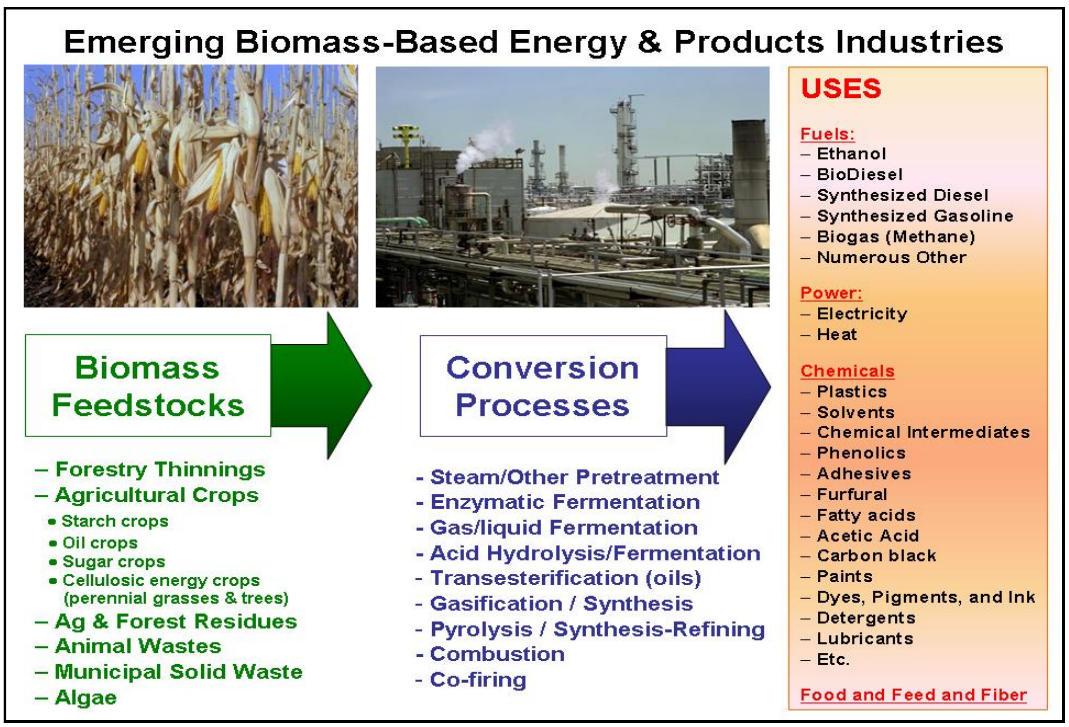


**Figure 8.** Emerging bio-industries will convert biomass to fuels, power, and products while displacing petroleum-based fuels and products. (adapted from Pacheco, Michael A., 2006).

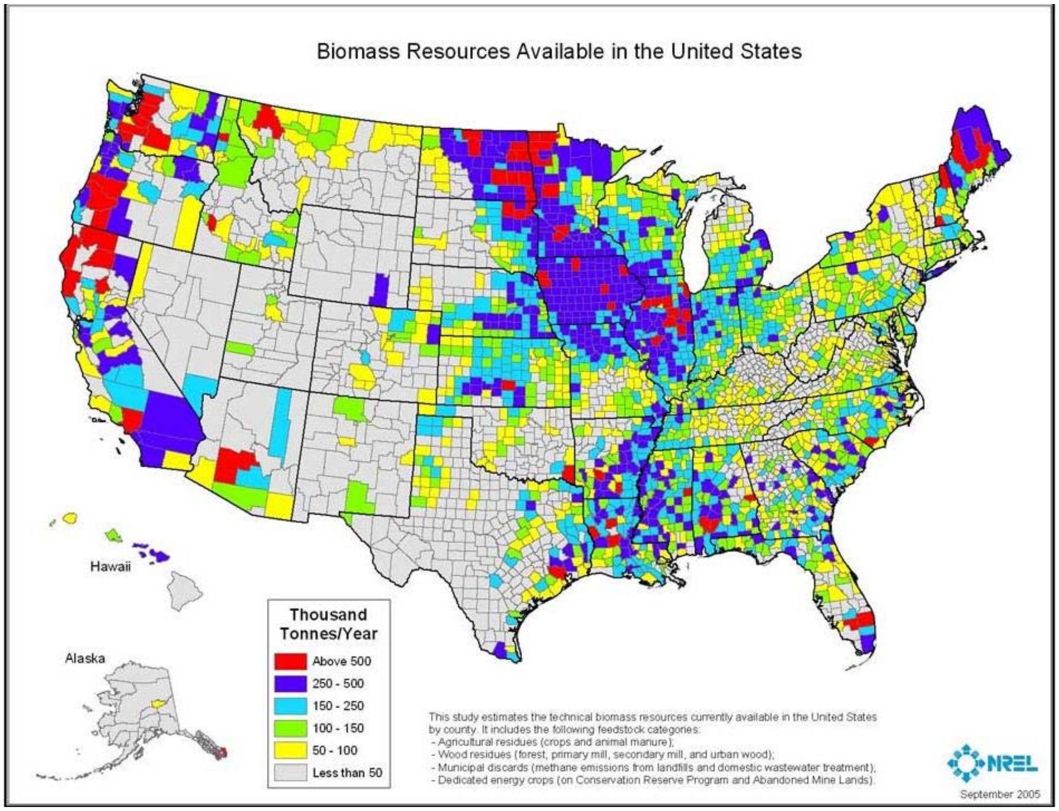


**Figure 9. Potential biomass resources available in the U.S. (NREL, 2005).**

In recent years, the phasing out of MTBE in favor of ethanol as an oxygen additive for gasoline, the Farm Security and Rural Investment Act of 2002, and the Energy Policy Act of 2005, along with higher prices for oil and concerns over the nation's heavy reliance on oil imports, have sharply expanded the production and use of ethanol. It took 20 years for the ethanol industry to reach 1.6 billion gallons of annual production in 2000, but it took only six more years for the industry to increase ethanol production to 5 billion gallons in 2006.

The Renewable Fuels Standard (RFS) established by the Energy Policy Act of 2005 mandates that at least 4 billion gallons of ethanol be used in motor fuels in 2006 and increase to 7.5 billion gallons by the year 2012. Beginning in 2013, and for every year thereafter, the use of a minimum of 250 million gallons of ethanol derived from lignocellulosic biomass is also called for. This provides additional incentive for development of the "next generation" of processes and technologies to convert lignocellulosic biomass to ethanol and other biofuels. Growth in ethanol production capacity is well ahead of the RFS schedule as noted in Figure 10.

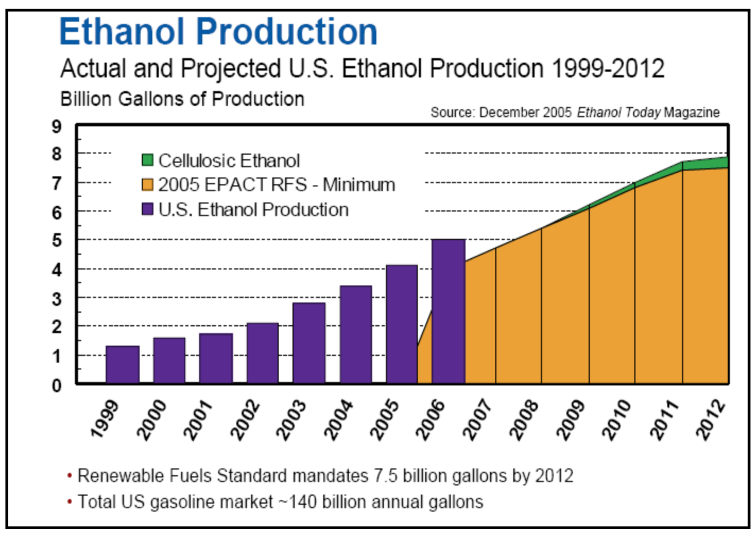


**Figure 10. U.S. Ethanol Production to 2012**

Domestic biodiesel production lags behind ethanol, but is also experiencing rapid growth. Production reached 75 million gal/yr in 2005, a three-fold increase over 2004 levels, and tripled again to about 225-million gallons in 2006 (BBI, 2007). Biofuel production based on commodity crops like corn, cane, soy, and others will likely increase significantly over current levels, but will be limited by other competing non-energy markets for these crops. Depending on market conditions and production incentives, ethanol from corn and other starch grains is expected to be limited to the 10-20 billion gal/yr range, which would account for less than 10 percent of the nation's current transportation fuel needs. Oil crops and other conventional bio-oil feedstock supplies for biodiesel are expected to have similar limits.

## Water Use for Biofuel Production.

Growth of grain-based ethanol and oil-crop-based biodiesel production in the U.S. today is reliant on a combination of irrigated and rain-fed crop acreage. This is expected to continue as long as energy market conditions and policies are favorable, or until competing market demands or other corrective forces curtail further expansion of commodity crop use for biofuel. The U.S. could soon be reaching this point with corn-based ethanol. The increased demand for corn for ethanol production has caused a nearly 70 percent increase in corn prices in the past six months, which is sooner than many agricultural economists had expected. The jump in corn prices is already affecting the cost of food and other corn-based products. According to USDA, 18 to 20 percent of the country's total corn crop will be used for ethanol production this year, and by next year will jump to 25 percent. The successful development of technologies to cost-effectively convert lignocellulosic biomass to biofuels will be key to the decoupling of commodity crop food/feed markets from fuel markets. As processes to convert lignocellulosic feedstocks like crop residues and rain-fed energy crops into ethanol become commercially viable, or as other competing biofuels emerge that are more compatible than ethanol with the nation's transportation infrastructure in the future, the incentives to increase the use of commodity crops like corn will change.

Table 4 provides an overview of the current water use and water consumption associated with biofuels processing and feedstock development. For example, a 100-million gal/yr conventional dry-mill ethanol plant typically uses 300 to 600 million gallons of water per year, with average water consumption currently about 4 gallons of water consumed per gallon of ethanol produced. Wet-mill processing uses somewhat more water per gallon of ethanol produced. Lignocellulosic ethanol production processes are still being developed and water use and consumption for commercial operations has not been established. Target projections are for commercialized enzymatic biochemical ethanol production to use on the order of 6 gallons of water per gallon of ethanol produced. The current state of the art with corn stover falls within in the range of 10 - 11 gallons of water per gallon of ethanol. Current projections are that thermochemical approaches using water based cooling systems will require twice as much water, with the 2012 water-use target with wood feedstock to be about 12 gallons per gallon of ethanol. However, the National Renewable Energy Laboratory (NREL) is nearing completion of a new baseline thermochemical system design using air cooling that reportedly could potentially reduce water use to about 3 gallons per gallon of biofuel produced (Aden, Andy, 2006).

Among the issues with the future expansion of biofuel production will be to assure that the availability, use, and sustainability of water and land resources is appropriately managed to avoid adverse impacts while not putting undue constraints on the transition toward more biomass-based energy and products industries, as illustrated in Figure 8. The application of irrigation to increase biomass feedstock yields and better insure the reliability of supplies in specific regions would be the largest single source of additional water demand to meet expanded biofuel production needs in the future. Use of irrigation can effectively result in thousands of gallons of water consumed per gallon of biofuel produced from the harvested biomass. This is less of an issue in using agricultural crop and animal wastes, and in moving toward the future use of largely rain-fed lignocellulosic energy crops. Perennial energy crops can bring benefits for improving soil and water quality (Tolbert, V.R., et.al., 1995 & 2000). Even so, the wide-scale planting of perennial energy crops can alter hydrologic flows due to their deep, extensive root systems and dense canopies. Depending on local hydrologic conditions, this can potentially contribute to local water deficit impacts during dryer periods (Stephens, William, et.al., 2001). The relative water use

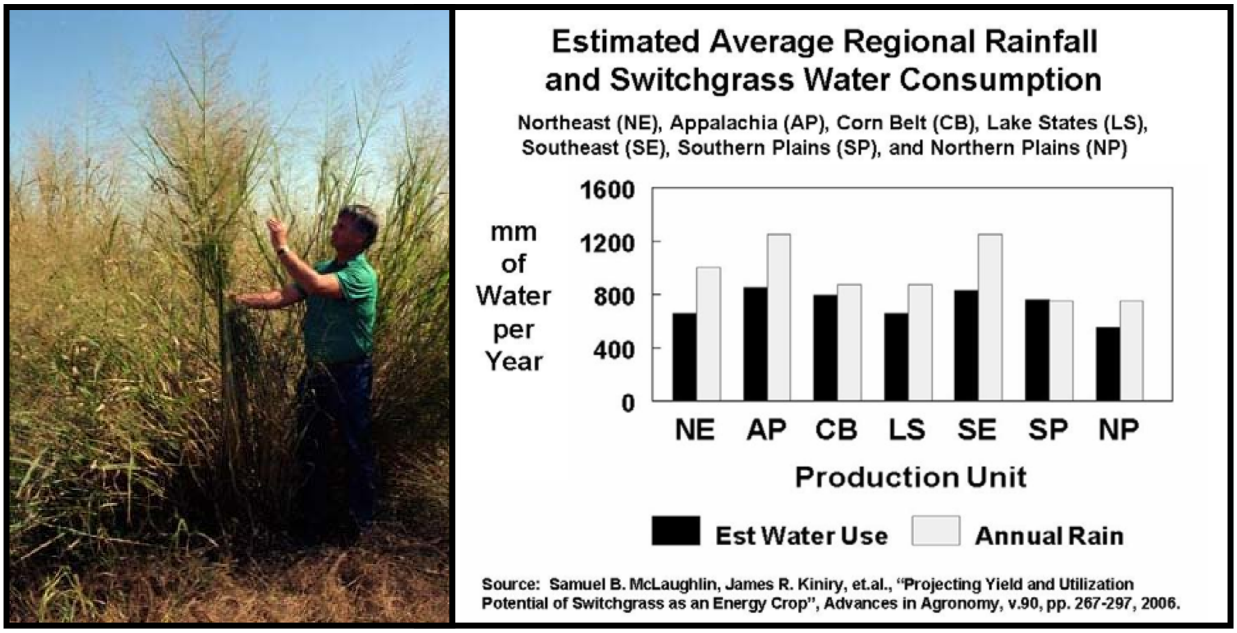


**Figure 11.** Comparison of estimated annual rainfall and switchgrass water use for seven proposed biomass production regions (McLaughlin, et.al., 2006).

**Table 4. Biofuel Water Use Intensity for Selected Feedstocks and Processes**

| Fuel Type and Conversion Process | Biomass Feedstock | Processing Water Use Intensity (gal $H_2O$/gal fuel) | | Feedstock Water Use Intensity | | |
|---|---|---|---|---|---|---|
| | | Process Water Use | Process Water Consumption | Feedstock Water Demand Ac-ft / Acre | Biofuel Yield gal fuel / Acre | Feedstock Water Consumption[d] gal $H_2O$/gal fuel |
| Ethanol, Starch or sugar-based Wet mill or Dry mill | Corn | ~ 2 - 6 | ~ 4 | ~ 1.2 | 400 | 980 |
| | Sorghum | | | ~ 1.0 | 170 | 1900 |
| | Sugar Cane | | | ~ 2.0 | 560 | 1160 |
| | Sugar Beets | | | ~ 2.3 | 550 | 1360 |
| Ethanol, Cellulose-based[a] Biochem or Thermochem | Switchgrass | ~ 3 – 12 [e] estimate | ~ 2 - 6 [e] estimate | ~ 2.3 | 500 - 800 (700 estimated)[b] | Rain-fed |
| | Woody biomass | | | ~ 2.5 | 500 – 800 | Rain-fed |
| Biodiesel from Oil Extraction and Trans-Esterification | Soybeans | ~ 0.3 - 3 | ~ 1 | ~ 0.8 | 40 | 6500 |
| | Sunflower | | | ~ 1.5 | 80 | 6100 |
| | Oil Palm | | | ≥ 2.5 | 510 | Rain-fed |
| | Algae | ~ 0.3 - 3 | ~ 1 | Not determined [f] | 3,000 - 15,000 [c] (5000 estimated) | Not determined [f] |

[a] Cellulose-based ethanol yields of 100 gal/dry ton based on laboratory data, processes are still experimental
[b] Switchgrass yields have exceeded 10 dry tons/acre experimentally, but more routinely range from 3 to 7 dry tons/acre
[c] Algal-based biodiesel production estimates based on laboratory and small scale test data; viable high-yield scale-up still uncertain
[d] Water consumption with irrigated feedstock production at per-acre water demand and per-acre biofuel yield levels shown
[e] Estimates based on unvalidated projections for commercial processing; [f] Non-fresh water used; losses mainly from evaporation

efficiency of biomass production with herbaceous and woody perennial energy crops is higher than for many other agricultural commodity crops, but the absolute water consumption is also relatively high, as shown in Figure 11 for switchgrass.

The major expansion of biofuels production and the broader transition to more biomass-based energy and products industries will require the establishment of high-volume, reliable, and cost-effective biomass production and supply. Among the challenges is to assure that the availability and sustainability of water resources will not be a constraint, and that potential adverse impacts, which will tend to be at the local and regional watershed level, can be identified and avoided through appropriate planning, management, and development of best operational and management practices. Key elements of this will be better understanding and characterization of the issues and tradeoffs associated with land use changes, increased use of irrigation for biomass energy crops, and the issues, risks, tradeoffs, and approaches to mitigate possible hydrologic flow impacts that could result from massive national expansion of perennial energy crop production. The exploration of alternative biomass feedstocks like oil-producing microalgae (NREL, 1998; Benemann, John, 2003) could also offer the potential for high biofuel productivity using non-conventional waters (e.g., brackish ground water, wastewater, produced water from energy mineral extraction) and land that need not be suitable for agriculture. Table 4 notes that the productivity of algae with high oil content for biofuel feedstock could potentially be an order of magnitude, or more, higher than for oil palm, which is currently the world's most productive oil crop. However, algal-based biofuel production is not yet commercially viable and is expected to require further time and significant R&D investments in biology, systems technology, and processes to increase performance and reduce costs.

In summary, virtually every alternative transportation fuel being considered will require more water than current petroleum refining. A major national scale-up of production capacity and use of nonconventional alternative transportation fuels to meet future domestic fuel demands could significantly increase water demands and impacts. Total water consumption for both conventional and alternative transportation fuels processing could increase by 3-4 BGD by 2030 depending on what combination of technologies are used and the expected fuel mix. By 2040 if nuclear hydrogen were to be implemented, water consumption could see an additional increase of 2-3 BGD. Potential water demands for even modest irrigation applications for biofuel feedstocks could require an additional 3-6 BGD of fresh water by 2030 depending on feedstock development approaches and irrigation needs to enhance and ensure production yields and reliability. Therefore, the range of water consumption that currently could be expected for future transportation fuels water consumption could range from 6-12 BGD by 2030.

## Addressing Future U.S. Water Needs

The U.S. energy infrastructure depends heavily on the availability of water, and there is cause for concern about the availability of that water as we look toward future demands on limited water resources. In some regions, power plants have had to limit generation because of insufficient water supplies, and citizens and public officials concerned about the availability of water have opposed new power generation and fuel processing facilities. Most state water managers expect shortages of water over the next decade (GAO, 2003), and water supply issues are already affecting existing and proposed power plants and nonconventional fuel production in various locations around the country.

**Enhancing Water Supplies.** Supplying the nation's freshwater needs requires energy, and enhancing those supplies will likely require more energy. Nationwide, about 3 percent of U.S. power generation is currently used for water supply and treatment, which is comparable to several other industrial sectors. Electricity represents 75 percent of the cost of municipal water processing and distribution. In California, where water is conveyed long distances by the State Water Project, 5 percent of state electricity consumption is for water supply and treatment. Overall, water supply and treatment (including waste water collection, treatment, and discharge) in California require from 620 kWh/acre-foot to 7,700 kWh/acre-foot. In locations dependent on groundwater, the energy required to supply water (excluding treatment) increases as water levels decline, from about 540 kWh per acre-foot at 120 ft to 2000 kWh per acre-foot at 400 ft (NRDC, 2004).

On a per capita basis, average use of electricity for non-agricultural water supply and treatment by region is similar across the country, but there are significant differences in use of energy to supply water for irrigation. Projections for 2050 show that energy requirements for water treatment and supply will grow with population (per capita energy requirements largely unchanged), except in the industrial and agricultural sectors. Energy use for water supply and treatment in the industrial and agricultural sectors is expected to triple, with strong per capita growth in the industrial sector in the East North Central region and in the agricultural sectors in the South Central, West North Central, and West South Central regions.

Substitution of impaired water, such as brackish groundwater, seawater, produced water, and wastewater can augment freshwater supplies where water users can accept either lower quality (e.g. irrigation and some industrial uses) or can afford the cost and energy to treat water. Saline groundwater underlies much of the country, and saline groundwater and seawater may be converted to potable water by using desalination. Desalination requires more energy than typical public water supplies. Energy requirements for desalination are similar to those for pumping water long distances via projects such as the California State Water Project.

**Coordinated Energy and Water Conservation.** Water and energy conservation measures represent an opportunity to stretch both resources. Reducing water consumption can save energy for water supply and treatment as well as for heating water, and thus reduce the requirements for water for the energy sector. Power companies often have the authority to invest in programs that save energy, but as noted by the California Energy Commission, utilities may not have the authority to invest in customer programs that lead to energy savings by reducing water consumption (CEC, 2005).

**Synergistic Energy and Water Production.** Throughout the energy sector, there are opportunities to co-produce energy and water. Locating power plants adjacent to water treatment facilities or more brackish or produced water resources could at least partially displace freshwater needs. In addition, waste heat from power plants can be used in some desalination cycles, and biogas from wastewater treatment plants can be used to generate power. Within the energy sector, the need to provide heat for re-gasification of liquefied natural gas fits well with the need to provide cooling for power plants.

Analysis of trends of increasing water demand for energy reveal several interesting issues:

- Current directions in energy development and energy production could significantly increase water consumption through 2035, making energy the sector with the largest non-agricultural water consumption,
- Additions of fresh water resources are somewhat limited and water reclamation and water reuse could become the major new source of future water supplies,
- If the growth in water reclamation continues, overall national water availability could be sufficient to support water demand growth, though regional shortages are likely to occur, especially through 2015,
- Energy sector processes for cooling, scrubbing, refining, etc. will need to become compatible and cost-effective for use with reclaimed or nontraditional waters,
- Through 2015, water supplies development will be under significant pressure to keep pace to meet emerging water demands,
- The siting priorities of energy facilities may change to use large reclaimed water sources in urban areas, and
- Energy planning will become increasingly dependent on interactions regional water, waste water, and agricultural water managers and planners because regional energy and water concerns may become common.

While these are major national trends, the large growth in certain regions of the country of electric power demand and alternative transportation fuel feedstock and refining demands suggests that water availability regionally or locally may not be able to support the high growth rate in energy development expected without significant improvements in both energy and fresh water use efficiency.

## Energy-Water Roadmap Process

Congress requested that the DOE prepare a National Energy-Water Roadmap in the Energy Policy Act of 2005. The Roadmap was to assess the effectiveness of existing programs within the DOE and other Federal agencies in addressing energy and water related issues and assist the DOE in defining the direction of research, development, demonstration, and commercialization efforts to reduce water demands in energy development. Sandia National Laboratories was selected to coordinate the Energy-Water Roadmap activities, assisted by the Electric Power Research Institute (EPRI), the other DOE national laboratories[†], and the Utton Center, a water law center at the University of New Mexico. An Executive Committee of national water and energy experts representing federal agencies and water and energy associations from around the country was also established to help oversee all Roadmap efforts and processes.

The Energy-Water Roadmap process was designed to assess and integrate regional issues and concerns into a nationally coordinated but regionally focused energy-water science and technology research and development program. The Energy-Water Roadmap was a needs-driven process and included three major elements:

- Identification and evaluation of regional and national energy-water issues and needs through three regional needs workshops,
- Identification and evaluation of the Gaps between current programs and initiatives and future needs, and
- Identification of science and technology options to address current and emerging issues and trends and support future energy-water research strategies and priorities.

The needs assessment workshops were designed to ensure that current and emerging needs and issues and research directions were user driven. The needs assessment workshops were held on November 14-16, 2005, in Kansas City, MO, on December 13-14, 2005, in Baltimore, MD, and on January 11-12, 2006, in Salt Lake City, UT. Seven categories of user/stakeholder participants were identified for invitation to the workshops including: Energy/Power/Utilities (energy mineral extraction, fossil & bio-fuels production, electric power generation); Water Utilities/Water Managers/Water Agencies Planners, Environmental and Ecological groups, Regulatory/Policy developers and agencies, Economics & Economic Development agencies and groups, other large water use sectors (agriculture, irrigation districts, mining, industrial/domestic), and special Interests such as Tribal and State Government associations. Overall, about 350 individuals participated in the regional workshops. Input was obtained from participants from over forty states. Based on these results, we were able to develop a synopsis of the national and regional level needs and issues.

Based on the regional needs workshops, a Gaps Analysis Workshop was held in Albuquerque in March 2006 and included a broad mix of technical experts and researchers to assess the major gaps between existing programs and the emerging issues and needs. Based on the Gaps Analysis results, a Technology Innovations Workshop was held in San Diego on May 2006 to suggest research directions and priorities necessary to meet the needs and gaps identified in the previous workshops.

## Summary of National Energy-Water Needs and Suggested Research Directions

The Western, Central, and Eastern Regional Energy-Water Needs Workshops possessed a variety of similarities, yet each displayed unique attributes. Eastern region participants generally had a more difficult time 'seeing' the interactions between energy and water than their Western and Central

[†] Participating DOE laboratories were Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Idaho National Engineering Laboratory (INEL), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), National Energy Technology Laboratory (NETL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Savanna River National Laboratory (SRNL).

counterparts, and generally did not seem to view water availability for energy production as a significant long-term problem—this may be a result of 'Eastern' water law and the relatively high precipitation rates in the region (and thus a perception that water is not now a problem).

The Central Region provided an interesting comparative look at the issues and concerns that arise when 'Western' and 'Eastern' water law collide in a region characterized by increasing water demand and energy production. The region's states display radically different approaches and levels of intensity for measuring, monitoring, and managing their water resources; this is caused by legal structures, perceptions of scarcity, and budget limitations. Participants at the Western Region meeting, not surprisingly, were heavily engaged. It is this region that faces the greatest water-energy challenges due to high population growth and scarce water resources. Several common problem areas were identified in all three workshops that drove suggestions for major research and development needs. These include:

<u>Improved Energy and Water Resources Planning and Management</u>

- The **lack of long-term or integrated resource planning** that effectively addresses energy-water interactions at a state, watershed, or regional level. Models and decision support tools to improve energy water planning were identified as major research needs.
- The **lack of consistent and detailed data and the lack of models** that can be used to address current and emerging problems at the energy-water nexus. Development of better sensors and better ways to collect water data and manage the collected data were identified as major research needs.
- Participants noted a **lack of fundamental understanding of the nation's surface and groundwater resources**, including location, quantity, quality, interactions between surface and groundwater, sustainable yield, and even the current volumes extracted or returned. Improved monitoring techniques, data management, and data display were identified as major research needs.
- Western region participants were more **interested in climate change and its impacts on water supplies and energy production** than other groups. Research and development of validated regional climate variation models were identified as major priorities.
- Eastern region participants were **particularly concerned about the decay of water treatment and delivery infrastructures**, noting significant energy consumption and water loss from leakage. Research on ways to address infrastructure decay and degradation were identified as major needs.
- Central and Western region participants noted **significant transmission and distribution problems and constraints**, with a lack of carrying capacity for electricity and natural gas noted. They also commented on the difficulties presented by large-scale integration of renewable energy technologies into the grid. Research on infrastructure improvements to reduce water use for energy production and generation were identified as having a major impact on future water efficiency in energy and electricity production.

<u>Improved use of Non-traditional Water for Energy Production</u>

- Participants in all regions **expressed concern over (and see opportunities in) the volumes of produced waters** discharged from oil, coal bed methane, and mining activities. Technology research and development to treat and utilize these waters in an energy efficient manner to supplement water supplies were identified as major research needs.
- The **utilization of brackish groundwater and waste water in energy production and generation** were identified as a mechanism to reduce fresh water use. Research to develop or improve materials and processes compatible with the use of non-fresh water and assess health impacts to workers and the public from these uses are major needs.

Improved Energy and Water Conservation and Improved Water Use Efficiency in Energy Production

- Participants noted that the **water intensity of conventional electricity generating technologies is a problem**, they cite the **lack of water-intensity considerations in current energy RD&D programs** as an indication of the division between energy and water communities, and **note the insufficient resources devoted to developing less-water intensive alternative electricity generation technologies** (solar, wind, etc.) Better science on dry or hybrid cooling issues and technologies as well as infrastructure improvements to improve the use of less water intensive technologies were seen as necessary. Hydropower research and compatibility with river ecology and overall management was an important research direction suggested.
- The **cost and value of water was also a topic of significant interest and concern** in all regions—participants noted that at present, end-users do not pay the true cost of the water they consume; that water has historically been (and continues to be) undervalued in the United States; and that the legal and regulatory frameworks that bound water make it highly problematic to address this problem. Regulatory and policy studies were identified as needed to help address these issues.
- **Conservation programs were a significant focus at the Western region meeting**; they noted needs for both increased energy conservation programs and the development of national-scale water conservation efforts and programs. Approaches and incentives to encourage conservation were seen as providing major improvements in energy and water efficiency.
- **Co-location of energy and water facilities** was identified as a way to improve energy and water use efficiency and resource conservation in all regions.
- The **potentially massive water demand posed by biofuels production** is a significant concern for those in the Central and Western regions. New directions in national biofuels supply and demand suggest that new research into techniques that reduce fresh water consumption are needed.

## Conclusions

Trends in energy use, water availability, and water demand suggest that the U.S. is at a critical crossroads in the development, utilization, and management of the critical resources of water and energy. Increasing population will increase demand for water for direct use, as well as water for energy and agriculture. Withdrawals for domestic water supply are growing at about the same rate as the population. If new power plants continue to be built with evaporative cooling, consumption of water for electrical energy production could more than double by 2030, and consumption by the electric sector alone could equal 1995’s domestic water consumption by the entire country. Consumption of water for extraction and production of transportation fuels from domestic sources also could grow substantially. Meanwhile, climate concerns and declines in groundwater levels suggest that less freshwater, not more, may be available in the future. A more proactive approach to energy and water development and management should be considered. Although new technologies can reduce water use, these technologies cost more and will not be deployed overnight. Given the above constraints, it may not be possible in many areas of the country to meet the country’s growing energy and water needs by following the current U.S. path of largely managing water and energy separately while making small improvements in freshwater supply and small changes in energy and water-use efficiency.

Additional information regarding the Energy-Water Roadmap process, including results of the Needs Workshops, Gaps Workshop, and the Technology Innovation Workshop can be found at www.sandia.gov/energy-water.

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