The Thesis Committee for Kelly Marie Twomey
Certifies that this is the approved version of the following thesis:

The Energy-Water Nexus;
An Examination of the Water Quality Impacts of Biofuels

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Michael E. Webber

____
Desmond F. Lawler

The Energy-Water Nexus;
An Examination of the Water Quality Impacts of Biofuels

by

Kelly Marie Twomey, B.S.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2010

Dedication

I dedicate this thesis to my mother, Mary Twomey, and father, Matthew Twomey, without whose love and support I would not have had the opportunity to reach this achievement.

Acknowledgements

I would like to thank my adviser, Dr. Michael Webber, for his guidance and support through all of my research endeavors thus far. His enthusiasm and expertise regarding issues at the intersection of engineering and policy have served as important sources of inspiration to me during my graduate studies.

I would also like to express my gratitude for the guidance that Ashlynn Stillwell offered to the development of this work. In addition to coauthoring several bodies of work that contributed to this thesis, her mentorship over the past two years has been integral to my foundation of knowledge regarding the energy-water nexus. Likewise, I thank Dr. Carey King who also served as a mentor and a coauthor on several other collaborative reports.

I also thank Dr. Desmond Lawler who generously offered his expertise and insight during the development of this work as a member of my supervising committee.

I must also acknowledge the National Science Foundation whose generous funding through its Graduate Fellows Program has made my research at the University of Texas at Austin possible.

Lastly, I would like to express gratitude for my family and friends for their love and support.

Abstract

The Energy-Water Nexus; An Examination of the Water Quality Impacts of Biofuels

Kelly Marie Twomey, M.S.E.

The University of Texas at Austin, 2010

Supervisor: Michael E. Webber

Water and energy share an important relationship since it takes water to produce energy, and likewise, energy to pump, treat, and distribute water. This thesis explores the energy-water nexus in regards to electricity and transportation fuel production, as well as water treatment. It investigates how the Energy Independence and Security Act of 2007 might affect this interrelationship in the future since increases in corn cultivation for biofuels production are likely to lead to higher nitrate (NO_3-N) concentrations in US water reservoirs, which could trigger the requirement for additional energy consumption for drinking water treatment.

The analysis indicates that advanced drinking water treatment might require an additional 2360 million kWh annually to treat drinking water currently exceeding the Environmental Protection Agency's maximum contaminant level (MCL) limit of 10 mg L^{-1} NO_3-N. This is a 2100% increase in energy consumption for advanced water

treatment to meet this MCL in comparison with surface water treatment alone. Although results indicate that most large surface and groundwater drinking water resources are not likely to exceed safe drinking water standards due to the expansion of corn-starch based ethanol production, smaller water reservoirs in agricultural regions are susceptible to NO_3-N contamination in the future. Consequently, these sources might require energy-intensive drinking water treatment to reduce nitrate levels below 10 mg L^{-1} NO_3-N.

Based on these results, I conclude that projected increases in nitrate contamination in water may impact the energy consumed in the water treatment sector, because of the convergence of several related trends: (1) increasing cornstarch-based ethanol production, (2) increasing nutrient loading in surface water and groundwater resources as a consequence of increased corn-based ethanol production, (3) additional drinking water sources that exceed the MCL for nitrate, and (4) potentially more stringent drinking water standards for nitrate.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AEO – Annual Energy Outlook

CRP – Conservation Reserve Program

CSP – Concentrating Solar Power

CWA – Clean Water Act

DDG – Dried Distiller's Grain

DIN – Dissolved Inorganic Nitrogen

DOE – Department of Energy

E10 – 10% ethanol and 90% gasoline

E85 – 85% ethanol and 15% gasoline

EIA – Energy Information Administration

EISA 2007 – Energy Independence and Security Act 2007

EMM – Electricity Market Module

EPA – Environmental Protection Agency

EPACT 2005 – Energy Policy Act of 2005

EPRI – Electric Power Research Intuition

FWPCA – Federal Water Pollution Control Act

GAO – Government Accountability Office

GHAP – Gulf Hypoxia Action Plan

GHG – Greenhouse Gas

HR.2454 – American Clean Energy and Security Act of 2009

HR.3598 – Energy and Water Research Integration Act

LDV – Light-Duty Vehicle

MARB – Mississippi-Atchafalaya River Basin

MCL – Maximum Contaminant Level

MCGL – Maximum Contaminant Level Goal

N – Nitrogen

NERC – North American Electric Reliability Corporation

NETL – National Energy Technology Laboratory

NGCC – Natural-gas Combined Cycle

NO_3-N – nitrate-nitrogen

NRC – Nuclear Regulatory Commission

NREL – National Renewable Energy Laboratory

P – Phosphorus

POTW – Publicly Owned Treatment Works

PV – Photovoltaic

R&D – Research and Development

RES – Renewable Electricity Standard

RFS – Renewable Fuel Standard

RFS 2 – Renewable Fuel Standard (Updated 12/2009)

S.1462 – American Clean Energy Leadership Act

S.531 – Energy and Water Integration Act of 2009

SDWA – Safe Drinking Water Act

UN – United Nations

US – United States

USCB – United States Census Bureau

USGS – United States Geological Survey

Chapter 1: Introduction

1.1 The energy-water nexus

Energy and water are both vital to the US economy and quality of life. Together they enable such things as an ample food supply, electricity production, and safe drinking water. Insufficient access to energy and water has already placed strain on many societies abroad as well as within the US. In the future, these strains are expected to intensify because of factors such as population and economic growth, climate change, and changing policy environments.

Despite the looming challenges that face each resource, an opportunity exists to approach both challenges together, since these resources share an important interdependency referred to as the energy-water nexus. This relationship is characterized by the fact that it takes water to produce energy and energy to pump, treat and distribute water. Consequently, a constraint in one resource imposes a constraint on the other, but at the same time, savings in one resource also creates a savings in the other. Thus, as we move forward through the 21st century, the ways by which we moderate the intricate relationship between energy and freshwater resources will affect our continued security, and economic and environmental health.

Recent action in the US Congress indicates that policymakers are beginning to recognize the importance of energy-water nexus issues. HR.3598, The Energy and Water Research Integration Act, was passed in the House of Representatives in December 2009.[1] The Senate version of the act (S.531) was introduced in March 2009 through the Energy Natural Resources Committee[2] and has been incorporated into S. 1462, the American Clean Energy Leadership Act of 2009.[3] Three Government Accountability

Office (GAO) reports were also released in 2009 regarding energy-water nexus issues, affirming Congress' increasing attention to the subject.

Although these Congressional measures mark progress toward more holistic energy and water policy, the effects of other legislative actions regarding future energy production are unclear. The American Clean Energy and Security Act of 2009 (HR.2454) proposed a nationwide Renewable Electricity Standard (RES), and the Energy Independence and Security Act (EISA) of 2007 instituted a Renewable Fuel Standard (RFS), which may markedly change electricity generation and fuel production in the US. While some renewable technologies are more water-efficient than conventional energy sources (e.g., wind and solar photovoltaic electricity; biofuels derived from non-irrigated feedstocks), others are more water-intensive than the baseline (e.g., solar thermal with water cooling and enhanced geothermal; biofuels from irrigated crops). Additionally, renewable sources derived from agricultural feedstocks grown with heavy chemical inputs, such as fertilizers, pesticides, and herbicides, often have negative water quality effects that can be difficult to reverse without using energy-intensive treatment methods. The RES and RFS mandated by these bills are discussed more in the body of this work.

Three major interdependencies form the energy-water nexus (Figure 1). The first is the electricity-water nexus, which describes the water that is used for electricity production. Second is the transportation fuel-water nexus, which describes the role of water in producing fuel for our transportation fleet. And third is the energy for water treatment nexus that describes the energy that is used to pump, sanitize, distribute, and prepare water for end-use. Analyzing the sustainability of each of these subdivisions requires consideration of the *quantities* of water and energy that are used throughout associated processes, as well as the water *quality* impacts that energy production and water treatment have on surrounding freshwater and saline resources. Chapters 2, 3, and 4 explore each of these energy-water nexus topics as they exist today, identify the implications that growing resource demands and shifting policy environments might have, and present the challenges that they will likely present in the future. Water quantity and water quality impacts are both considered in each chapter.

A background on the water use implications of power generation in the US is summarized in Chapter 2. The water use of thermoelectric and non-thermoelectric generators is detailed in terms of water withdrawals and consumption by different technologies. Next, a snapshot of the current electricity-water nexus is provided, illustrating how water constraints are already affecting electricity reliability in the US, and why these strains will likely be intensified in the future. Trends indicate that these strains will likely be exacerbated in the future by population and economic growth, climate change, and competition with other sectors, although looming policy shifts and the unclear role of renewable energy deployment make it difficult to project the water-intensity of the future electricity generation mix itself. Potential means of placating the electricity-water nexus in the future by utilizing water-efficient cooling technologies and alternative water sources are also explored throughout this chapter.

The transportation fuel-water nexus is discussed in Chapter 3. This chapter focuses primarily on how the increasing role of biofuels in our transportation fleet might significantly affect both water withdrawals/consumption and water quality in the future. Biofuels derived from agricultural feedstocks tend to consume large amounts of water during cultivation, especially if feedstocks are irrigated. Furthermore, growing feedstocks can have water quality consequences when chemicals used for crop production (e.g., fertilizers, pesticides, and herbicides) percolate into adjacent surface water or groundwater reservoirs. Analyses published in the literature concerning the water quality effects of the projected expansion of ethanol are summarized. These projections are used as reference points in the analysis completed in Chapter 5.

The energy implications of treating, pumping, and distributing water and wastewater to meet drinking water standards are the focus of Chapter 4. The energy consumption of the water treatment sector is highly dependent on (1) the volume of water to be treated, (2) the quality of the source water, and (3) the intended end-water quality. Thus, the water quantity and water quality consequences of electricity and transportation fuel production discussed in Chapters 2 and 3 have important implications in these energy requirements.

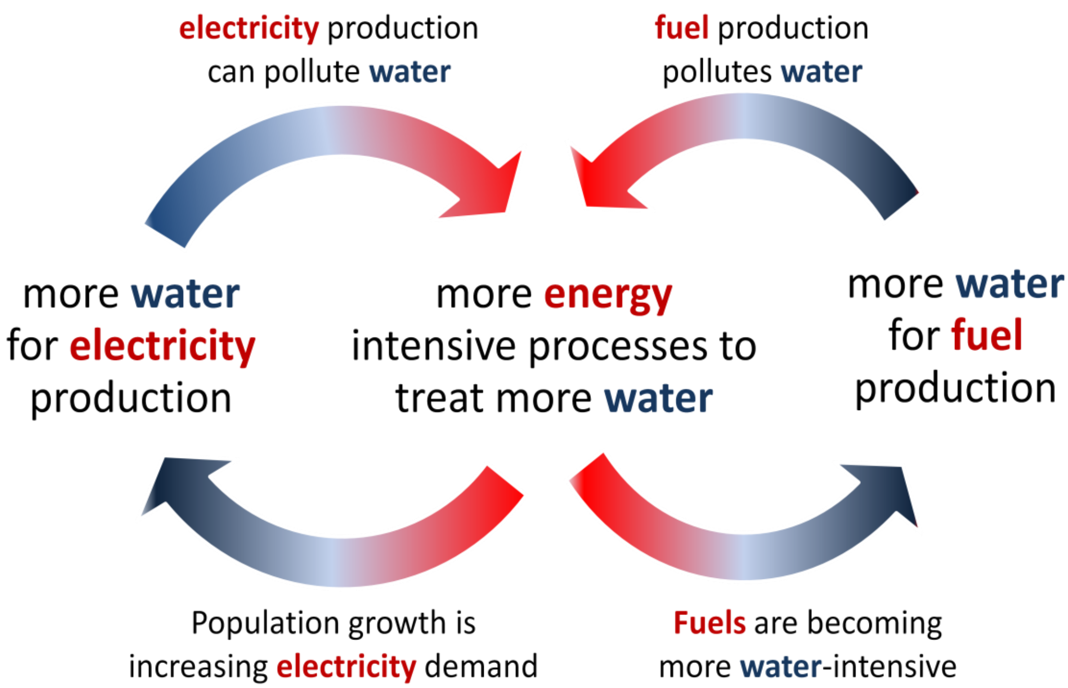


Figure 1. The Energy-Water nexus describes the interconnection between the water for electricity and transportation fuel production and the energy used for water treatment.

Chapter 5 provides fresh analysis regarding the future energy requirements of water treatment, which are considered in the context of the current energy policy environment.

Although many confounding factors will influence the energy consumption in the water treatment sector in the future (i.e., freshwater availability, population and economic growth, climate change, tightening water treatment standards, increases in water demand, etc.), this analysis focuses specifically on the water quality implications due to the RFS mandated by EISA 2007.

Chapter 2: The Electricity-Water Nexus

2.1 Introduction to the Electricity-Water Nexus

Water is critical to electricity production. Currently, thermoelectric power production constitutes 49% of all water withdrawals (and 39% of fresh-water withdrawals) in the US, more than any other sector.[4] While there are water implications across the entire electricity generation lifecycle, most water is used to cool power plants. The majority of water used for cooling, however, is only displaced for a period of time and then returned to its source. Thus, it is important to categorize the water used for electricity generation in terms of water that is displaced versus that which cannot be recovered at its original source or hydrologic basin in liquid form. USGS water data distinguish these nuances in terms of water *withdrawals* and water *consumption*. Water withdrawal refers to the volume of water removed from a water source; this water is not lost, but it cannot be allocated by other sources while it is being used. Consumption, on the other hand, refers to the volume of water lost via evaporation, transportation or any other means in which water is not replaced in its native reservoir. Since consumption is a small subset of withdrawals, it is inherently smaller. Consequently, the thermoelectric sector only consumes 3% of the US water supply despite its large water withdrawals.

Withdrawal and consumption metrics are important to consider since excessive withdrawals might detrimentally affect marine ecosystems, while excessive consumption reduces the amount of water that is available for other uses. Figure 2 and Figure 3 illustrate the breakdown of the water withdrawn and consumed in the US, respectively. Note that the relative distribution of water withdrawals is very different from that of consumptive water use, especially in the thermoelectric and irrigation sectors.

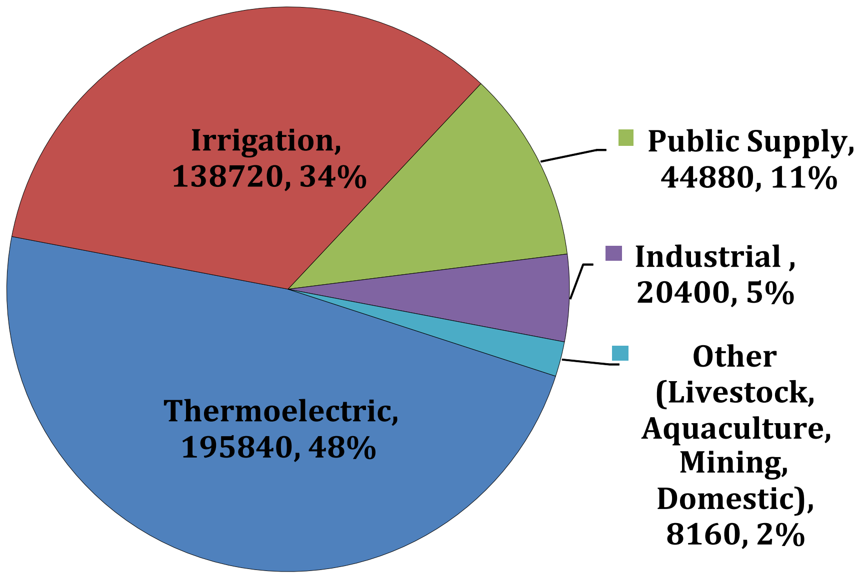


Figure 2. 2000 US Water Withdrawals by Sector (Mgal/day) [5]

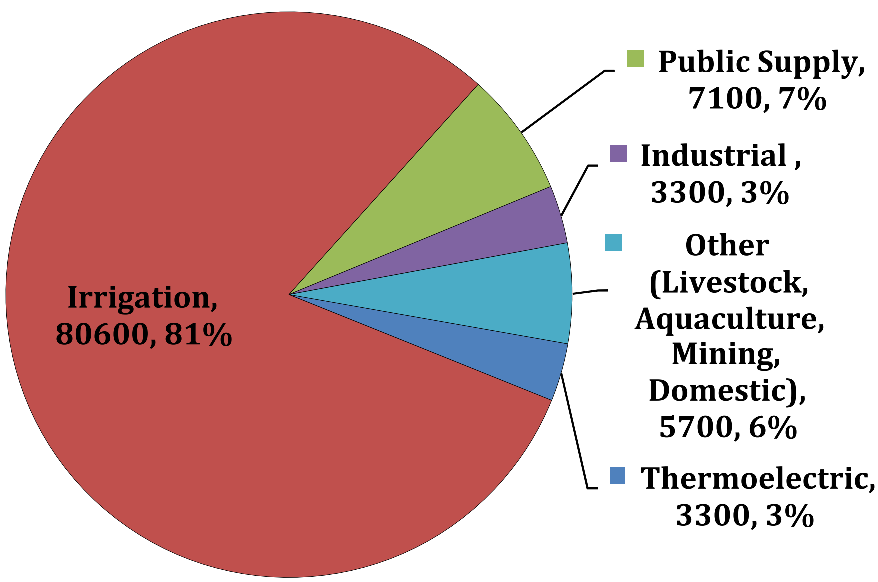


Figure 3. 1995 US Water Consumption by Sector (Mgal/day)[a][4]

[a]Note that consumptive data has not been collected by the USGS since 1995 because of the difficulty of data collection and funding constraints.

The discrepancy is because the majority of water used for thermoelectric power generation is used for cooling processes that return water back to its original reservoir or recirculate it back through the system. Irrigation, on the other hand, loses large quantities of water to evapotranspiration, which is not recovered in that basin. As a result, irrigation accounts for 81% of total water consumption despite only representing 34% of withdrawals.

2.2 THE WATER IMPLICATIONS OF ELECTRICITY GENERATION

The US electricity mix is currently dominated by coal, natural gas, and nuclear power

Figure 4).[6] Large quantities of water are typically needed to mine, transport, process, and convert these fuels into electricity. Water constraints have already affected electricity reliability and are likely to place increasing strain on the electricity-water nexus in the future. In addition to water quantity concerns, electricity production also raises water quality issues. These issues are discussed in detail in this chapter.

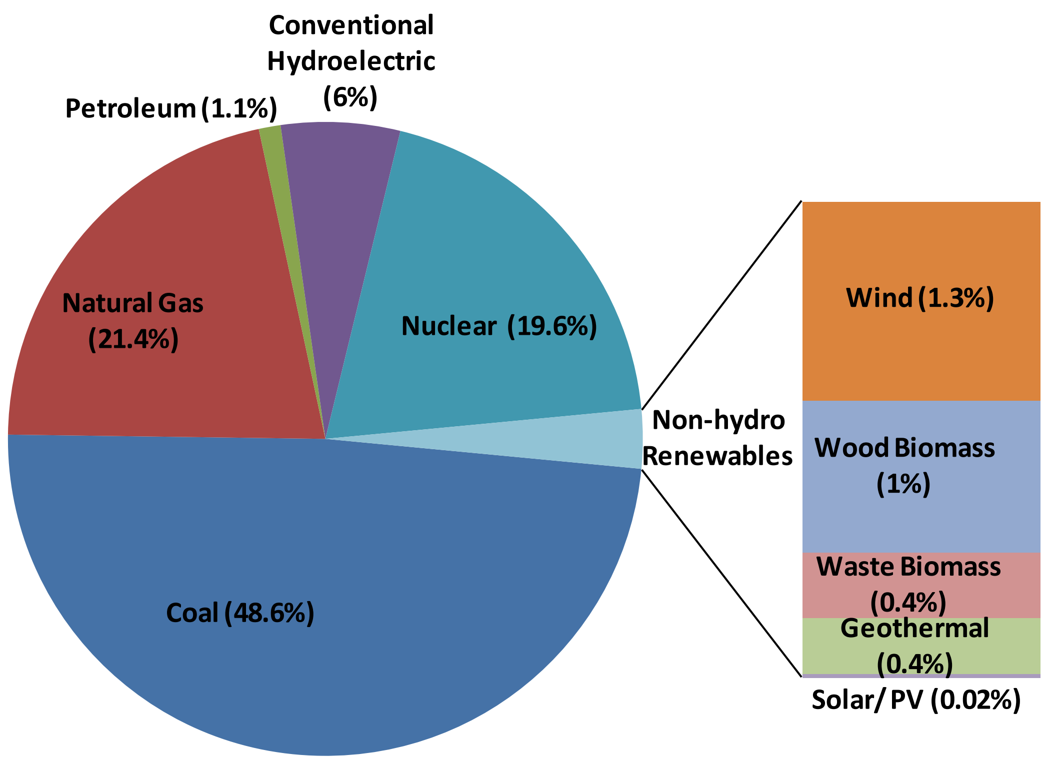


Figure 4. 2008 US Net Electricity Generation (Total 4,110.3 billion kWh)[6]

2.2.1 Water Use for Thermoelectric Power Generation Technologies

The majority of water use in electricity generation is allocated to cooling thermoelectric power plants. Typically, thermoelectric power plants generate electricity by burning or reacting fuel in a firebox to provide heat to a high-pressure boiler, which is used to generate steam. The superheated steam is used to turn a turbine connected to an electric generator to produce electricity. The steam expands as it travels through the turbine and is released. Cooling water is used to condense the exiting steam into boiler feed water to improve performance and so that the process can begin again. Process heat can be supplied by many fuel sources including coal, fuel oil, natural gas, nuclear, solar, biomass, waste, or geothermal energy.

Natural gas power plants may use conventional thermoelectric steam boilers or open-cycle combustion gas turbines that use a hot gas as working fluid instead of steam to generate electricity. A natural gas combined cycle (NGCC) plant combines both systems by using waste heat from the combustion turbine to drive the steam unit. Natural gas power plants are more efficient than coal-fired and nuclear power plants, and thus, typically have lower water requirements for cooling.[7]

Traditionally, one of two wet cooling technologies is used for condensing steam at thermoelectric plants: open-loop cooling or closed-loop cooling. Open-loop cooling (also referred to as once-through cooling) withdraws large volumes of water from a source (typically a lake, river, or ocean) that are passed through the tubes of a condenser to cool steam discharged from the turbine. The water, now warm from heat transferred from the steam, is released back into its original reservoir. The water implications of these systems are primarily from water withdrawals, since most of the water is returned to the original source and minimal water is released through evaporation. However, water is returned to its original reservoir at temperature higher than natural reservoir temperatures, which can have detrimental effects on natural ecosystems existing in the area. These systems are becoming less common and are being phased out in some states like California, due to these detrimental thermal effects as well as risks posed to aquatic organisms that become trapped against water intake screens.[8]

Closed-loop cooling (also referred to as wet-recirculating cooling) withdraws smaller volumes of water for recirculated use in a cooling tower or cooling pond, compared to once-through cooling. However, these systems consume larger volumes of water via evaporation during recirculation when heated cooling water is pumped through a cooling tower and exposed to circulating air in order to remove excess heat. The cooled water is recirculated for use again. Only the water lost to evaporation and "blowdown" need be replaced. Blowdown is water discharged in order to remove excess minerals and contaminants that can potentially foul equipment when remaining cooling water becomes concentrated after water loss from evaporation. A manmade cooling pond may be used in place of a cooling tower in wet recirculating systems. In these systems, warmed cooling water is discharged by contact with the cooling-pond water and the atmosphere, rather than by towers.

More water-efficient cooling technologies exist, but these systems have drawbacks. Dry-cooling systems use virtually no water, but have an associated energy penalty to implement since cooling is done by fans which require electricity to run, and therefore can reduce a power plants' peaking capacity. Hybrid wet-dry cooling systems provide a compromise between wet and dry cooling systems, having both closed-loop cooling towers and cooling fans. These systems can be operated as dry-cooling systems or wet-cooling systems, or some combination of the two. Consequently, hybrid wet-dry cooling systems compromise water efficiency for power generation efficiency, but they are an improvement over traditional wet-cooling. This technology is not yet economical on the commercial power scale under current policy regimes, although this might change if water prices increase dramatically.

Table 1 provides a range of water requirements for each type of thermoelectric cooling system. Large differences in water use exist, even within specific cooling technologies, due to power-plant type, efficiency, operating conditions, etc. (See Table 2 for a summary of water consumption by electricity generation technology for wet and dry cooling technologies.)

Table 1. Water withdrawals and consumption vary widely across thermoelectric cooling technologies depending on electricity generation technology[a].[9]

Cooling Technology	Withdrawal ($gal\ MWh^{-1}$) low	Withdrawal ($gal\ MWh^{-1}$) high	Consumption ($gal\ MWh^{-1}$) low	Consumption ($gal\ MWh^{-1}$) high
Open-loop cooling	7,500	60,000	100	300
Closed-loop cooling[b]	230	1,100	180	920
Hybrid wet-dry cooling[c]	<100	1,100	50	920
Dry cooling	0	0	0	0

[a]Data presented are at the point of cooling; they do not include water at the point of manufacturing.

[b]Range includes NGCC cycle at low end and nuclear at high end.

[c]Range includes virtually dry operation at low end and virtually wet operation at high-end.

Despite merits in terms of water savings, dry and hybrid cooling systems both have financial and efficiency trade-offs. Total annualized costs for dry cooling towers can be four times those for wet cooling towers.[10] Additionally, generating efficiency is lost when ambient air temperatures exceed the design specifications of dry cooled facilities. The efficiency loss is due to insufficient cooling of the turbine exhaust steam, which increases steam turbine back pressure. Although this efficiency loss is also typical of wet-cooled systems when inlet water temperatures exceed design temperatures, the lower cooling capacity of air versus water makes dry cooling more sensitive to temperature changes and efficiency losses than wet cooling. A power plant with dry cooling can experience a 1% loss in efficiency for each 1°F increase of the condenser, and is therefore limited by ambient temperatures.[11] The plant's electricity output is also reduced by additional electricity requirements to run the fans and pumps in the air cooling system.

Another means for decreasing freshwater impacts is employing alternative water sources in closed-loop cooling. Freshwater is more valuable than brackish water and seawater since it does not require advanced water treatment methods to achieve potable quality. Unfortunately, it is also a small fraction of total water supply. Freshwater represents only 2.5% of the global water supply, two-thirds of which is stored in ice or permanent snow cover; only about 0.02% is in a form that is easily recoverable for potable uses.[12]

Alternatives to freshwater sources for cooling applications can include seawater, brackish water, or reclaimed water from wastewater treatment facilities. However, concern exists regarding the use of seawater for once-through cooling because of the harm to marine ecosystems. The California legislature is considering legislation to phase out open-loop cooling in California.[8] The legislation aims to protect fish nurseries and other sensitive marine populations, including species important to California's recreational and commercial fishing industries. This shift from open-loop cooling to closed-loop systems could add to the electricity sector's freshwater use.

Other alternative water sources include brackish or low-quality groundwater[13] and mine pool water.[14] Recycling effluent from wastewater treatment plants or other reclaimed water has also been a viable means of reducing strain on freshwater resources. The Palo Verde Nuclear Generating Station near Phoenix, AZ, has already begun using wastewater effluent for cooling.[15] Use of these water supplies can be an effective method of recycling wastes while preserving freshwater for other purposes. However, availability of alternative water sources in proximity to electricity generation facilities might limit their use. These alternative water sources could also lead to additional corrosion, scaling, and fouling of cooling equipment.

Fresh surface water sources supply approximately two-thirds of thermoelectric power water withdrawals. The majority of the remaining volume is supplied by saline water sources. Groundwater sources supply a very small, but non-zero volume of water for thermoelectric generation.[4]

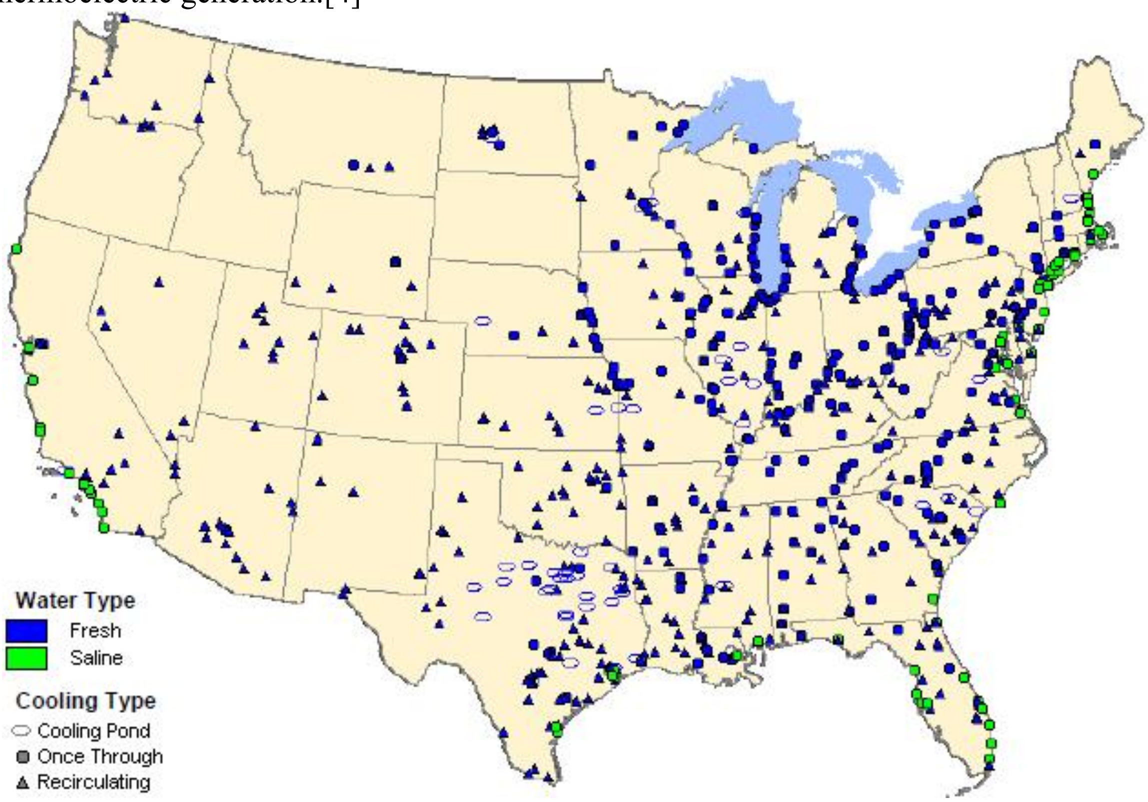


Figure 5. US Power plants (>100 MW) by Technology and Water Source [16]

Figure 5, created by NETL, identifies wet-cooled power plants in the US. Each plant is categorized by water quality and system type.[17] Approximately 42.7% of thermoelectric generation the US uses once-through cooling, 41.9% and 14.5% use wet recirculating with cooling towers and cooling ponds, respectively, and 0.9% use dry cooling.[17] These estimates only include thermoelectric power plants that exceed 100

MW generating capacity. Although once-through cooling systems are used more than other types, these systems are becoming less popular due to ecosystem impacts and in some cases might be illegal in the future (i.e., California).

2.2.2 Water Use of Non-Thermoelectric Power Generation Technologies

Although more than 70% of US electricity is generated at steam-driven facilities, non-steam driven generation provides an important contribution to the electricity generation mix, especially in terms of peaking power plants since these technologies tend to be easier and cheaper to ramp up and down[6]. Non-thermoelectric power is supplied by hydroelectric generation, distributed renewable energy systems, and any other means of generating electricity without the use of steam boilers.[18]

Hydroelectric power currently accounts for approximately 6% of the US's electricity generation.[6] The water use implications of hydroelectric power differ significantly from thermoelectric generation since it does not withdraw or consume water for cooling. Instead, hydroelectric facilities pass water through turbines to generate electricity. Consequently, hydropower only requires that sufficient water is available to pass through its turbines. Despite this fact, hydropower is typically considered to be an extremely water consumptive technology due to the large volumes of water that are lost via evaporation from the surface of reservoirs behind dams. Accounting for lost volumes of evaporated water is difficult since all sources of surface water lose water to evaporation. Thus, only the additional water evaporated from a reservoir due to the increased surface area produced by the existence of the dam in comparison to the free-flowing river is considered in consumption statistics.[19]

Although electricity at US hydropower facilities is produced with relatively low greenhouse gas (GHG) emissions, their environmental and water quality impacts can be significant. Conventional hydropower development through dam building often significantly alters river ecosystems, harming many indigenous species.

Constructing new large dams is contentious; therefore, efforts to identify opportunities for increasing hydropower generation have focused on smaller-scale opportunities or improved efficiency and expansion of hydropower at existing facilities. EPRI estimates that hydropower can potentially add 10 GW of additional capacity by 2025 without the construction of new large dams.[20] This estimate is based on additions by new small and low power conventional hydropower, capacity gains at existing conventional hydropower facilities, and new conventional hydropower at existing non-powered dams.[20] Six western states, Alaska, Washington, California, Idaho, Oregon, and Montana, have the highest potentials.[21] Despite this identified potential, little additional hydropower generation has been installed in recent years for a number of reasons (e.g., hydropower and water-related permit and regulatory requirements, and public concerns and perceptions about environmental effects).

Although non-hydroelectric renewable electricity generation provides very little of the current US generation mix, policies under consideration and various agency projections portend an increasing role for renewable sources in the future. HR.2454 passed in the US House of Representatives on June 26, 2009, includes provisions that require retail electric suppliers to meet 20% of their demand by renewable electricity or efficiency increases by 2020.[22] Qualifying renewable electricity includes electricity generated from wind, solar PV, Concentrated Solar Power (CSP), geothermal, renewable biomass, biogas and biofuels exclusively from renewable biomass, qualified hydropower, and marine and hydrokinetic renewable electricity from waves, tides, currents, free-flowing water, and differentials in ocean temperatures. Energy efficiency measures, such as improved building codes, improved lighting and appliance standards, and residential and commercial retrofits, may also be used to offset non-renewable electricity generation.

Some renewable electricity technologies that do not use thermoelectric processes have minimal water requirements for electricity generation. Wind turbines and solar PV panels require small volumes of water for cleaning, but otherwise use no water directly for generation. (However, water is used in manufacturing equipment for these systems.) A 2008 DOE analysis estimates that if wind power deployment increased gradually beginning in 2007 until it provided 20% of the nation's electricity by the year 2030, the US would save a cumulative four trillion gallons of water consumed compared to a business-as-usual scenario.[23] (Potential savings in water withdrawals are not analyzed in this study.)

However, the minimal water intensity of wind and PV comes with tradeoffs. Transmission constraints, cost, and regulatory, technical, and operational factors currently restrict the extent to which solar and wind resources has been exploited to meet electricity demand. Wind and PV are intermittent electricity sources and, although some storage options for these intermittent technologies exist (e.g.,wind used in conjunction with a pumped storage hydropower facility), their applications are limited and intermittency continues to limit generation from wind and PV.

Although CSP and PV are both solar technologies, CSP uses heat storage technology that allows CSP facilities to produce electricity into the night hours. [24] The first large-scale CSP plant with thermal storage began operations in Granada, Spain, in November 2008; the facility is a 50 MW plant with seven hours of thermal storage.[25]

Although CSP does not require fuel processing or emit greenhouse gases, it uses thermoelectric processes in conventional designs to convert heat into electricity, thus raising many of the same water use concerns as thermoelectric power plants using traditional fuels. In fact, the water consumed by wet-cooled CSP power plants is typically much higher than other types of thermoelectric generation since operating temperatures are higher. Furthermore, areas that provide the strongest solar resources for CSP are typically dry and hot, which may limit a plant's ability to use wet cooling. However, dry cooling may also be compromised by efficiency losses on hot days.

Electricity generation from combustion of renewable biomass requires similar cooling water use as coal- and nuclear-fueled thermoelectric facilities (Table 2). Just like any other thermoelectric power plant, implementation of dry or hybrid wet-dry cooling technologies can reduce the water intensity of biomass power generation.

The water required to grow different types of biomass feedstock can vary widely. Some biomass sources, such as National Forest trimmings and pulp and paper industry waste, generally do not require irrigation water for biomass growth. In contrast, dedicated energy crop grains and crop residues that come from irrigated lands can require large volumes of water, depending on local climate conditions. Though dedicated energy crop grains and crop residues are usually used for liquid transportation fuel production, electricity generated from these resources is considered renewable in the RES defined in H.R.5424.

Producing electricity from water-efficient (e.g.,non-irrigated) biomass sources is an option in some US regions. However, droughts, heat waves, and floods and their potential increased occurrence under a changing climate may decrease the reliability of biomass for electricity generation. Even in regions where precipitation may increase in the future (e.g.,the Great Plains), increasing temperatures are projected to cause a net drying effect in many regions, potentially harming agricultural productivity and water availability. [26]

The US has substantial geothermal electricity potential; however, it can consume significant quantities of water and is not yet feasible for commercial scale applications. A 2008 study by the USGS estimates that the US has adequate geothermal resources to supply half of the nation’s current electric power generating capacity, assuming enhanced geothermal systems could be successfully developed and deployed at a commercial scale.[27] There are several ways to use geothermal energy, including direct-use (recovering water heated by the earth), heat pumps (using the earth’s heat to cool/heat buildings), and for electricity production, which is the focus here.

Geothermal power plants generate electricity by means of water and thermal energy. Traditional geothermal power production utilizes naturally occurring convective hydrothermal sources inside hot rock to create steam to run the power plant’s steam-powered turbines. However, the majority of hot rock that is eligible for geothermal power generation is dry, and therefore does not contain adequate water to produce steam to generate electricity.

Enhanced geothermal power plants on the other hand, inject water into fractured rock to be heated and returned to the surface where its thermal energy can be used to generate electricity.[28] The cooled water is then injected back into the rock to form a closed loop system. Therefore, much of the geothermal resource in the US would require large volumes of water consumption in order to exploit the energy.

Enhanced geothermal power plants require relatively little land and can be used in coproduction with enhanced oil recovery to lengthen the lifespan of oil fields.[29] These enhanced systems are an emerging technology, so more research and development are needed for large-scale commercial development and deployment. Current research is investigating the possibility of replacing water with carbon dioxide as the working fluid, which would significantly reduce water usage, could improve oil production, and would be a means of carbon sequestration.

2.2.3 Summary of Water Consumption by Electricity Generation Technology

The water use of power plants is very inconsistent, even across similar types of generation with similar cooling technologies. NGCC cooling plants typically fall at the low-end of water use, while nuclear and CSP to tend have much higher cooling requirements. Table 2 compares the water use for different thermoelectric generating technologies for wet and dry cooled power plants, as well as non-thermoelectric generation technologies (hydroelectric, PV and wind). Data are reported in terms of volume of consumed water per unit of electricity generated.

Table 2. Water Consumption for Electricity Generation by Fuel Source and Generation Technology [9][1]

Electricity Generation Technology	Water for Fuel Production (gal/MWh)	Wet Cooling[a] (gal/MWh)	Dry Cooling[b] (gal/MWh)	Water for Non-Cooling Aspects of Power Generation (gal/MWh)
Geothermal	0	1,400	0	Not available
Enhanced Geothermal	Not available, potentially significant[c]	1,400	0	Not available
CSP – Solar Trough	0	760-920	0	80[d]
CSP – Solar Tower	0	750	0	90[d]
Nuclear	45-150	400-720	Unlikely technology choice[e]	30[f]
Coal	5-74	300-480	0	30[f]
Biomass – Irrigated	Highly variable, depending on geography[g]	300-480	0	30[f]
Biomass – Non-Irrigated	0[h]	300-480	0	30[f]
Natural Gas Combined-Cycle	11	200	0	7-10[f]
Coal IGCC[i]	5-74	200	0	7-10 (+ 130 process water) [f]
Hydroelectric	0	--	--	Highly variable; 4,500 to evaporation
PV	0	--	--	5[j]
Wind	0	--	--	1[k]

[1]Table from CRS Report in collaboration with Ashlynn Stillwell

a. Using wet cooling as closed-loop cooling tower or cooling reservoir.
b. Using dry cooling as air-cooled condenser.
c. Limited data is available since technology is not available at commercial scale.
d. [25]
e. Safety concerns and cost make dry cooling for nuclear power plants an unlikely choice.
f. Source references did not specify whether values are for withdrawal or consumption.
g. Water consumption for irrigated biomass fuel production was not reported. Reported withdrawal for dedicated energy crops is greater than 130,000 gal/MWh, but is highly variable. [30]
h. Non-irrigated biomass is rain-fed; CRS did not estimate the water consumed through plant evapotranspiration.
i. IGCC: Integrated Gasification Combined-Cycle.
j. [31]
k. AWEA estimate, based on data obtained by AWEA available at http://www.awea.org/faq/water.html.

2.3 THE US ELECTRICITY-WATER NEXUS IS ALREADY STRAINED

The electricity-water nexus is already strained in many parts of the country because of regional water shortages that have resulted from drought, changes in snowmelt patterns, and competition with other agricultural, municipal, and industrial users. The "Water Supply Sustainability Index" (Figure 6) was developed by EPRI to indicate the susceptibility of US water supplies to shortage on a county basis. The index categorizes a region's susceptibility to water resource constraints by considering six metrics; these include:

(1) Rate and extent of renewable water resource development

(2) Sustainability of groundwater use, measured as the ratio of groundwater withdrawal to available precipitation

(3) Environmental regulatory limits on freshwater withdrawals

(4) Susceptibility to drought

(5) Anticipated growth of water use

(6) New requirements for storage or withdrawals from storage

Each of these six metrics was evaluated quantitatively based on criteria established by EPRI. For example, indicators of unsustainable water use include allocating more than 25% or withdrawing more than 50% of a county's available precipitation. A less obvious indicator includes having two or more endangered species since there are stricter regulations regarding withdrawals from endangered species' habitats. Some counties may be considered sustainable according to some metrics, but unsustainable based on others. Therefore, the final susceptibility ranking is based on an average of these evaluated metrics.

Figure 6 indicates that the counties highly susceptible water resource constraints are concentrated in the Southwestern region of the US; however all regions contain counties considered at risk to water shortages by EPRI's considerations. Water shortages have already had detrimental impacts on electricity reliability in multiple regions of the US. Drought and changes in water storage have reduced the water available to power generators in multiple parts in the country.[26, 32, 33] New power plants have also encountered difficulties obtaining permits in water constrained areas.[18]

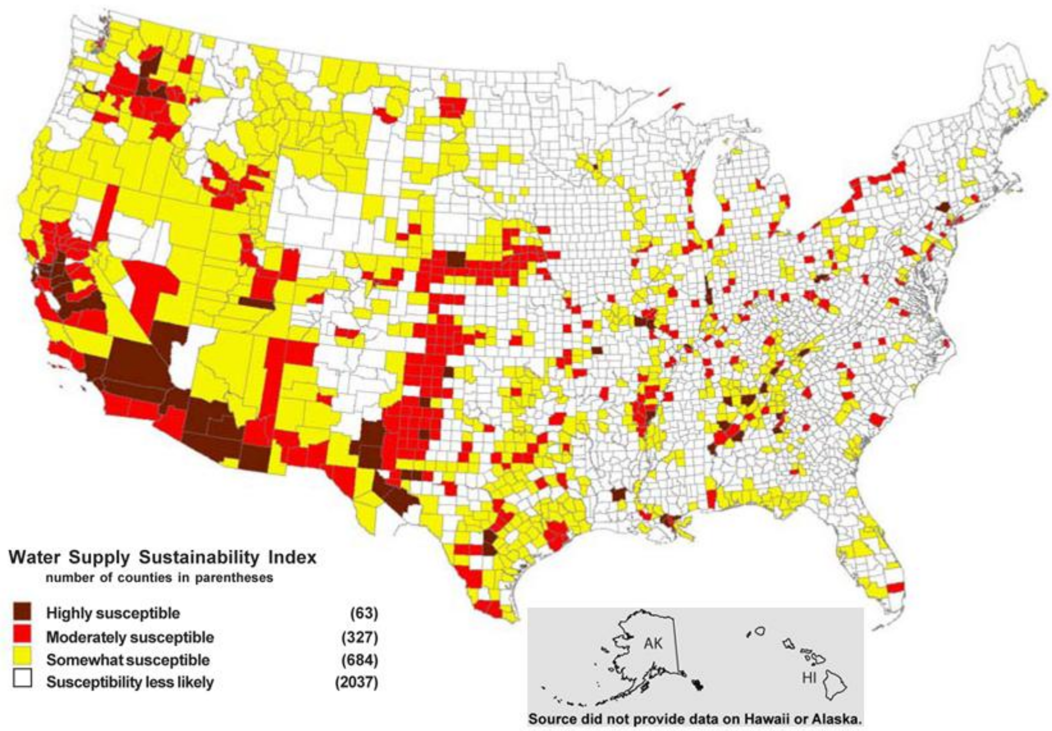


Figure 6. Water Supply Sustainability Index by US County [34]

Periods of drought increase the risk of electricity supply interruptions from generators that require water for operations. Unfortunately, water supplies are often most constrained during the summer months when ambient temperatures are highest, which is also when electricity demand is greatest in many regions. Drought severe enough to limit water use by electricity generators that need the water can force facilities to reduce generation or shut down.

The role of droughts and low water levels in the electricity-water nexus is particularly clear for nuclear power plants. The Nuclear Regulatory Commission (NRC) sets minimum water levels for plant operations to ensure that water levels do not drop below water intake structures.[35] Water quality regulations also require that cooling water discharged to water reservoirs from thermoelectric facilities remain below a specified temperature to protect the water quality of the receiving waters and the health of native species and ecosystems. If cooling water reservoirs (1) fall below minimum water level regulations or (2) exceed maximum thermal thresholds, facilities are required to power down or go offline completely. Nuclear power production has already been threatened at several facilities in the Southeastern US during recent droughts. On August 16, 2007, a nuclear reactor at the Browns Ferry Nuclear Power Plant in Alabama shut down for one day because cooling water discharge exceeded temperature regulations that protect the environment and wildlife.[32] Other plants sited near Raleigh, NC, and Charlotte, NC, have come close to mandatory shut downs. In total, 24 of the nation's 104 nuclear reactors are sited in drought-prone regions.[36]

Hydropower has also been compromised due to water shortages associated with dry climate and drought in multiple regions in the US. Reductions in streamflow can limit the amount of hydropower that can be produced and can potentially cause a loss of generation altogether if reservoir levels fall below the turbine intake structures. For instance, it is estimated that every 1% decrease in streamflow in the Colorado River Basin reduces hydropower generation by 3%.[26] Lower streamflows in the Southwestern US have reduced the reservoir levels at hydropower facilities (e.g., Lake Mead at Hoover Dam), which have consequently reduced generation.

Although hydropower does not supply the Southeastern US with a large proportion of its electricity demand, it is an important source of peaking power.[33] Low reservoir levels reduced generation of hydropower by the Tennessee Valley Authority (TVA) and Duke Energy in North Carolina during the 2007/2008 drought. Consequently, the price of electricity in this region has increased as more expensive types of generation replace hydropower. Population growth in the region has also resulted in pressure to reallocate storage capacity at existing multipurpose reservoirs from hydropower to municipal and industrial water supply and to maintain lake levels for recreational use. These types of lake management and reallocation issues are a significant part of the ongoing conflicts between Alabama, Florida, and Georgia over the management of the federal reservoirs in the Apalachicola-Chattahoochee-Flint basin, and between Georgia and South Carolina over reservoirs in the Savannah River basin.

In general, changes in streamflow all over the country have reduced water storage in water reservoirs, and consequently, water availability throughout the year; these changes can adversely affect hydroelectric facilities even in regions that are not characteristically dry. Climate change and its effect on variability in the region's hydrology have raised concerns in the Pacific Northwest about the region's future for hydropower generation from existing facilities.[37] Although hydroelectric dams have provided cheap and reliable power to this region for decades, climate models predict less Northwestern mountain snowpack in the winter and earlier peak runoff in the spring.[26] Northwestern dams do not have enough reservoir storage capacity to handle this shift in maximum runoff, so more snowmelt will be passed through their turbines in a short period of time, rather than being stored for use during drier and hotter months. In effect, the function of snowpack as a naturally occurring reservoir will be greatly compromised. Projections indicate that hydropower dams in the Columbia River system might experience 10-20% reductions in the hydroelectric generation in order to maintain sufficient volumes of water for annual salmon runs.[37] Opportunities for expanding hydropower capacity in the region have been identified, but their vulnerability to changes in hydrology, financial viability issues, and other concerns require additional study.

Seasonal runoff from mountains is in the Southwestern US is also likely to become less dependable as increasing temperatures continue to shift the quantity, timing, and duration of snowpack melt.[26] Projections of earlier snow melt, less snowpack, and more frequent and severe drought conditions indicate that water supply issues will likely be exacerbated in the future, increasing competition between municipal, agricultural, and electricity sector demands. Early season water is often difficult to store at multi-purpose reservoirs in the region since it coincides with the need for storage space to be available in case of floodwaters. Climate change models suggest that the Southwestern region of the US will continue to warm and dry out placing increasing strain on water supplies.

While water supply constraints have affected electricity generation at existing power facilities, they have also limited the development of new water-intensive generation in very dry region. Water scarcity has reduced the expansion of new thermoelectric capacity in the Southwest, which currently generates the majority of its electricity from water-intensive coal power plants (with the exception of California). Three proposals for wet-cooled thermoelectric plants in Arizona have been denied state water permits to build.[10] Similarly, Sempra Energy of Nevada has halted the development of new coal power plants because of concerns over local water resources.[18] Water scarcity has also raised concerns in siting new power plants in the inland regions of the Northwest, which are relatively dry and susceptible to extended droughts.[26] From 2006 to 2008, the state of Idaho instituted a moratorium prohibiting the construction of new coal-fired power plants because of water supply and environmental concerns.[18]

Despite their economic and efficiency drawbacks, dry cooling systems are becoming increasingly utilized at Southwestern power plants as an alternative to abandoning facility proposals because of water constraints.[10] Unfortunately, these systems are susceptible to operability reductions on hot days when electricity is at peak demand, as discussed earlier. Nonetheless, more than 50 dry cooled power plants, in states such as Nevada, New Mexico, California, and Texas, are now in operation.[10]

2.4 STRAIN ON THE ELECTRICITY WATER NEXUS IS LIKELY TO INCREASE

Population growth projections in conjunction with a number of other converging trends suggest that the electricity-water nexus will become increasingly strained in the future. Population and economic growth are also likely to increase water demands in other competing sectors. Projections regarding the levels of expansion in other sectors, however, are unclear due to potential advances in technology and gains in efficiency, especially in water intensive sectors such as agriculture and industrial facilities. Compounding these uncertainties are shifting policy regimes that make it hard to predict what the future electricity generation mix will look like. Changes in energy and climate change policy will greatly influence the water demands of the electricity generation sector in the future. Potential carbon pricing might foster the large-scale deployment of renewable energy sources; however, these sources have a large range of water use requirements. These trends are detailed on the following sections.

2.4.1 Population and Economic Growth

Population growth augments total water and electricity demand due to sheer increases in number of people that must meet their basic needs. Increases in economic growth will exacerbate the effects of a rising population since per capita electricity and water demand are likely to rise. (For instance, when people become wealthier, they typically eat more meat, demand more products, and have higher sanitation standards, all of which, come with energy and water implications.[38, 39])

Figure 7 and Figure 8 summarize the United Nation’s (UN) population growth projections to 2050 for the US and the world, respectively[40, 41]. Even in the low-growth scenario, population is expected to increase substantially.

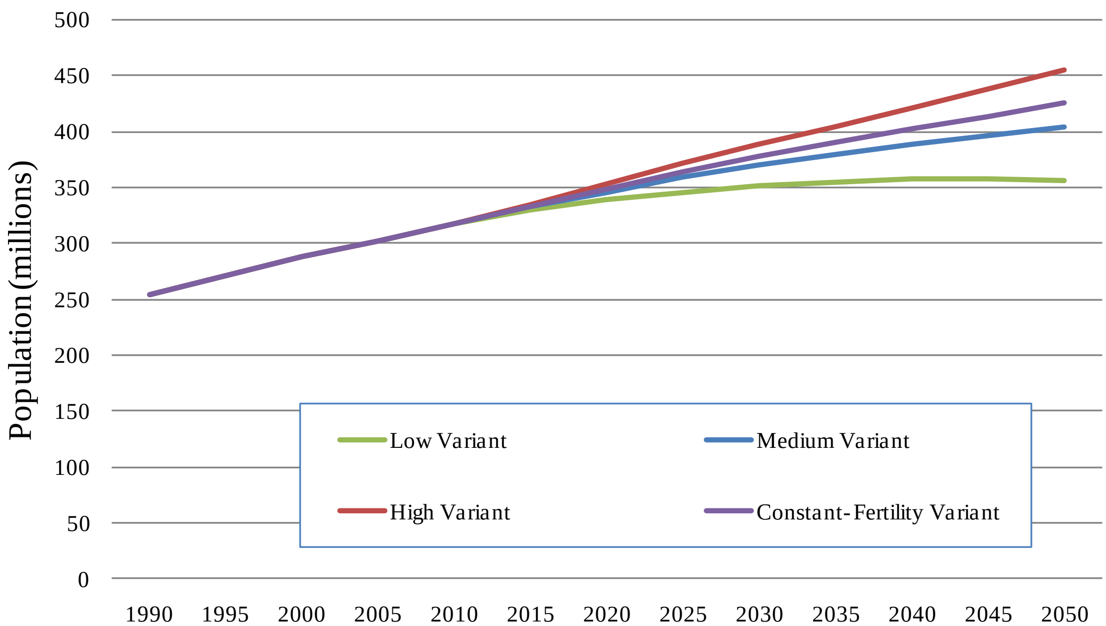


Figure 7. US Population Projections to 2050 [41]

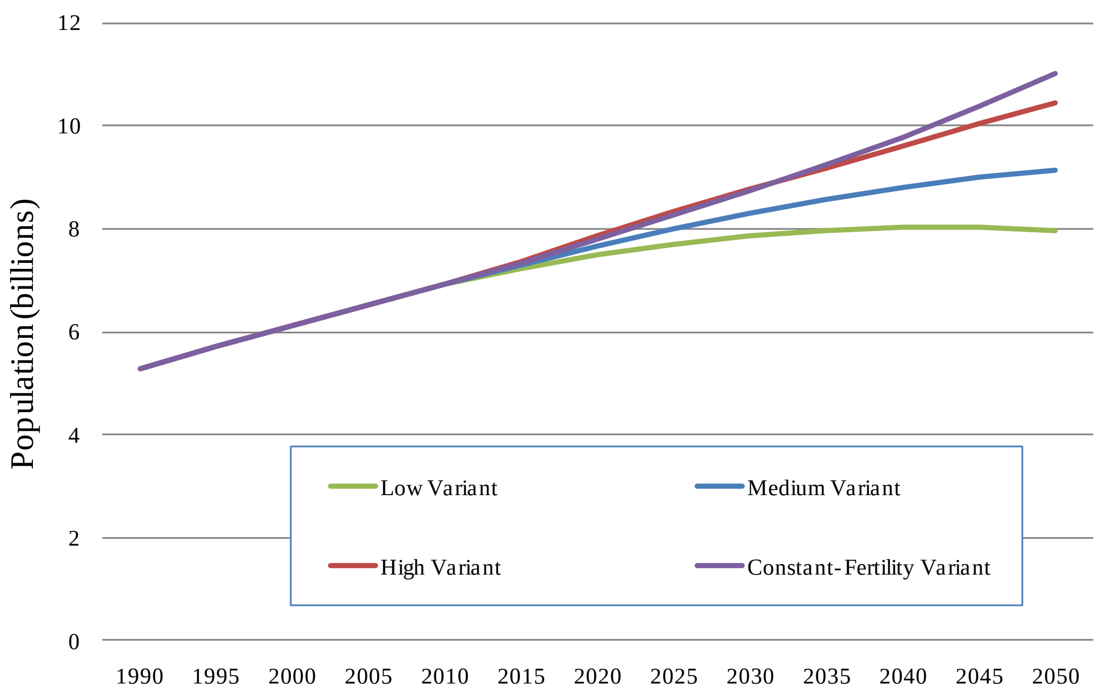
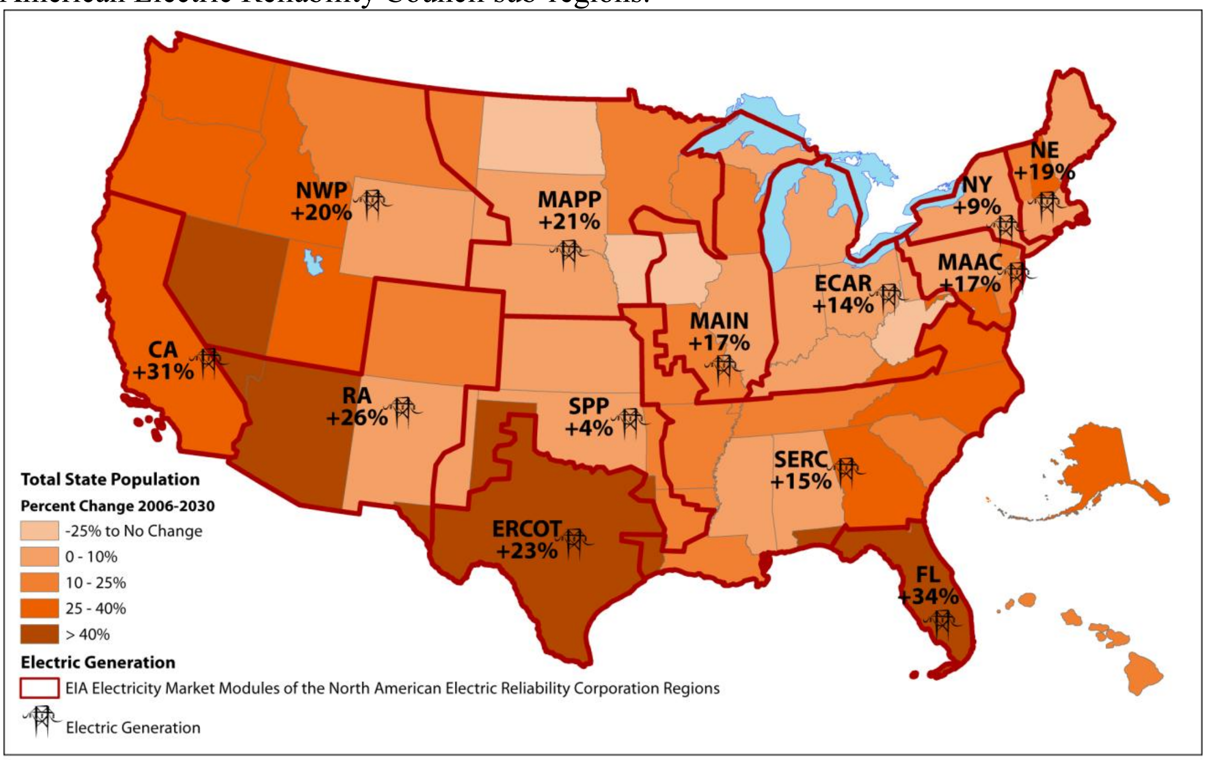


Figure 8. World Population Projections to 2050 [41]

Population growth typically couples with increases in electricity demand, which consequently increases water use. The Energy Information Agency's Annual Energy Outlook (EIA AEO) 2009 projects in its reference case that cumulative electric power sector additions will total 218 GW between 2006 and 2030.[6] Figure 9 shows EIA projections for electricity generation in 2030 as a percentage change from 2006. Estimates are based on the Electricity Market Module (EEM) supply regions defined by the North American Electric Reliability Council sub-regions.



ECAR - East Central Area Reliability Coordination Agreement
ERCOT - Electric Reliability Council of Texas
MAAC - Mid-Atlantic Area Council
MAIN - Mid-America Interconnected Network
MAPP - Mid-Continent Area Power Pool
NY - Northeast Power Coordinating Council / New York
NE - Northeast Power Coordinating Council / New England
FL - Florida Reliability Coordinating Council
SERC - Southeastern Electric Reliability Council
SPP - Southwest Power Pool
NWP - Western Electricity Coordinating Council / Northwest Power Pool
RA - Western Electricity Coordinating Council / Rocky Mountain Power Area and Arizona-New Mexico-Southern Nevada Power Area
CA - Western Electricity Coordinating Council

Figure 9. US Population and Electricity Generation Projections for 2030, by State and Electricity Market Module [9]

These projections indicate that substantial increases in generation will be necessary to meet demand in the future. Since most electricity generation requires water, increases in water consumption are expected unless efforts are made to promote freshwater-efficient electricity generation and cooling technologies.

Figure 9 also indicates changes in state population based on the US Census Bureau's projected population increase to nearly 364 million people by 2030, up from the current population of roughly 307 million.[40]

Many of the states that expect the largest growth in population and electricity demand already face water shortages, especially in the Southwestern US. In these water stressed region, the additional demand for water in electricity generation will be exacerbated by concurrent increases in water use in other sectors.

Table 3. Although water withdrawals per capita are projected to stay constant or decrease in all sectors, total withdrawals will likely increase.

	Percent Change between 1995 to 2040 in:	
Sector Name	Total billion gallons per day per sector	Gallons per capita per day per sector
Livestock	40.0%	0.0%
Domestic and Public Use	40.6%	0.0%
Industrial and Commercial	5.4%	-47.3%
Thermoelectric	8.3%	-22.8%
Irrigation	-3.0%	-31.1%

In addition to increased water demand for electricity demand, other sectors are expected to experience growth in the future, which might exacerbate competition for valuable freshwater resources. Population growth will drive much of this growth in total water withdrawals.[42] Projections released by EPRI indicate that total withdrawals are expected to increase in the future, despite the fact that per capita withdrawals might decrease. Decreases in per capita demand in the industrial and commercial, thermoelectric, and irrigation sectors indicate that these sectors are expected to become more water-efficient with time; despite these efficiency gains, population growth will possibly cause a net increase in total withdrawals in all sectors except for irrigation (Table 3).

The local or regional distribution of water uses between power generation, agriculture, industry, and municipal uses may change subject to the water intensity of electricity generation. Under a status quo scenario, NETL predicts an increase in water consumption for thermoelectric power generation of 1 billion gallons per day between 2005 and 2030. Since open-loop cooling is slowly being phased out because of environmental regulations, a regulatory-driven scenario was created in which 5% of existing open-loop cooled power plants were converted to closed-loop cooling. This scenario increases water consumption by 1.8 billion gallons per day, but reduces water withdrawals. [17] Increasing freshwater use for electricity generation requires a transfer of water from other uses either directly or through conservation, since freshwater is a finite resource.[9]

2.4.2 Shifting Policy Environments

In addition to the uncertainties regarding future water and electricity demand discussed above, uncertainty about the makeup of the electricity generation mix confounds projections over electricity sector's future water use. The EIA projects that 250 GW of total added capacity will be installed between 2008 and 2035.[6] Natural gas and renewable electricity supplied by non-hydroelectric sources are projected to supply this majority of this added capacity. Capacity additions by generation type are summarized in Figure 10. Currently, HR.2454 is stalled in the Senate after passing in June 2009 in the House of Representatives. The final ruling on the RES introduced in this bill will likely influence the future deployment of renewable electricity in the future.

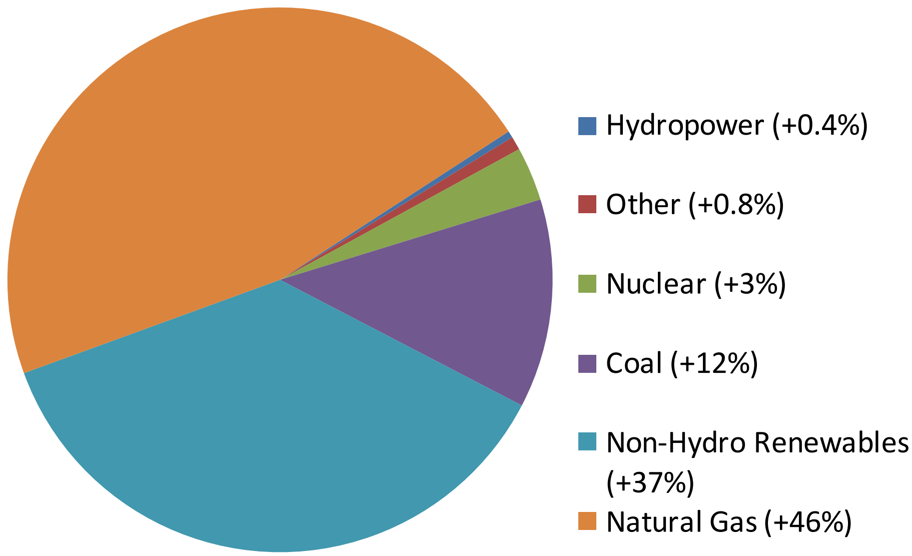


Figure 10. Additional US capacity between 2008 and 2035 is projected to be supplied predominantly by natural gas and non-hydro renewable electricity technologies.[43]

Electricity deployment predictions have been made by various agencies, but they vary a great deal in regards to the level of deployment of different renewable electricity alternatives. Figure 11 and Figure 12 compare renewable energy deployment projections from the EIA and NREL.

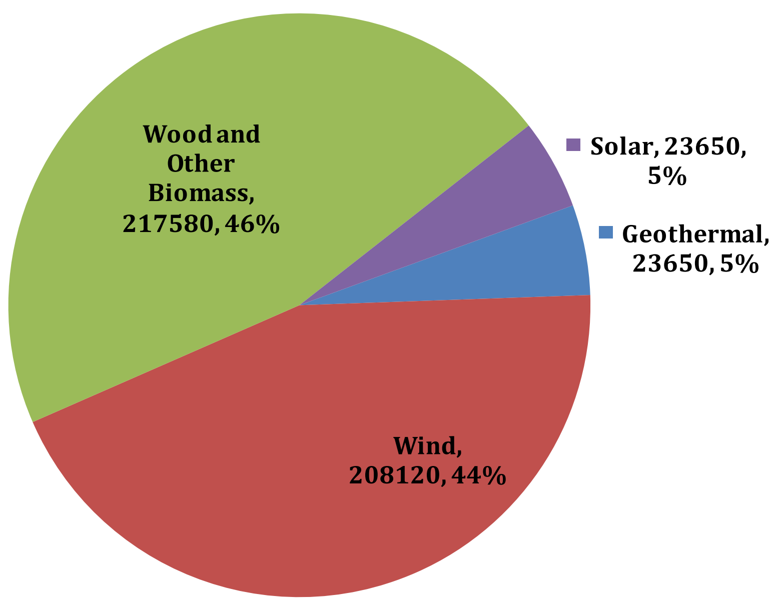


Figure 11. EIA's US Renewable Electricity Projections to 2030 (Million kWh) [9, 43] [1]

The EIA projects that total renewable electricity generation will reach 473 billion kilowatt-hours (kWh) in 2030, produced by facilities with installed capacity of 250 GW (Figure 11).[9] Wind and biomass are roughly equally dominant accounting for 90% of projected renewable generation in total.

NREL's projection, by contrast, estimates that over three-quarters of renewable generation in 2030 will be supplied by wind alone. Solar energy is also considered a significant contributor. In terms of total renewable electricity generation, NREL's projection is slightly higher (493 billion kWh) (Figure 12).[9] Note that each projection is markedly different, illustrating the large uncertainty that exists in regards to future renewable electricity generation deployment. Future deployment will likely be dependent on changes in legislation that might radically change the future electricity generation mix from the current baseline.

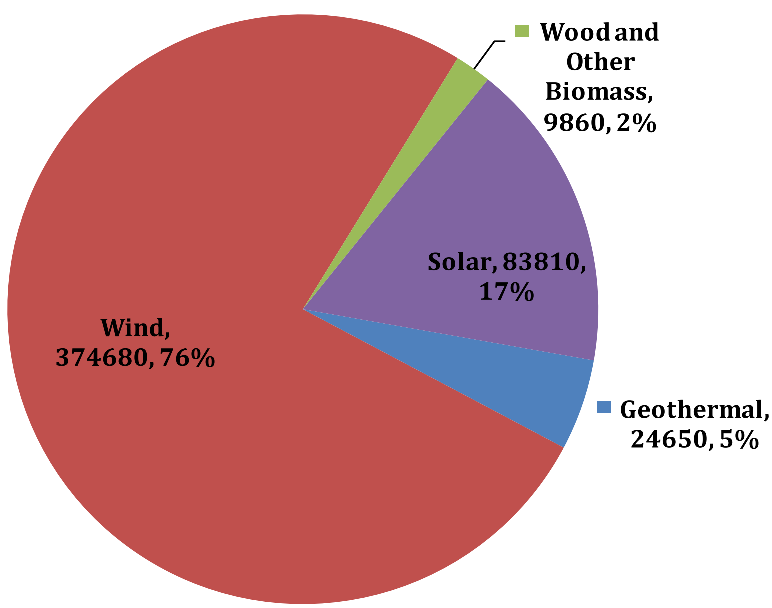


Figure 12. NREL's US Renewable Electricity Projections to 2030 (Million kWh) [9][1]

[1]EIA and NREL projections exclude hydropower and municipal waste-to-energy renewable sources

Each of these scenarios has very different water use implications. For example, wind power requires very little water, and thus, water use in a high wind deployment scenario would be less than meeting this demand with conventional sources. The high biomass scenario, on the other hand, would essentially be an expansion of thermoelectric generation since the conversion of biomass to electricity typically requires steam driven turbines. Additional water use might be required to grow agricultural feedstocks, as well, depending on what type of biomass is utilized. The water implications of a high solar scenario are unclear since PV technology has very low water requirements, whereas CSP can be several times more water-intensive than average thermoelectric generation from fossil fuels. How and where these technologies actually become deployed will be important to moderating the electricity water nexus.

2.4.3 Climate Change

The changing climate has many predicted consequences for water resources. Researchers predict more precipitation in the form of rain and less in the form of snow, changing the seasonal nature of water availability in some areas. Additionally, climate models predict more frequent floods and droughts. These changes might be challenges for electricity generators that depend on a reliable water supply for power plant cooling or hydroelectric dam operation. Water resource availability and temperature might also affect power plants operations if cooling water discharged to cooling water reservoirs exceeds thermal discharge limitations. Climate change also increases the demand for air conditioning, the electricity it consumes, and the water used to produce the electricity.

Chapter 3: The Fuel-Water Nexus

3.1 INTRODUCTION TO THE FUEL-WATER NEXUS

Water is important to the production of transportation fuel. As concerns over geopolitical disputes, climate change, and the rising price of oil rise, the US has looked to increasing the role of alternatives to petroleum-based gasoline and diesel as sources of transportation fuel. Although first-generation, corn-starch based, ethanol is the major focus of this work, other alternatives exist such as advanced biofuels (i.e., cellulosic ethanol, algae), and unconventional fossil-fuels (i.e., oil shale, tar sands). Although some of these fuels have large water-implications, they will not be discussed in detail here.

3.2 THE WATER IMPLICATIONS OF TRANSPORTATION FUEL GENERATION

Figure 13 details the life-cycle steps associated with transportation fuels. Each of these steps has water implications that vary across all fuel types. For example, growing irrigated feedstock requires water for crop cultivation, which is not required for conventional fuel production. Oil production, on the other hand, typically requires water to extract the resource out of the ground; water is injected into a well to increase the pressure of a reservoir to force oil out. After resource cultivation, both forms of fuel production have water implications for processing and refinement into a form that is usable in combustion automobiles.

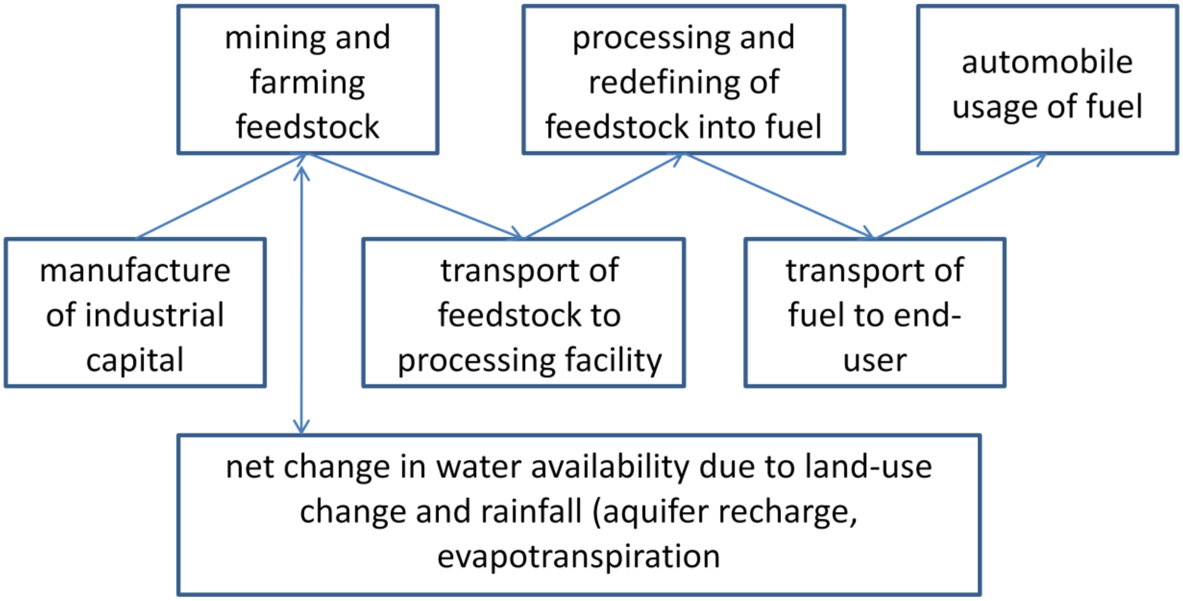


Figure 13. The Transportation Fuel Life-Cycle [44]

The following sections detail the water implications of the current and projected fuel mix in the US over the upcoming decades.

3.3 THE CURRENT US FUEL MIX REQUIRES LITTLE WATER

According to the EIA's 2009 AEO, 95% of total energy used for transportation was supplied by petroleum-derived sources. Ninety-seven percent of the miles traveled in 2005 by Light Duty Vehicles (LDV) were fueled by petroleum-derived gasoline and diesel fuels (140 billion gallons of gasoline, and 40 billion gallons of diesel, annually).[44] In general, these conventional fuel sources are less water intensive than fuel sources derived from irrigated biofuels or unconventional fossil fuels, withdrawing and consuming approximately 12.5 and 1 to 2.5 gallons of water per gallon of refined fuel during the oil refining process, respectively [44].

Figure 14 indicates that the water-intensity of conventional fossil fuels can be order of magnitudes lower than that of some types of renewable fuels, especially irrigated biofuels. Thus, the future deployment of water intensive fuels (Section 3.4) will likely have substantial water-use implications.

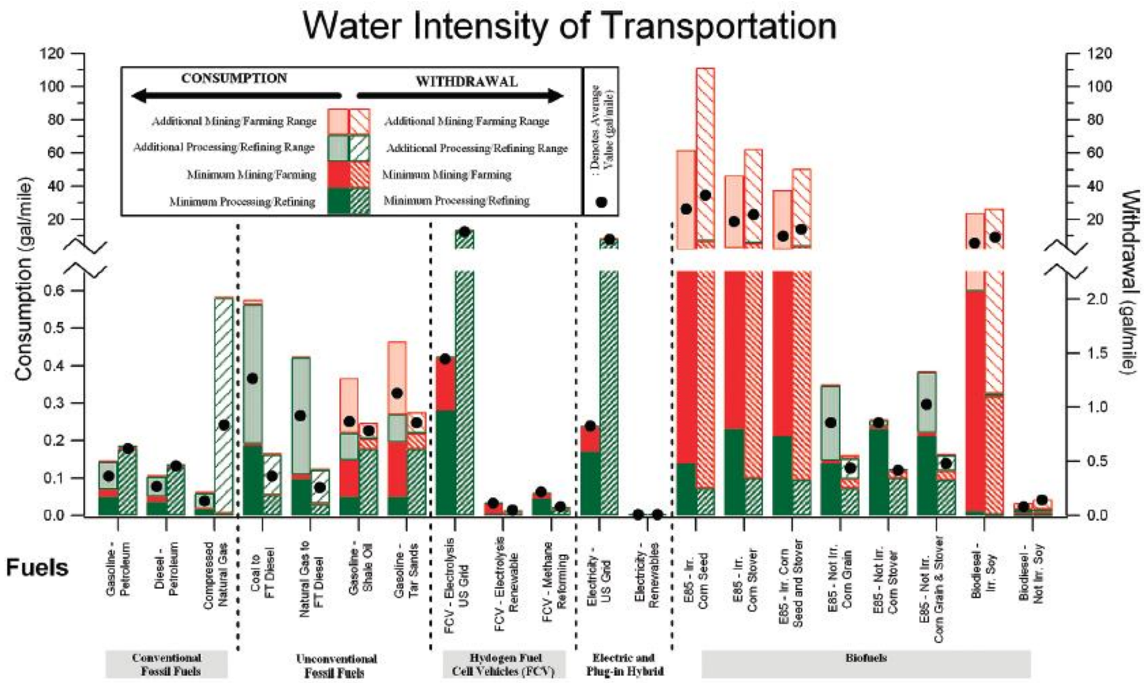


Figure 14. The water intensities of conventional fossil fuels are low compared to many renewable fuels.[45]

3.4 THE WATER INTENSITY OF FUEL IN THE FUTURE WILL LIKELY INCREASE

The US's growing attention to the environmental and economic issues regarding petroleum has affected trends in transportation fuel production in the US in recent years. The following sections detail the implications of the nationwide RFS on the transportation fuel-water nexus in the US.

3.4.1 The Energy Independence and Security Act of 2007

Since the 1970s, the federal government has promoted biofuels as an alternative to petroleum-based fuels; however, it was not until The Energy Policy Act (EPACT) of 2005 that a national RFS was instituted. This RFS required US transportation fuel to contain 4 billion gallons of renewable fuels in 2006 and 7.5 billion gallons in 2012. After rapid growth in ethanol production following this 2005 law, production of corn-starch based ethanol exceeded 10 billion gallons in 2009. EISA 2007 expanded the 2005 RFS by requiring that US transportation fuel contain 9 billion gallons of renewable fuels in 2008 and increases this amount annually to 36 billion gallons in 2022 (

Table 4).

Table 4. US Renewable fuel standard as outlined by the Energy Independence and Security Act of 2007.[46]

Year	Cellulosic biofuels requirement	Biomass-based diesel requirement	Total advanced biofuels requirement	Total renewable fuel requirement
2008	n/a	n/a	n/a	9.00
2009	n/a	0.50	0.60	11.10
2010	0.10	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.50	1.00	2.00	15.20
2013	1.00	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.00	a	5.50	20.50
2016	4.25	a	7.25	22.25
2017	5.50	a	9.00	24.00
2018	7.00	a	11.00	26.00
2019	8.50	a	13.00	28.00
2020	10.50	a	15.00	30.00
2021	13.50	a	18.00	33.00
2022	16.00	a	21.00	36.00
2023+	b	b	b	b

a. To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.
b. To be determined by EPA through a future rulemaking.

No more than 15 billion of the 36 billion gallons of renewable fuels can be provided by first-generation biofuels (Figure 15). Moreover, the 36-billion-gallon total must also include at least 21 billion gallons of advanced biofuels, defined as renewable fuels other than ethanol derived from corn-starch that also meet certain criteria, primarily limits on life cycle greenhouse gas (GHG) emissions. At least 16 billion gallons of the 21-billion-gallon advanced biofuels requirement must be made from cellulosic feedstocks, such as perennial grasses, crop residue, and woody biomass [47]. The combined target of 36 billion gallons per year represents approximately 20% of today's consumption for liquid fuels.

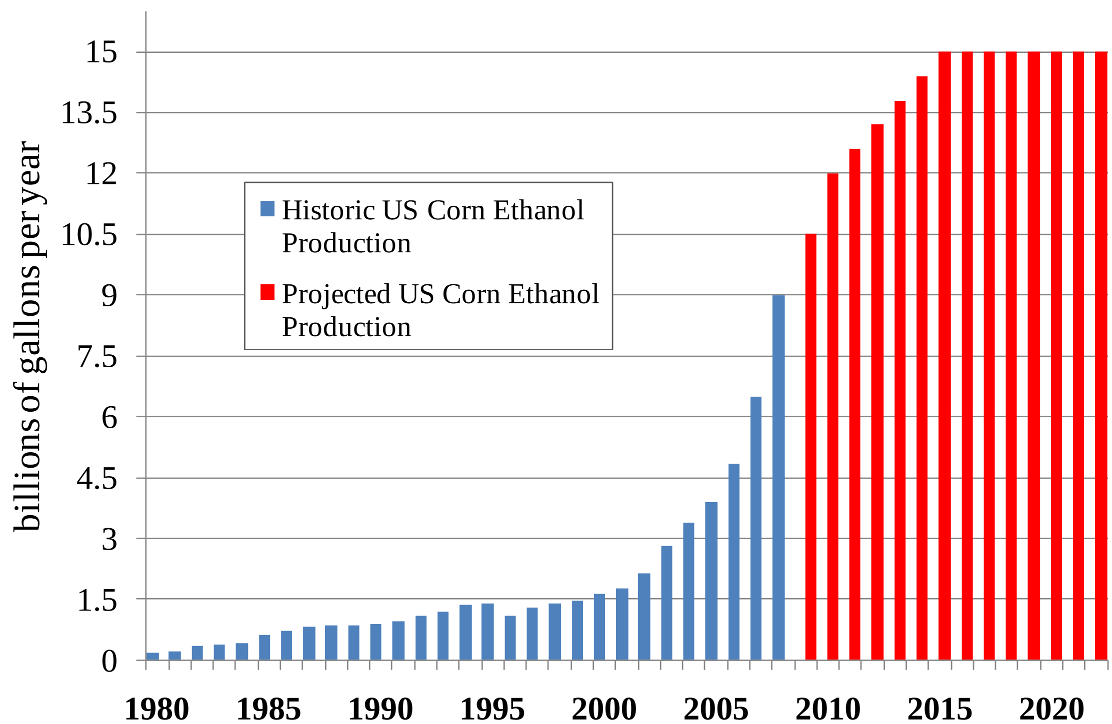


Figure 15. Historic and Projected US Corn-starch Based Ethanol Production [46] [48]

Table 4 details the required volumes for renewable fuels established by EISA 2007 with updates from the second rulemaking for the Renewable Fuels Standard, RFS2. [46] Figure 16. Projections indicate that US biofuels growth will fall short of the 36 billion gallon mandate in 2022, but will exceed it by 2035 [43]. Figure 16 shows the EIA's projected scenario for renewable fuel production in the year 2022. Although total projected renewable fuel production falls short of the volume targets set in EISA 2007, first-generation biofuels production reaches its capped volume.

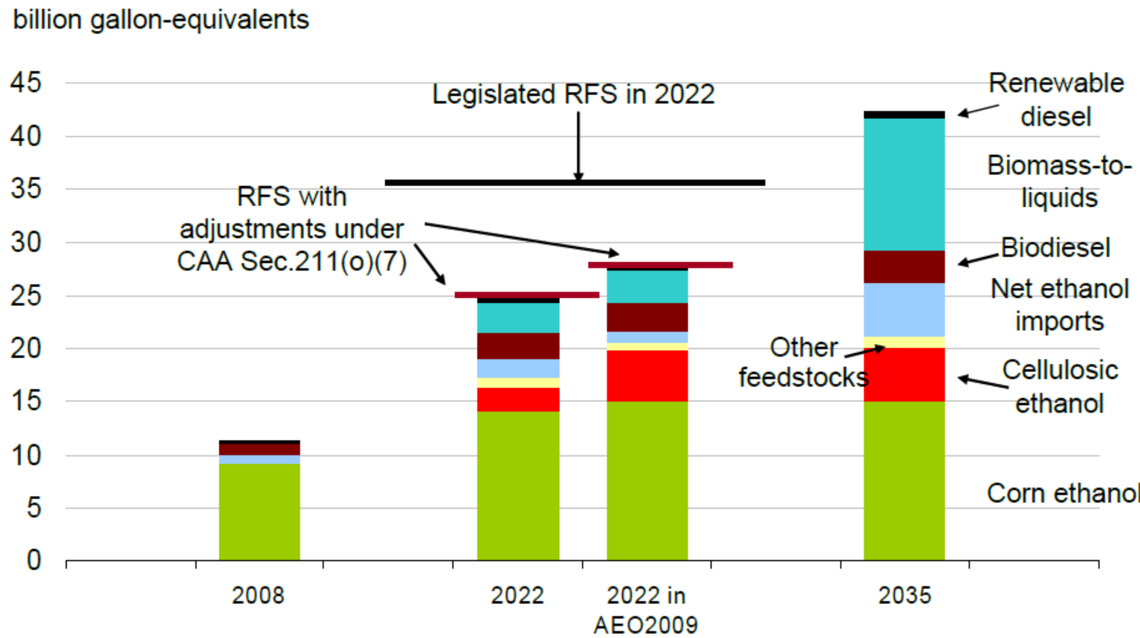
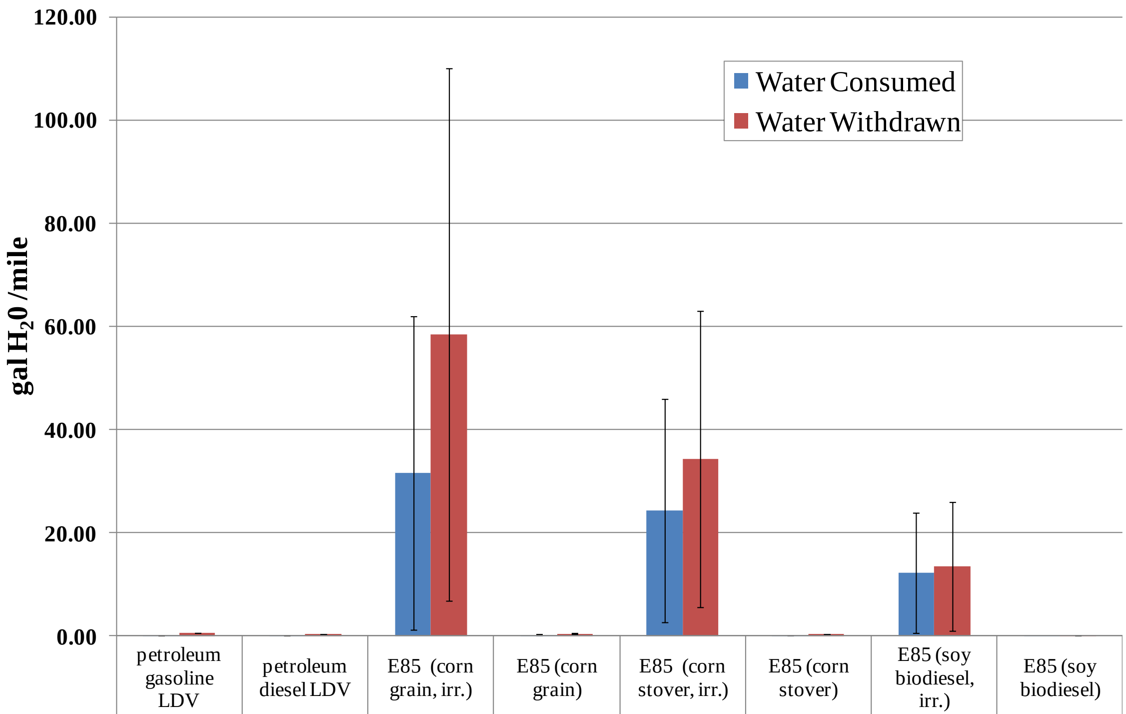


Figure 16. Projections indicate that US biofuels growth will fall short of the 36 billion gallon mandate in 2022, but will exceed it by 2035 [43].

Since the majority of first-generation biofuels are derived from irrigated corn grain, a shift toward these fuel sources will have large water use repercussions in comparison to a petroleum-dominated fuel mix. Figure 17 estimates the water-intensity of first-generation biofuels. These data indicate that fuels derived from irrigated E85 ethanol from corn-grain can consume thousands of times more water than conventional fuel production. The large error bars indicate the large disparity in water use for biofuels derived from agricultural feedstocks. Water use for irrigation varies considerably, both regionally and seasonably.



	petroleum gasoline LDV	petroleum diesel LDV	E85 (corn grain, irr.)	E85 (corn grain)	E85 (corn stover, irr.)	E85 (corn stover)	E85 (soy biodiesel, irr.)	E85 (soy biodiesel)
Water Consumed	0.11	0.08	31.65	0.25	24.30	0.25	12.30	0.02
Water Withdrawn	0.63	0.46	58.45	0.45	34.30	0.41	13.55	0.08

Figure 17. The water-intensity of irrigated first-generation biofuels can be several orders of magnitude greater than conventional transportation.[44]

3.4.2 The Implications of EISA 2007 on Fuel-Water Nexus

Although conventional transportation fuels derived from petroleum have environmental and geopolitical drawbacks, they have relatively low water intensity in comparison to first-generation biofuels, especially when considering those derived from irrigated crops. Meeting the volumes of renewable biofuels mandated by EISA 2007 will likely increase water use substantially in the transportation fuel sector. According to EIA projections, biofuels will indeed have a large role in the transportation fuel supply in the future (Figure 18).

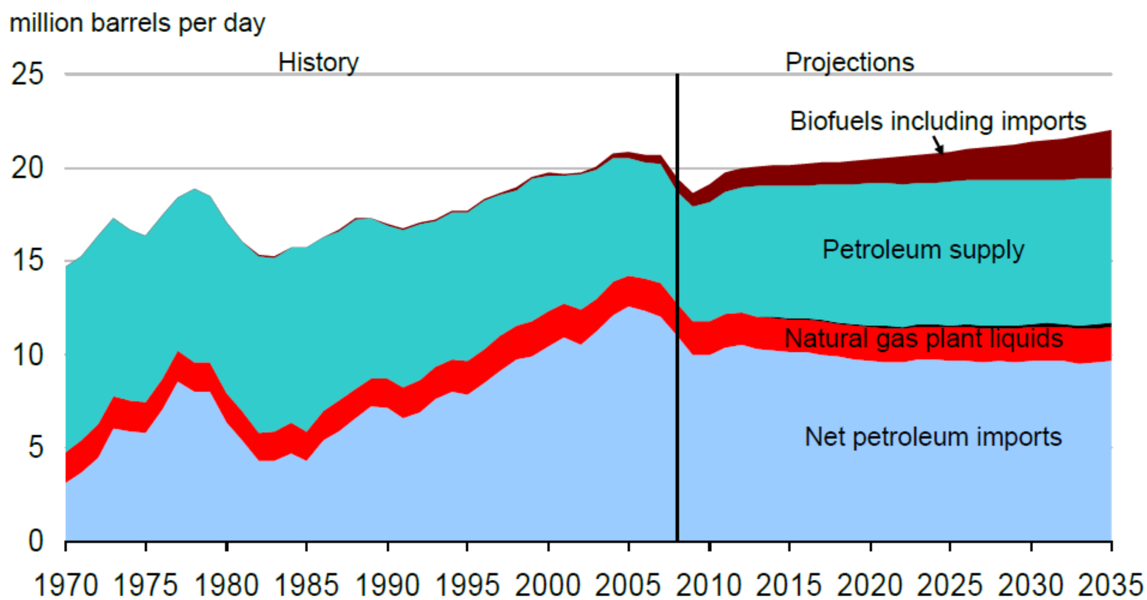


Figure 18. EIA projections indicate that biofuels will supply the majority of liquid fuel growth in the US.[43]

King *et al.* estimated the water implications of projected fuel use scenarios in a 2009 analysis.[45] Figure 19 illustrates the water consumption consequences of shifts in the US's fuel mix according to EIA and NETL's transportation fuel projections. Their analysis concludes that water consumption by petroleum-derived fuels remains a small, relatively constant portion of total water consumption for transportation fuel production. Irrigated fuels, on the other hand, have large water consumption implications. Although the water consumed for irrigated E10 fuels decreases with time, these reductions are less than the increase in water consumption necessary to produce irrigated E85 and irrigated cellulosic ethanol, resulting in a net increase in water use. Both projected scenarios indicate that future water demand in the transportation sector will be several times larger than the current mix.

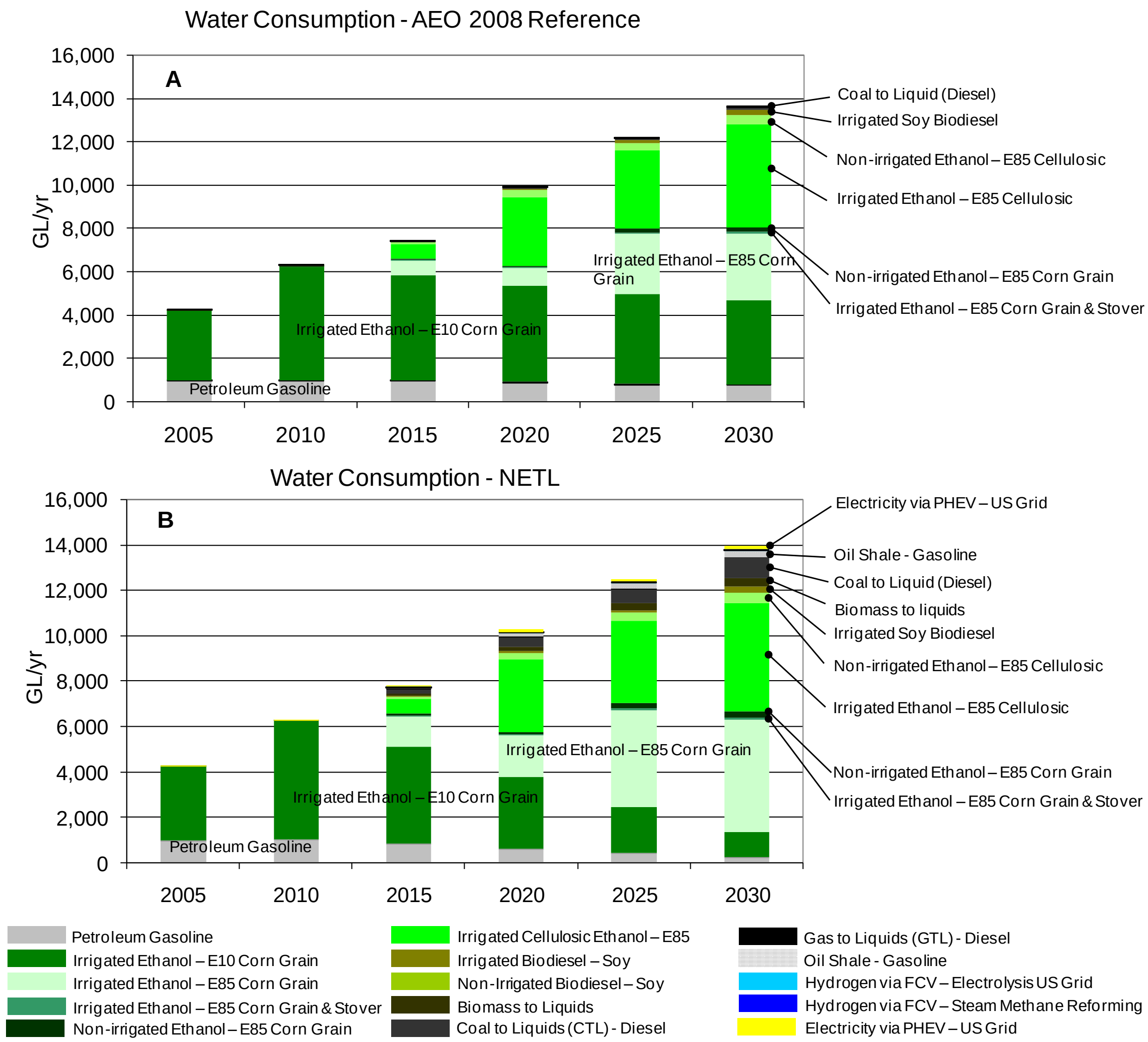


Figure 19. The water consumed for different US fuel scenarios is dominated by the water requirements for irrigated biofuels.[45]

3.5 WATER QUALITY WILL LIKELY SUFFER AS BIOFUELS PRODUCTION INCREASES

The agricultural production of crops (and consequently, the production of feedstocks for biofuels) has water quality consequences due to large quantities of chemical inputs which can be transported from fields to adjacent water bodies. These chemicals can cause excessive nutrient loading (i.e., eutrophication) and in extreme instances, hypoxia. Section 3.5.1 summarizes these water quality effects.

While there are many metrics that may be used to quantify water quality, this work considers nitrate -nitrogen, NO_3-N, since nitrogen-based fertilizer is a predominant agricultural chemical. It is also a major contributor to drinking water contamination when NO_3-N levels exceed levels deemed healthy for human consumption. Section 3.5.4 summarizes some of the potential health effects associated with excessive NO_3-N consumption and the EPA's metric for regulating the contaminant. Section 3.5.5 the challenges that face regulatory bodies in moderating these water quality repercussions.

3.5.1 Water Quality Consequences of Agricultural Activity

Crop production can have detrimental effects on water quality, especially when nutrients from agricultural chemicals percolate into adjacent surface water and groundwater reservoirs. Nutrient loading occurs because corn and other crops are unable to use organic nitrogen from fertilizer directly. Instead crops must use NO_3-N, an inorganic, plant-available form of nitrogen that is released as organic matter decomposes.[49] Corn is particularly inefficient, only using 40-60% of the NO_3-N that is delivered to its roots; the rest is subject to leaching through soil to downstream water bodies by means of infiltrating water.[49] In many instances, nutrient leaching is exacerbated by farmers that apply excessive amounts of fertilizer to their fields since using too little nitrogen fertilizer will lower crop yield, but using too much will have little, if any, detrimental impact to yields.[50] Thus, as agricultural activity increases, so do quantities of agricultural runoff that are laden with nitrogen and phosphorus contaminants that, consequently, degrade surface water and groundwater water bodies downstream.[49, 51-53]

In addition to corn, soybean cropping systems also have significant water quality impacts, but are less severe since soybeans are more efficient in terms of nutrient uptake (so less nutrients are delivered to adjacent water-bodies via run-off and soil erosion). In

2006, Hill, *et al.* compared the efficiency of corn and soybean crops in terms of the ratio of agrichemical input to the net energy that they produce. Soybean biodiesel was found to require only 1.0% of the N, 8.3% of the P, and 13% of the pesticide required by corn-starch ethanol per unit of energy gained.[54]

Hypoxia commonly occurs when excess nutrients are carried soil into nearby water bodies by percolating surface water.[9] This increased nutrient loading in conjunction with sunlight and slow-moving, poorly-mixed water provides ideal conditions for algal blooms, which sink to the bottom of the water and decompose when they die.[9] During decomposition, carbon dioxide is released and oxygen is consumed. As more and more algae growth occurs, the water body becomes increasingly hypoxic. Hypoxia is characterized by water with very low dissolved oxygen concentrations, usually less than 2 mg L^{-1}. [6] At these low concentrations, fish and other aquatic life that require oxygenated water to survive are forced to move to healthier water. The aquatic life that cannot relocate usually suffocates.

One of the regions most affected by nutrient loading from agricultural runoff is the large oxygen deplete or "hypoxic zone" at the base of the Mississippi-Atchafalaya River Basin (MARB). This area, commonly referred to as the "dead-zone" of the Gulf of Mexico, currently covers an area the size of New Jersey and is considered to be the second-largest hypoxic region in the world as of 2007 [55] when it peaked at an area of 20,720 square kilometers.[9] Although hypoxic conditions can be naturally occurring, they are largely exacerbated by nutrient enrichment from anthropogenic sources.[6] A study completed by Alexander *et al.* in 2008 suggest that 70% of the N and 25% of P the delivered to the Gulf of Mexico originates from agricultural sources in the MARB.[56]

The next section describes how these trends might worsen as more crops are grown for biofuels production.

3.5.2 Effect of EISA 2007 on Nitrate in Water

Several studies have been conducted to quantify expected increases in nutrient loading to water bodies downstream of agricultural land due to the projected expansion of biofuels. A few of these studies focus solely on the MARB region; others consider the whole US. Pertinent results are described below.

In 2008, Donner and Kucharik developed a series of six land use scenarios to assess the potential impact of the RFS proposed by EISA 2007 on levels of terrestrial and aquatic nitrogen export by the MARB to the Gulf of Mexico.[57] Their analysis only considered the effects of increasing first-generation biofuels (i.e., corn-starch based ethanol and soybean biodiesel); the effects of projected advanced biofuels expansion were not considered. Two land-use scenarios were created to provide a baseline estimate of current nitrogen loading in the MARB. Data describing actual corn, soybean, winter, and spring wheat plantings by grid cell were averaged over the time period of 2004-2006. Based on this control period, a land-use scenario was created to project 2007 nitrogen export, which modeled the effect of subtle shifts in wheat and soybean crop production to corn crop production.

Three land-use scenarios were consistent with meeting the 15 billion gallon target of first-generation biofuels in 2022, but varied in their feasibility based on current agricultural practices and policy. The authors attempted to account for increased corn-to-ethanol conversion rates over time since efficiencies are likely to increase with time. Although two of these land-use models are relatively realistic, the third is a mitigation scenario intended to evaluate the feasibility of meeting EISA 2007's RFS while simultaneously reducing N export to the Gulf of Mexico to levels consistent with N reduction goals specified in the EPA's Gulf Hypoxia Action Plan (GHAP) of 2008.

The EPA's Gulf Hypoxia Action Plan of 2008 was established to reduce nitrogen and phosphorous loading by 45% in order to shrink the hypoxic region in the Gulf of Mexico to 5,000 square kilometers. Achieving this reduction is unlikely since nitrogen leaching from fertilized corn fields in the Midwest into the Mississippi–Atchafalaya River system is the primary cause of the growth of this hypoxic region each summer. The authors conclude that generating 15 billion gallons of corn-based ethanol by the year 2022 will increase the probability that annual DIN export to the Mississippi River Basin will exceed the level specified by the GHAP to >95%, since large shifts in food production and agricultural management would be necessary.[57] Thus, without large reductions in exports and animal feed (and thus, meat consumption), substantial increases in nitrogen fertilizer efficiency, and widespread restoration of riparian land, this scenario is highly unlikely.[53]

The last land use scenario was developed to model the effects of producing the entirety of the 36 billion gallon RFS from first-generation biofuels. Although this scenario is likely to be unrealistic without modification to the current RFS (since EISA 2007 caps first-generation biofuels production at 15 billion gallons), it is useful in providing an example for the case of aggressive agricultural expansion.

Results indicate that the increase in corn cultivation required to meet the goal of 15 billion gallons of renewable fuels by the year 2022 (EISA 2007) would increase dissolved inorganic nitrogen (DIN) export by the Mississippi and Atchafalaya Rivers to the Mississippi River Basin by 10–18%. Meeting the entire 36 billion gallon RFS with first-generation biofuels would increase DIN export by approximately 34% over the control scenario. However, the authors noted that the results of all these biofuels scenarios are likely to be conservative since the models assume large increases in crop yield without associated increases in nitrogen fertilizer use. The models also assume no loss in productivity for corn grown on marginal land converted to cropland.

Another similar study by Costello, *et al.* compared the occurrence of NO_3^-N loading to the Northern Gulf of Mexico for several different fuel-mix scenarios that are consistent with the RFS specified by EISA 2007. Corn, corn stover, and switchgrass were considered as ethanol feedstocks; soybeans were considered biodiesel feedstock. Results indicate that switching from corn to cellulosic feedstock for ethanol production would effectively decrease NO_3-N loading to the Northern Gulf of Mexico by 20%; however, this reduction is still not sufficient to decrease the hypoxic zone to the EPA's GHAP target[3] of 5000 km^2. The authors note that the EPA's GHAP N reduction target cannot be met under current conditions without an aggressive nutrient management plan even in the absence of increased biofuels production.

In 2008, an analysis by Simpson, *et al.* estimated the water quality impacts of increasing corn acreage in the US to 95.6 million acres in order to meet future ethanol expansion. While the aforementioned analyses ([57, 58]) estimated increases in N loading in the isolated MARB region, this analysis projects the increases in N loading nationally due to increased biofuels production. Unlike Donner and Kucharik's analysis, this projected increase in corn acreage was based on a paper by Elobeid, *et al.* in 2006 [59], which estimated future ethanol expansion based on the rising price of corn since the 2007 RFS was not yet in effect. Consequently, their analysis was based on an ethanol production rate of 31.5 billion gallons a year, nearly double the cap placed on first-generation biofuels in EISA 2007. However, despite the increased production volume, the land-use scenario (in terms of area) defined in this study, which assumes 95.6 million acres of corn, is relatively consistent with the two 15 billion gallon land-use scenarios described above by Donner and Kucharik which assumed total corn acreage to approximately 95-105 million acres. Results indicate that the associated increase in corn acreage assumed in this study will likely increase N and P loss to water nationally by 37% (117 million kg) and 25% (9 million kg), respectively. Even with recommended fertilizer and land conservation measures, expanded corn cultivation will likely be a major source of N loss (8–16 kg acre^{-1} yr^{-1}) to water.

In 2009, Han, *et al.* estimated the additional river export of N to 18 Lake Michigan Basin Watersheds based on the USDA's 2017 projections for expanded corn-based ethanol production, which include a 54% and 41% increase in corn and soybean production and a 60%, 54%, 64% and 10% decrease in sorghum, barley, oats, and wheat production, respectively, from the baseline year. Results indicate that expected increases in biofuels production might increase riverine N export to the Lake Michigan Basin by 21-24% based on projected increases in fertilizer use. Increased livestock populations were assumed to increase due to the additional production of distiller's grain, which will also have an effect on nutrient export to the basin.

3.5.3 Indirect Water Quality Effects

Aside from runoff from agricultural sources, other indirect effects contribute to reductions in downstream water quality. Simpson, *et al.* noted the effects of replacing corn and soybean meal with the ethanol byproduct, dried distiller's grain (DDS), for animal feed. Animals that are fed DDS have increased levels of P and N in their manure, which can exacerbate nutrient loading in adjacent waterways due by means of runoff. As ethanol production increases, using DDS to feed animals is becoming increasingly popular. The EPA's updated Renewable Fuel Standard (RFS2) released on February 3, 2010 suggests a target of replacing 1.0 lb of distiller's grain for every 1.196 lbs of corn/soybean meal currently used in animal feed by 2015.[60]

3.5.4 The EPA's Safe Drinking Water Standard

Nitrate contamination in water sources used for drinking water also raises health concerns, in addition to environmental concerns. In 1974, the EPA passed the Safe Drinking Water Act (SDWA) in to protect drinking water quality in the US. Each regulated contaminant is assigned a Maximum Contaminant Level (MCL) which indicates the highest concentration that is allowable in the public drinking water supply.[61] MCL is typically measured in units of milligrams of contaminant per liter water. The MCL is established based on a second EPA metric called the Maximum Contaminant Level Goal (MCLG) that indicates the threshold, below which there is no known or expected health risk. Occasionally the enforceable MCL for a particular contaminant is higher than the MCLG when economic or technical issues limit the degree to which it can be reduced in a water supply. MCLs are only regulated in public drinking water supplies or entities supplying water to more than 25 people.[62]

The EPA originally adopted the MCL of 10 mg L^{-1} of NO_3-N for drinking water to protect infants from the acute condition, methemoglobinemia, more commonly known as "blue baby syndrome."[62] This potentially fatal condition occurs when infants cannot adequately convert nitrate to nitrite, compromising the oxygen carrying capacity of their blood.[62] The formation of N-nitroso compounds (NOC), as a result of nitrate digestion, has also been linked to the formation of cancerous tumors in the esophagus, stomach, colon, bladder, lymphatic, and hematopoietic system of animals; this causal link has not yet been confirmed in humans.[62]

The MCL for NO_3-N is one pertinent metric for assessing the water quality impacts of biofuels, since nitrogen fertilizer is a primary input in corn production. The EPA's MCL for NO_3-N (established in 1974) is 10 mg L^{-1}. In this case, the MCL is equal to the MCGL, indicating that the EPA's enforceable standard to consistent with levels deemed safe for human ingestion. However, the results of several clinical studies suggest that long-time exposure to this level of NO_3-N may have greater health repercussions than previously realized when the standard was adopted.[62]

3.5.5 Water Quality Regulation Challenges

All forms of liquid fuel production have water quality impacts, but the severity of those impacts varies by fuel and lifecycle production step. While the water quality consequences regarding the oil, natural gas, coal, and uranium industries are relatively well understood, those associated with non-traditional forms of transportation fuel are lesser known.

Regulations to protect water resources during fossil fuel extraction are well established. The Clean Water Act (CWA) of 1977, administered by the US EPA, regulates the water quality impacts of "all field activities or operations associated with exploration, production, processing, or treatment operations, or transmission facilities" associated with the oil and natural gas industries.[63] Its predecessor, the Federal Water Pollution Control Act (FWPCA) of 1972, was the first federal legislation to address the surface water quality concerns associated with fuel production [64].

One major distinction that exists between monitoring the pollution from traditional fossil fuel production versus biofuels production from agricultural feedstocks is that the contaminants discharged as a result of fossil fuel production are considered "point source" discharges and are therefore regulated under the National Pollutant Discharge Elimination System (NPDES) of the CWA. Under this system, any entity that discharges pollutants (excluding individual homes) into surface water must obtain a NPDES permit. This permit effectively places a limit on the amount of discharge that that the polluting entity can release to a US water body.[65] Since coal and uranium mining operations, and oil and natural gas operations fall within the CWA's definition of point sources, the water quality impacts associated with traditional fossil fuel sources are relatively straight-forward to regulate.

Quantifying the water quality impacts of biofuels presents new challenges since most agricultural producers fall under the classification of “nonpoint source” polluters [65]. Nonpoint sources of pollution are defined by the US EPA as pollution that comes “from many diffuse sources” [65]. Unlike point source pollution, which enters surface water sources by direct conveyance or manmade ditches, nonpoint source pollutants are transferred into water bodies by means of rainfall or snowmelt that flow over and through the ground as runoff, collecting manmade pollutants as it moves. Since pollutants transferred to water bodies via contaminated runoff or percolation through the ground cannot be attributed to discrete sources, this type of water pollution is much more difficult to regulate. Consequently, even though the relationship between nutrient loading to surface and groundwater and upstream agricultural activity is widely accepted, pollution from agricultural sources is largely unregulated. Exceptions include discharge from concentrated animal feeding operations (CAFOs), concentrated aquatic animal production facilities, and forestry, which are treated as point source polluters[66].

3.6 ADVANCED BIOFUELS PRESENT POTENTIAL FUEL-WATER NEXUS OPPORTUNITIES

Although irrigated biofuels and some other forms of advanced fuels have large water quantity and quality trade-offs, several types of advanced fuels might actually placate the transportation fuel-water nexus. The water implications of cellulosic ethanol from perennial grasses and algae are discussed briefly in this section.

3.6.1 Perennial Grasses Derived Biofuels

Biofuels, namely cellulosic fuel-stocks from perennials (e.g., switchgrass and woody materials) have the potential to produce ethanol with less water quality impacts than row crops due to the reduced need for agricultural chemical inputs and reduced soil erosion.[49] In addition to high yields, high geographic distribution, resistance to drought, and high carbon sequestration, perennials provide important services in terms of soil management and nutrient uptake which in turn have many positive water quality attributes.[49] Perennial grasses improve soil structure, soil porosity, and increase soil water retention, all of which reduce soil erosion to water bodies adjacent to water. Accordingly, perennial crops such as switchgrass can be used as a buffer between agricultural land and surface water to increase soil retention and resistance to flooding; percolation of nutrients to groundwater is also reduced with increased soil porosity. Furthermore, unlike row crops that require heavy inputs of fertilizers and pesticides, switchgrass typically only requires herbicide application every growth cycle, which is usually at least 10 years. Switchgrass also requires only about half of the nitrogen of corn production.[67] The net effect of reduced nutrient transport to groundwater and surface water sources and high nutrient uptake efficiency is considerable in terms of water quality. However, to date, technological and economical limitations make it uneconomical to produce these fuels at a large scale.[49]

The role of perennial grasses as a buffer is well known practice. In 1985 the US instituted the Conservation Reserve Program (CRP) incentivizes farmers to retire land adjacent to water bodies from row crop production in response to unsustainable soil erosion rates. This program has effectively retired approximately 32 million acres of land, much of which has been covered with perennial grasses to buffer against soil loss to water.[67] However, future expansions of row-cropping system may incentivize farmers to convert their CRP land back to corn cultivation land, rather than renew their CRP contracts, which might have repercussions in terms of soil erosion and runoff.[68]

3.6.2 Algal Biofuels

Biofuels produced from algae (which fall into the category of "advanced" biofuels) present the opportunity to utilize degraded water and wastewater streams since microalgae tend to grow in nutrient rich, oxygen deplete waters; thus, they provide the potential for using undesirable waste streams from sources such as wastewater from treatment plants or flue gas from power plants.[69] Using brackish, saline, or wastewater sources, however, can increase the risk of contamination in sensitive strains of algae, especially due to the variability in nutrient concentrations.[69] However, careful strain selection in conjunction with advances in breeding, engineering, and strain adaptation will likely increase the potential for cultivating algae in water of variable quality.[69] Although producing biodiesel from algal biomass has the potential for reducing some of the environmental and water quality impacts associated with other biofuels' feedstocks, this technology is still immature and is not yet economical for large-scale production.

Chapter 4: The Energy-Water Treatment Nexus

4.1 Introduction to the Energy-Water Treatment Nexus

The final piece of the energy-water nexus is the energy that is used to move and treat water from its native reservoir to the end-user. Moving and treating water and wastewater currently represents 4% of the US's total electricity use.[70] As water treatment standards tighten and/or incoming water quality drops, the energy intensity of treating water rises.

4.2 The Energy Implications of Water Treatment

The energy intensity of water treatment typically correlates to source water quality. Often, several treatment processes are used in combination to achieve the intended quality for end-use; a given series of treatments are selected based on contaminant size. Figure 20 lists examples of water treatment technologies, sorted by basic contaminant separation technique.

<table>
<tr><th>Clarification</th><th>Filtration</th><th colspan="2">Disinfection</th></tr>
<tr><td>Coagulation
Flocculation
Sedimentation
Flotation</td><td>Sand filter
GAC filter
Dual Filter</td><td colspan="2">Ozonation
UV radiation
Oxidation</td></tr>
<tr><th>Membrane treatments</th><th>Chemical Treatments</th><th>Thermal distillation</th><th>Other Treatments</th></tr>
<tr><td>Prefiltration
Microfiltration
Ultrafiltration
Nanofiltration
Reverse Osmosis</td><td>PAC injection
Softening
Remineralization
Neutralization</td><td>Multi-flash Distillation
Multi-effect Distillation
Mechanical Vapor Compression</td><td>Electrodialysis
Biological
Ion Exchange</td></tr>
</table>

Figure 20. Multiple water treatment processes are selected based on raw source water quality.

Table 5 illustrates the energy costs of several types of water treatment technologies, both conventional treatment methods and advanced technologies effective in the removal of smaller contaminants such as NO_3-N. Energy intensive methods of desalination for treating saltwater are already being used by states such as California and Texas as their surface and groundwater sources become increasingly rare.[71] Since the energy consumption of these technologies is highly variable depending on initial NO_3-N concentration, salinity, voltage application, pH, and other water quality parameters, general ranges of typical energy consumption are provided.[72] Gravity-based treatment with chlorine disinfection is included for comparison since this is the conventional treatment method for surface water. The nationwide average energy consumption during surface water treatment is also shown.

Table 5. Energy consumption of different water treatment technologies varies widely with level of treatment.[13, 70, 73]

Treatment Process	kWh per million gallons treated
Average groundwater treatment	9
Gravity-based with chlorine disinfection	78
Average surface water treatment	211
Electrodialysis/Electrodialysis Reversal	2,000-7,400
Reverse Osmosis (Brackish)	3,900-9,700
Multi- Effect Distillation	7,670-15,340
Reverse Osmosis (Sea)	9,700-16,500

According to EPRI, electricity consumption by public water systems in the year 2000 was estimated to be 30 billion kWh. This annual use is expected to reach approximately 36 and 46 billion kWh by 2020 and 2050, respectively. Electricity consumption for wastewater treatment by publicly owned treatment works (POTWs) was estimated to be 21 billion kWh.[70] Table 6 lists the average energy intensity of four commonly used wastewater treatment technologies. It is important to note that even the most energy-intensive treatment processes consume less energy than desalination methods per quantity of treated water.

Table 6. Energy Intensity of Waste Water Treatment Processes Vary According to Water Quality[70]

Treatment Type	Energy [kWh/Mgal]
Trickling Filter	955
Activated Sludge	1,300
Advanced Treatment w/o Nitrification	1,500
Advanced Treatment w/ Nitrification	1,900

4.3 AS WATER QUALITY DECREASES, ENERGY FOR WATER TREATMENT INCREASES

When standard water treatment processes are not effective in removing regulated contaminants to acceptable levels, more energy intensive treatment processes are necessary. Blending and long-haul pumping of uncontaminated water are also options, but typically have large energy implications as well.

4.3.1 Standard Water Treatment Processes

Water is usually pretreated by removing large debris with a filter, then disinfected to remove any disease carrying bacteria or other organisms that may foul equipment in subsequent steps. Typically, a clarification step is used next to agglomerate smaller debris so that it can be removed by sedimentation or filtration. A second disinfection method is usually needed to kill and inhibit the growth of harmful organisms. Standard clarification, filtration, and disinfection methods have relatively low energy requirements in comparison to treatment methods that are used to remove very small particles and soluble molecules.

4.3.2 Advanced Water Treatment Processes

Treatment processes that are able to remove contaminants that are smaller than water molecules themselves require much more energy than simple filtration methods because they must effectively reverse the process of dilution to separate a contaminant back into its concentrated form.[74] Methods such as nanofiltration and reverse osmosis require large pressure gradients to separate water molecules from very small contaminants, while thermal distillation methods require large amounts of heat to vaporize water in order to recover volatile compounds from gaseous water (that is subsequently condensed); these processes require large energy inputs.

NO_3-N is a common contaminant in the US water supply and the focus in this chapter to provide adequate background content for the analysis completed in Chapter 5. Conventional water treatment methods such as clarification, filtration, and disinfection have no effect in removing NO_3-N from drinking water since nitrate ions are very small.[75] Effective NO_3-N removal processes include distillation, reverse osmosis, electrodialysis, and ion exchange.[74] (Biological dinitrification is also used for NO_3-N removal but has not been approved for potable water treatment in the US.[76]) Since these processes are energy intensive, they are used only when source water exceeds drinking water standards.[74]

Ion exchange processes commonly use resins to reduce nitrate by exchanging a common ion such as sulfate, chloride, bisulfate, bicarbonate, or carbonate for the nitrate ion. [77] Ion exchange membranes might also be used, which utilize electricity to exchange ions in the membrane in order to reduce NO_3-N to nitrogen gas. [13] Electrodialysis is an effective ion exchange membrane process for removing NO_3-N from water and consumes approximately 3,000 kWh per million gallons of water treated. [13]

Reverse osmosis separates dissolved solutes by pushing water through a semi-permeable membrane by means of a high-pressure gradient. [74] Since reverse osmosis is very expensive, it is typically used for NO_3-N removal in fresh water when there are other water quality issues such as high concentrations of other dissolved solids. [74] However, in recent years it has become more common, as the incidence of NO_3-N contamination has increased. The energy consumption of reverse osmosis varies a great deal depending on the quality of source water. Brackish water typically requires 3,900-9,700 kWh per million gallons to reduce nitrogen to an acceptable concentration [13], while the desalination of saltwater can require as much as 37,800 kWh per million gallons using RO (Note: Table 5 indicates average treatment cost). [74]

Reverse osmosis, unlike some other advanced treatment processes, is already common in large-scale treatment plants. A pressurized feed stream containing a solute is forced through a semi-permeable membrane, which must effectively exceed the osmotic pressure of the feed stream.[78] The water permeates through the membrane, leaving the solutes. Obtaining these pressures typically requires high energy inputs from a pump.

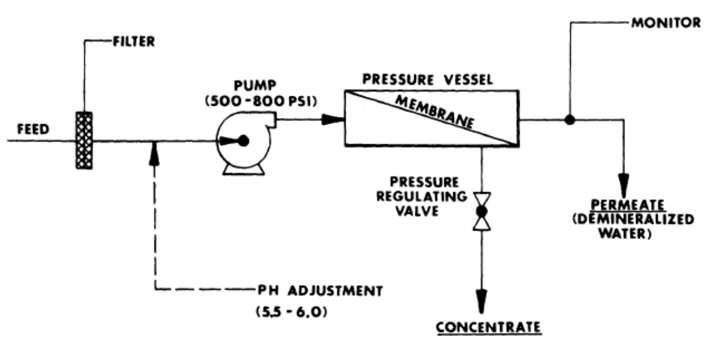


Figure 21. General Schematic of Reverse Osmosis Water Treatment System[79]

Several reverse osmosis module designs exist; the most common are the hollow fiber, spiral wound, and tubular configurations.[78] In the hollow fiber module, feed water enters the fiber unit, which is housed by a pressure vessel, and moves outward radially through the individual fiber layers, separating the feed water into potable product water and a concentrated waste stream. Figure 21 shows a more general schematic of a reverse osmosis treatment system. Single membrane units are typically in parallel as shown in Figure 22.

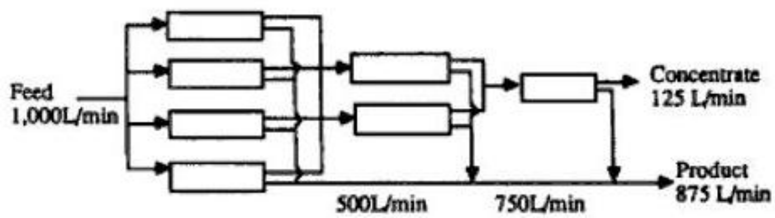


Figure 22. Three-stage cascade for the reverse osmosis of brackish water. [78]

4.3.3 Non-Treatment Options

Non-treatment methods can be used if NO_3-N contamination is localized to a specific source and the surrounding supplies are not contaminated. Non-treatment methods include blending contaminated water with low nitrate water or raw source substitution.[80]

Blending contaminated water with uncontaminated water is a convenient way to dilute water sources with high concentrations of NO_3-N, but is not always an option since contamination often occurs in multiple aquifers in a given region. When blending is not economical, raw source substitution is also an option. Raw source substitution involves retiring the contaminated source of water completely and pumping in healthier sources of water as replacement.[80] This method, however, may require significant amounts of energy to pump water across further distances unless contamination is localized to a very small area, which is not typically the case, especially in cases of contamination due to agricultural run-off.

Pumping water is typically the most energy-intensive aspect of the water treatment process, and therefore must be considered when selecting whether or not non-treatment methods are economical. A typical groundwater treatment plant consumes 30% more energy than a surface water treatment plant per unit water due to the increased energy cost of pumping water out of the ground.[42] On average, over 99% of the energy consumed to transport, treat, and deliver groundwater occurs during well-pumping and booster pumping to and from the treatment facility.[42]

Table 7 display the amount of energy consumed to pump water out of the ground (for groundwater sources) and to the water treatment facility over various depths and distances, respectively.

Table 7. Energy consumption for source water collection and treatment varies with different water sources. Long distance and deep aquifer pumping require more energy than other local water sources.

Description[1]	Energy Consumption (kWh per million gallons)	Source
GW Well-Pumping (from 120 ft)	540	[81]
GW Well-Pumping (Average)	602	[21]
GW Well-Pumping (from 400 ft)	2000	[81]
GW Pumping to Treatment (Average)	1213	[21]
SW Pumping to Treatment (Average)	1205	[21]
Pumping from Colorado River to Treatment in Southern CA	6134	[29]
Pumping from SJ Valley to Treatment in Southern CA	6966	[29]

[1]GW = groundwater, SW = surface water, SJ = San Joaquin

When alternate sources of water are not available close to a treatment plant, water must be pumped over great distances. In California, water is pumped from the San Joaquin Valley in Northern California to Southern California, consuming nearly 7,000 kWh per million gallons of water pumped. [71] Other parts of the state receive water from the

Colorado River, which requires about 6,100 kWh per million gallons to be transported to where it is needed. [71]

Transistioning dependence from shallow groundwater sources to deeper aquifers will have energy repurcussions in the water treatment sector since the power required to pump groundwater varies according the aquifer's depth. For example, 540 kWh per million gallons is required to pump groundwater from a depth of 120 feet, whereas it requires 2000 kWh per million gallons to pump water from a depth of 400 feet, an increase of 270%. [82] As more and more shallow wells are retired, the energy needed to pump groundwater from increased depths and greater distances may be substantial.[82]

Chapter 5: The Unintended Energy Impacts of Increased Nitrate Contamination from Biofuels Production

5.1 The Biofuels-Water Quality-Energy Nexus

The projected water quality effects of increasing first-generation biofuels production are well-cited in terms of soil degradation/erosion, losses in aquatic biodiversity, increases in eutrophication, and increases in hypoxic zones. However, secondary consequences might transpire if nutrient concentrations in drinking water sources rise to levels above the EPA's MCL. The analysis in this chapter examines the potential energy impacts that could occur if the total volume and energy intensity of water treatment are increased to meet the EPA's drinking water quality standard for NO_3-N. Currently, the majority of the nation's public surface and groundwater sources have NO_3-N concentrations that fall below the EPA's MCL (10 mg L^{-1} NO_3-N) and, therefore, do not require energy-intensive water treatment processes to remove the contaminant.[83] Depending on the severity of corn ethanol expansion and the ways by which agricultural practices are managed, more water sources may require energy intensive NO_3-N removal processes in the future to meet safety regulations.

5.2 Significance of Analysis

The purpose of this analysis is to provide a snapshot of the current contamination level of the public water supply in the US in regards to NO_3-N and then to calculate the amount of energy that would be necessary to treat the current volume of contaminated water with advanced treatment processes to meet the acceptable drinking water standard of 10 mg L^{-1} NO_3-N. It compares this amount of energy to the amount of energy that is necessary to treat the same volume of water with average surface water treatment. The percent increase from the energy consumed in the baseline treatment scenario to the energy consumed in the advanced treatment scenario was calculated. Based on this estimate, the potential energy impacts in the water treatment sector due to the expansion of corn-starch based ethanol are estimated based on projected NO_3-N increases in surface and groundwater sources.

5.3 METHODOLOGY

First, the volume of contaminated water distributed by public drinking water suppliers in the US was estimated based on data from the Environmental Working Group's *National Tap Water Quality Database,* which quantifies the number of people who were supplied water that exceeded acceptable levels of NO_3-N between the years of 1998 and 2003.[84] This analysis assumes that every public water supplier that reported at least one instance of NO_3-N contamination over the EPA's MCL in this 5 year period would use an advanced treatment process to remove NO_3-N contamination in the future. This assumption was made on the basis that public water suppliers only report an average of 1.0 NO_3-N tests per year[84], so without more frequent testing, one violation is considered to be indicative that the water supply may be of public health concern in the future.

Based on these data, the total volume of contaminated water distributed to this population was calculated assuming an average daily water usage of 140 gallons per person per day.[85] This water use represents all household water uses, not only water for drinking water purposes. This daily per capita water usage is a conservative estimate based on water conservation best management practices.[85]

Equation 1 was used to calculate the total volume of contaminated water distributed to public supply users:

$$\boldsymbol{V_{tot} = p \times c_{tot}} \qquad \textbf{(Equation 1)}$$

where V_{tot} is contaminated water volume supplied by public water systems between 1998 and 2003 to number of people, p; c_{tot} is per capita water consumption in gallons per year calculated by:

$$\boldsymbol{c_{tot} = 365\frac{days}{year}\times\ 140\frac{gallons}{capita - day} = 634\frac{gallons}{capita - year}} \qquad (\textbf{Equation 2})$$

A second scenario was included to consider the volume of water used by this population exclusively for drinking purposes. Per capita drinking water consumption is assumed to be 12.5 gallons per day according to American Water Works Association Research Foundation data.[86] This calculation provides reference for a scenario in which personal water treatment systems are used to treat contaminated drinking water at the home, rather than at public facilities, so that water for non-drinking uses is not treated with costly treatment processes.

Equation 3 was used to calculate the total volume of contaminated drinking water public supply users between 1998 and 2003:

$$\boldsymbol{V_{dr} = p \times c_{dr}} \qquad (\textbf{Equation 3})$$

where V_{dr} is total volume of drinking water supplied to population, p, and c_{dr} is per capita water drinking water consumption in gallons per capita per year summarized in Equation 4..

$$\boldsymbol{c_{dr} = 365\frac{days}{year}\times\ 12.5\frac{gallons}{capita - day} = 57\frac{gallons}{capita - year}} \qquad (\textbf{Equation 4})$$

Point-of-entry or point-of-use systems are types of personal water treatment systems that can be installed where water enters a household or in specific locations where water is used, respectively. Small-scale systems effective in the removal of NO_3-N, including reverse osmosis, ion-exchange, and distillation are available, but operate at lower efficiencies in comparison to large-scale treatment facilities. Thus, the first scenario examines relatively efficient large-scale treatment of vast volumes of water, while the second scenario examines relatively inefficient small-scale treatments of smaller volumes of water.

The baseline energy consumption was calculated for each of the two scenarios assuming average energy consumption per unit volume of surface treatment in the US as reported by the Electric Power Research Institute.[70]

Equation 5 was used to calculate the energy required to treat contaminated volume, V_{tot}, with standard treatment:

$$\boldsymbol{E_{st} = V_{tot} \times e_{st}} \quad \textbf{(Equation 5)}$$

where E_{st} in electricity consumption in kWh and e_{st} is unit energy consumption of standard water treatment.

This baseline estimate represents the annual amount of energy that would be required to treat water delivered by public water suppliers that reported NO_3-N concentrations exceeding the acceptable drinking water standard between the years of 1998 and 2003 without existing advanced NO_3-N removal processes. This calculation was repeated for the same volume of water, assuming the average energy consumption per unit volume of water for reverse osmosis treatment, a process that is effective in the removal of NO_3-N.

Equation 6 was used to calculate the energy required to treat contaminated volume, V_{tot}, with reverse osmosis water treatment:

$$\boldsymbol{E_{ro} = V \times e_{ro}} \quad \textbf{(Equation 6)}$$

where E_{ro} in electricity consumption in kWh and e_{ro} is unit energy consumption of reverse osmosis water treatment.

Subsequently, the percent increase in energy consumption from the baseline was calculated. It is important to note that since efficiencies vary amongst different types and brands of personal treatment systems, energy consumption estimates for the second scenario are based on large-scale treatment energy consumption values reported in Table 5. Therefore, the results are likely an underestimate of actual energy consumption for home water treatment.

Although several water treatment options exist for the removal of NO_3-N, this analysis only considers reverse osmosis since it is currently the most economical, energy-efficient, and feasible option at the commercial scale. Ion-exchange methods are not always effective for NO_3-N removal, especially in hard water where other cations may reduce the effectiveness of ion-exchange resins.[87] Disposal of highly concentrated waste is also difficult. Electrodialysis and distillation are very effective for NO_3-N removal, but are not economical at the commercial scale due to energy consumption and treatment efficiency.

The following subsections provide a qualitative assessment of the nation's surface water and groundwater sources, followed by a description of potential treatment processes to remove NO_3-N from contaminated water.

5.3.1 Current State of US Surface Water Quality

Surface water sources supply 61% of the population with water.[70] In 2006, the US Geological Survey (USGS) released a report establishing baseline water quality conditions in 51 of the nation's major river basins and aquifer systems.[88] The report was the USGS's preliminary attempt to collect consistent and comprehensive national water quality data and, as a result, was limited to data collected at 300 sites that were largely inconsistent in terms of temporal and spatial distribution.[88] Results indicated that watersheds downstream of agricultural land-use typically had the highest NO_3-N concentrations because of high nitrogen inputs from fertilizers and manure.[88] The Midwest was particularly susceptible to high NO_3-N loading because of the prevalence of subsurface drains that facilitate NO_3-N's movement through the soil.[88] This movement is accelerated by heavy use of irrigation water that carries nitrogen from the soil into surface water via runoff and groundwater via percolation.[88]

In total, 14 of 115 sites monitored in the area had NO_3-N levels upwards of 10 mg L^{-1} NO_3-N.[88] However, these are not typically streams used for public drinking water supply. Only 3% of streams used for public supply were found to exceed drinking water standards for NO_3-N.[88] The Heinz Center found that the average NO_3-N level recorded in 372 stationary sites was 2.24 mg L^{-1} NO_3-N, with 10 of these sites exceeding 10 mg L^{-1} NO_3-N.[89] The low occurrence of contamination is partly due to the fact that the public drinking water supply typically originates in large watersheds that are not likely to have high NO_3-N contamination since higher volumes of water tend to dilute contaminants.

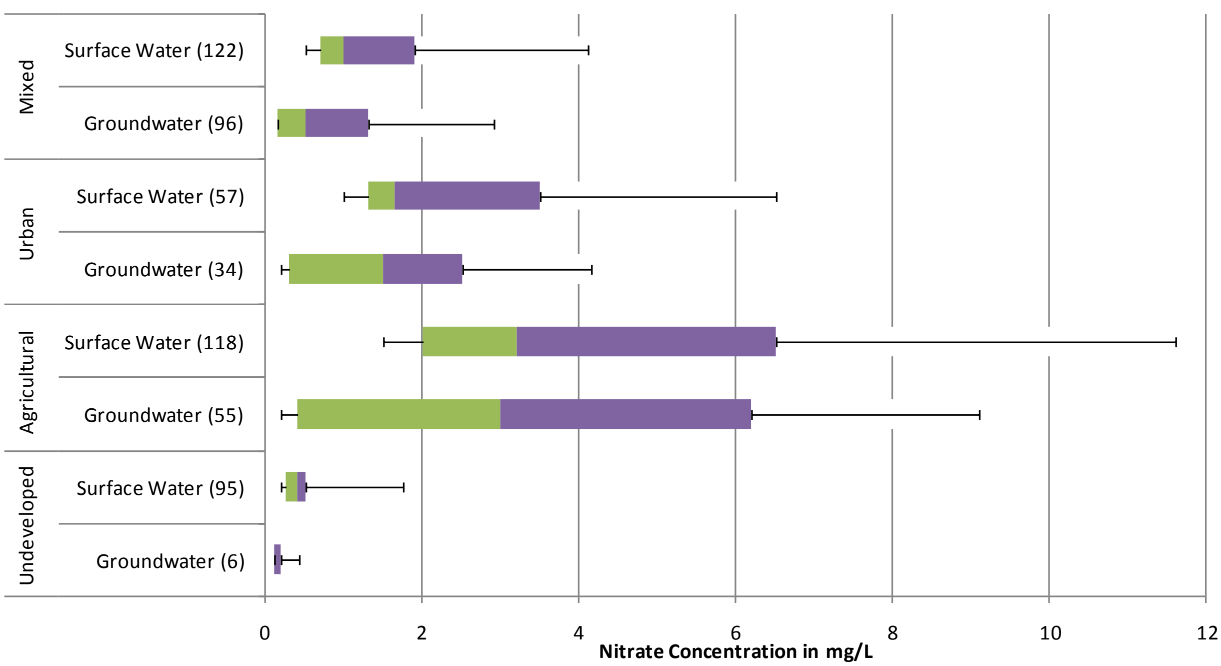


Figure 23. Interquartile range of total nitrogen in streams and NO_3-N in groundwater for different land-uses[1].[62]

[1] Number in parentheses are the number of stream sampling stations and groundwater networks (group of wells in an aquifer). Upper and lower bounds of bar represent the 90th and 10th percentile, respectively.

Although various types of non-point sources contribute to water pollution, nutrient leaching due to high application rates of nitrogen fertilizers in agricultural areas is considered the primary cause of the nation's impaired lakes and estuaries and the second most prevalent cause of impairment in rivers.[42] Other sources, such as discharge from wastewater treatment plants and run-off from animal manure, fertilized lawns, and golf courses, as well as the atmospheric disposition of nitrogen, are also smaller contributors to eutrophication.[55]

5.3.2 Current State of US Groundwater Quality

Groundwater aquifers supply 39% of the nation's population with drinking water and account for 98% of the nation's total domestic withdrawals.[70] While contamination of surface water sources is very small, data measurements indicate that NO_3-N contamination in groundwater sources is widespread. Recent studies have attributed increasing NO_3-N concentrations in groundwater in the Great Plains and Midwest to excess NO_3-N leaching from agricultural areas.[75] Aquifer contamination often occurs when excess NO_3-N from organic nitrogen fertilizers accumulates in soil and percolates downward into groundwater aquifers below.[90] While public community supply wells tend to be deeper and less inclined to be contaminated, public non-community wells and privately-owned groundwater wells are often vulnerable to NO_3-N contamination.[90] These wells are typically served by their own supply of water and tend to be small and shallow, and thus, more susceptible to NO_3-N contamination.[70] Although non-community sources are required to maintain the level of water quality defined by the federal Safe Drinking Water Act, private wells are not monitored.[62]

The USGS recently released a report that summarizes the findings of two nonlinear models developed to predict the NO_3-N contamination of shallow (less than 5 m deep) groundwater aquifers from non-point sources, as well as the NO_3-N concentration in deeper nearby wells.[91] The models conclude that there is a positive relationship between agricultural area and/or the application of fertilizer loading, and NO_3-N concentration in groundwater sources.[91] Results classified groundwater aquifers by their "vulnerability" to contamination, which was determined by factors such as soil drainage characteristics and the ratio of woodland acres to cropland acres, since these factors largely influence the rate at which NO_3-N percolates through soil.[92] Groundwater sources found to be the most vulnerable to NO_3-N contamination were shallow wells downstream of agricultural land.[92] Similar to trends observed in surface water sources, areas downstream of the Corn Belt region had high contamination levels due to high agricultural activity, well-drained soil characteristics, high use of irrigation, and high rainfall.

The USGS estimates that over 24% of shallow groundwater aquifers in areas classified as "high vulnerability" already exceed drinking water standards for NO_3-N. [90] The areas that receive the highest nitrogen input and are most vulnerable to groundwater contamination are concentrated in the Corn Belt region, as indicated in Figure 24. Although various types of non-point sources contribute to water pollution, nutrient leaching due to high application rates of nitrogen fertilizers in conjunction with high soil erosion rates in agricultural areas are considered the primary cause of the nation's impaired lakes and estuaries and the second most prevalent cause of impairment in rivers.[70] Other sources, such as discharge from wastewater treatment plants and run-off from animal manure, fertilized lawns, and golf courses, as well as the atmospheric deposition of nitrogen, are also smaller contributors to excessive nutrient loading in downstream water bodies.[55]

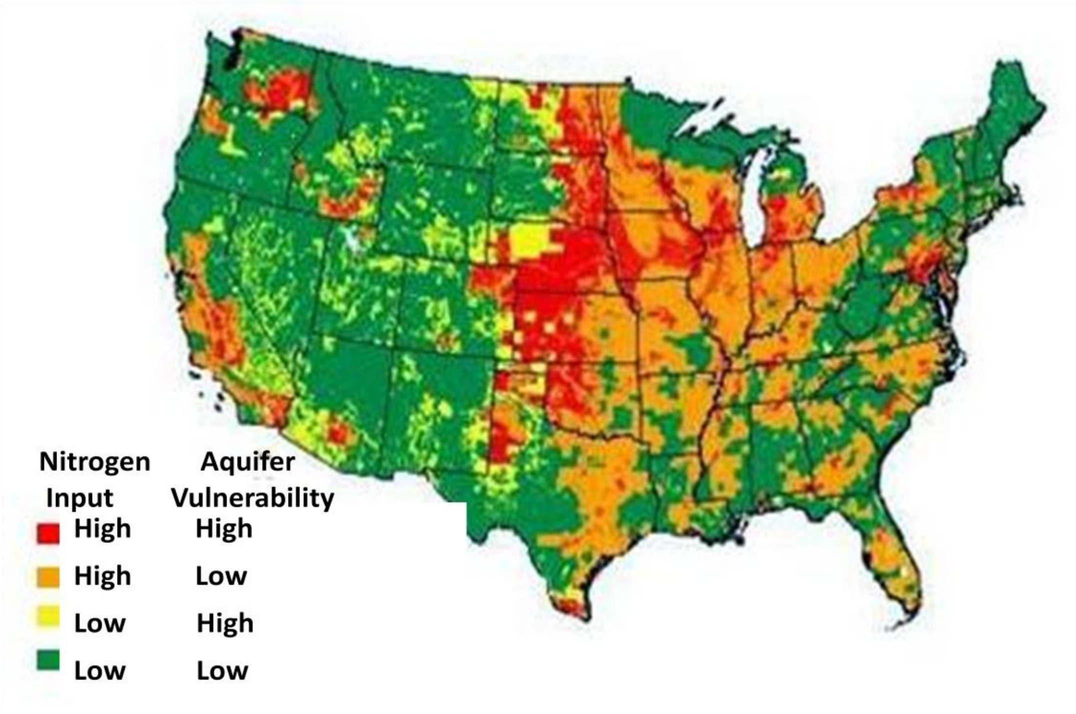


Figure 24. Regions of high Nitrogen input and high vulnerability are concentrated in the Corn Belt Region [93]

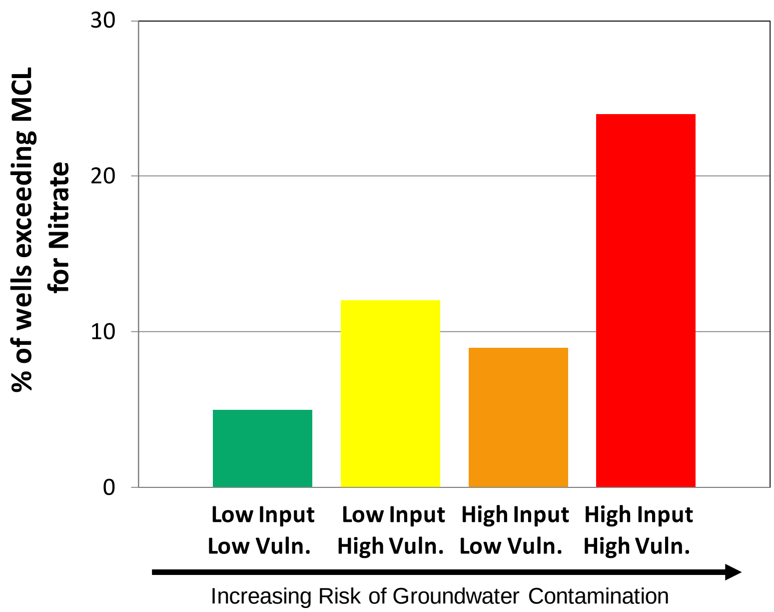


Figure 25. Twenty-four percent of wells of shallow (<5m deep) groundwater aquifers exceed the NO_3-N drinking water standard[93]

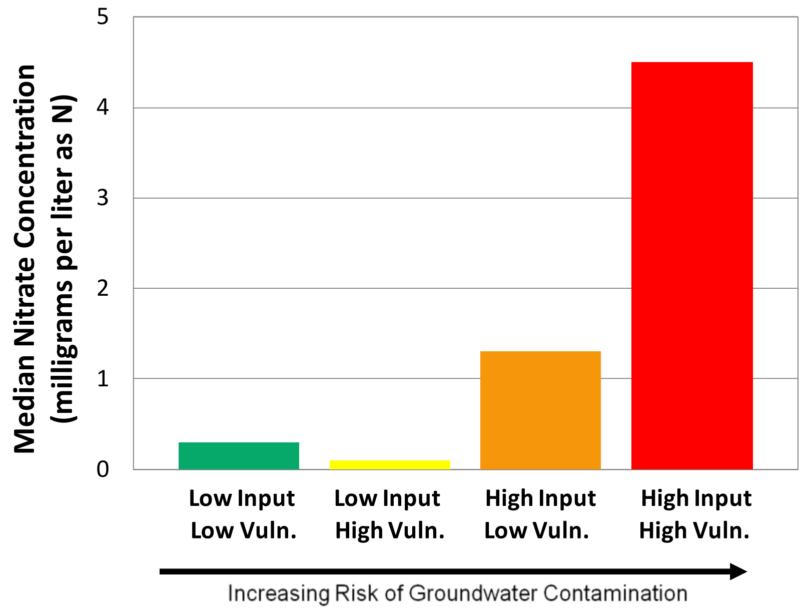


Figure 26. High input, high vulnerability shallow groundwater aquifers exhibit median NO_3-N concentrations less than 5 mg L^{-1} as N [93]

5.4 RESULTS AND DISCUSSION

Between the years of 1998 and 2003, 12.4 million people drank from public water supply systems that reported exceeding the EPA's MCL for NO_3-N.[84] Assuming that the average person used 140 gallons of potable water a day[85], approximately 634 billion gallons of water was delivered through public supply systems without meeting acceptable drinking water standards. This volume is significantly lower (57 billion gallons) for the second scenario in which only drinking water is considered. (See Equations 1 and 2)

Baseline energy consumption for treating water in the overly-contaminated areas was calculated by assuming that standard surface water treatment consumes, on average, 175 kWh per million gallons (Table 8) of water treated.[70] Thus, using standard treatment over a year for this quantity of water that exceeds MCL standards would consume 111 million kWh for the first scenario and 10 million kWh for the second scenario.

Increasing treatment to address the NO_3-N contamination would raise energy consumption dramatically in both scenarios. For example, the energy consumption required to treat the same quantity of water using reverse osmosis was calculated assuming that reverse osmosis requires 3,900 kWh per million gallons (Table 5) of water treated. (Note that this calculation represents a conservative estimate, since reverse osmosis might require more energy depending on the quality of the raw source water.) Treating 634 billion gallons of water with reverse osmosis, by contrast, would consume approximately 2,471 million kWh per year. Treating 57 billion gallons of water in the second scenario would consume 221 million kWh. Each scenario experiences an increase of 2100% over the baseline energy consumption for the affected areas. Also of note is the fact that treating 57 billion gallons of water with reverse osmosis in the second scenario requires approximately double the amount of energy as treating 634 billion gallons of water with standard surface water treatment in scenario 1. All results are summarized in Table 8.

Properly treating this small area alone would represent a 4.2% increase in total energy consumption for the entire water treatment sector nationwide. Thus, if increased biofuels production causes even greater amounts of water to exceed acceptable contamination levels, we can expect to see significant additional energy requirements as an unintended consequence.

Table 8. Results indicate that advanced water treatment processes have a substantial energy cost over the baseline.

Number of people affected by NO_3-N contamination (1998-2005)	Daily per capita water use (gallons)	Annual energy consumption using standard surface water treatment (millions of kWh)	Annual energy consumption using Reverse osmosis (millions of kWh)	Percent increase of reverse osmosis from baseline
12,400,000	140.0	111	2,471	+2,129%
12,400,000	12.5	10	221	+2,129%

Although an additional portion of the population drank water supplied from contaminated private groundwater wells in this period of time, they were not considered in this analysis since private wells are not regulated according to EPA drinking water standards. That is, while it might be wise to treat water in those wells, it is not a statutory requirement to do so, and thus the energy requirements for that treatment were excluded from this analysis.

Based on future projections, it is likely that the increase in nitrogen export to the MARB and in agricultural regions across the nation will be between 10 and 37% from the control scenario depending how cropland is allocated and managed.[49, 53, 94] Even if this increase occurred, less than 5 of the 362 sites monitored in the Heinz Center report[89] that currently fall below the federal MCL for NO_3-N in drinking water would surpass the standard. It is also important to note that surface water treatment plants are typically supplied by large water sources that are not likely to be susceptible to NO_3-N contamination due to higher volumes. Of the nation's total supply of public water, 61% is supplied by surface water, yet only 8% of this volume is supplied to small, non-community systems.[70] The remaining 92% is fed to community systems that tend to be much larger than non-community systems and are usually closer to towns and cities, and therefore are less likely to experience significant shifts in nitrogen loading due to the increased production of biofuels. Consequently, it is improbable that the energy consumption associated with water treatment in surface water sources will be influenced by the large shifts in corn cultivation.

However, the impacts are different for ground water sources, which are the primary reservoirs of water to non-urban communities. While these communities typically avoid contamination risks such as urban and industrial run-off, damaged septic tanks, and wastewater treatment plants, they will be the most likely to be impacted by increased agricultural activity in the Corn Belt region.[90] Although data exist on current concentrations of NO_3-N in groundwater wells across the US, few studies have successfully quantified the rate of change of NO_3-N in groundwater wells.[95] Recently, high priority has been placed on establishing trends in terms of the nitrification and denitrification in wells so that realistic methods of modeling the effect of anthropogenic influences on water bodies can be developed.[95] However, considering that 24% of highly vulnerable wells are already contaminated, and a large proportion of groundwater sources in the Midwest tend to be smaller, private aquifers, it is likely that more wells may become contaminated as agricultural activity increases in the next few decades.

Groundwater treatment typically requires minimal energy for purification when below the MCL.[82] In fact, much of the groundwater pumped from private wells does not receive any type of treatment.[70] However, water treatment that can adequately remove contaminants is much more energy intensive than standard gravity based treatments with chlorination, which are typically used for groundwater treatment.[70] A shift towards these advanced processes may be costly in terms of additional electricity consumption. Treating a volume of water with reverse osmosis treatment may require more than one hundred times the energy required to use gravity-based treatment with chlorine disinfection. It is difficult to quantify the number of wells that are used as drinking water sources and that have an increased risk of nitrogen contamination, but considering that approximately 83 billion gallons of groundwater are pumped per day in the US, even a small shift in treatment methods could have large repercussions in terms of increased energy consumption.[42]

Quantifying the increase in energy consumption due to the expansion of ethanol is hindered because significant data gaps exist in terms of NO_3-N levels in current surface water and groundwater sources. Changes in NO_3-N concentration will vary according to the volume of the water supply, whether it is a surface or groundwater source, how far away it is from the source of contamination, as well as other characteristics such as climactic and seasonal variation. Furthermore, projected increases in NO_3-N contamination will not affect all drinking water sources equally, since most wells in agricultural areas are not used for public supply, and therefore are not subject to EPA regulations. Thus, private, unmonitored wells cannot be assumed to have an associated energy penalty for exceeding the MCL. Finally, water treatment facilities often rely on multiple sources of water, so it is difficult to project how contamination in individual sources may influence the net NO_3-N concentration of water being treated at water treatment facilities.

This analysis considered the impact that future increases in corn-starch based ethanol will have on the energy consumed for surface and groundwater treatment based on the current MCL of NO_3-N in drinking water. However, growing concerns over the public health ramifications of water pollution in drinking water in the recent years may result in more stringent standards in the future.[62, 96] If the number of regulated contaminants in source water increases simultaneously with tightening of acceptable MCL standards, the growth in energy consumption by the water treatment sector will be compounded.

Chapter 6: Conclusions

6.1 Conclusions

This manuscript explores the intricate relationship between water and energy; water is critical to the production of electricity and transportation fuels, and energy is critical to the treatment, pumping, and preparation of water. Although Chapters 2, 3, and 4 explore three main subsets of the energy-water nexus independently, Chapter 5 demonstrates that there are important interrelationships that exist across these three areas that are important to consider to avoid unintended energy and water repercussions.

The analysis presented in Chapter 5 is the first to consider the unexpected energy ramifications of water quality degradation from increased biofuels production, but it is hindered by a lack of suitable data regarding the current state of contamination in groundwater sources. However, the analysis does identify that drinking water contamination already affects a significant amount of water that would be costly and energy-intensive to treat with processes effective in the removal of contaminants such as NO_3-N. In addition, other analyses [49, 53, 94] suggest that increases in nutrient loading due to the expansion of ethanol will be in the range of 10 to 37%. Therefore, the expansion of biofuels in the future might be accompanied with a significant energy cost for water treatment. Ironically, policy choices to improve our energy situation, namely EISA 2007 would be responsible in these scenarios for inducing these increases in energy consumption.

The first conclusion, based on current concentrations of NO_3-N in surface water, is that projected increases in NO_3-N in surface water in the MARB are unlikely to cause a significant increase in the number of drinking water sources that exceed 10 mg L^{-1} NO_3-N.

However, the second conclusion is that it is likely that groundwater sources might become more vulnerable to NO_3-N contamination as a result of increased corn ethanol production. This consequence is largely due to the fact that groundwater sources, unlike surface water sources, are often small, shallow, and more vulnerable to pollutants like NO_3-N.

This analysis highlights the following trends that may be exacerbated as a result of recent legislation promoting the expansion of biofuels:

- Corn-starch based ethanol production in the US will grow significantly due the Renewable Fuel Standard implemented through the Energy Independence and Security Act.
- Increased ethanol production will cause increased nutrient loading to surface water and groundwater sources downstream of agricultural land.[49, 53, 94]
- Increased nutrient loading will increase NO_3-N contamination in source water for drinking water treatment facilities.
- Downstream water treatment plants in areas where increased runoff causes water contamination to exceed EPA drinking water standards will substantially increase their energy consumption.
- Drinking water standards may become more stringent in the future due to growing public health concerns regarding NO_3-N.[62, 96]
- As drinking water standards tighten in parallel with higher contamination from increased biofuels production, the energy requirements to treat water to acceptable standards might have compound growth.

6.2 FUTURE WORK

This analysis is a starting point in assessing the water quality and energy impacts due to the expansion of biofuels. However, great uncertainty still exists regarding the current state of NO_3-N contamination, the pace of new technology deployment, the composition of the future fuel mix, and potential technology improvements that might affect the water/energy implications of fuel production. As time progresses, this analysis should be updated to reflect new transportation fuel deployment.

In addition to these uncertainties, large data gaps exist which hindered the current analysis, since an accurate baseline scenario could not be adequately modeled in terms of the current state of NO_3-N contamination in US drinking water sources. Future work would include surveying public drinking water suppliers to form a more accurate representation of current NO_3-N contamination. After conducting a high-fidelity survey of the existing state of contamination, a more detailed estimate for increased energy consumption can be determined.

Other future work might include considering the increases in other contaminants, namely phosphorus, which is a large input in agricultural activity.

References

1. *H.R. 3598: Energy and Water Research Integration Act*. 2009 [cited March 11, 2010]; Available from: http://www.govtrack.us/congress/bill.xpd?bill=h111-3598.

2. *S. 531: Energy and Water Integration Act of 2009*. 2009 [cited March 11, 2010]; Available from: http://www.govtrack.us/congress/bill.xpd?bill=s111-531.

3. *S. 1462: Clean Energy Leadership Act of 2009*. 2009 [cited March 10, 2009]; Available from: http://www.govtrack.us/congress/bill.xpd?bill=s111-1462.

4. USGS, *Estimated Use of Water in the United States in 2000*. 2004, USGS: Denver, CO.

5. USGS, *Estimated Use of Water in the United States in 1995*. 1998, USGS: Denver, CO.

6. EIA, *Updated Annual Energy Outlook 2009 Reference Case with ARRA*, in *Supplemental Tables*. 2009, EIA: Washington, DC.

7. NGSA. *Electric Generation Using Natural Gas*. 2004 [cited March, 13, 2010]; Available from: naturalgas.org.

8. Corbett. *Senate Bill 42*. January 6, 2009 [cited March, 13, 2010]; Available from: http://info.sen.ca.gov/pub/09-10/bill/sen/sb_0001-0050/sb_42_bill_20090414_amended_sen_v97.pdf.

9. Twomey, K. and A. Stillwell, *Electricity Generation: Water Resource Challenges and Opportunities*, N. Carter, Editor. 2009, CRS: Washington, DC.

10. *The Last Straw: Water Use by Power Plants in the Arid West*. 2003, Hewlett and Energy Foundation.

11. Kutscher, C., A. Buys, and C. Gladden. *Hybrid Wet/Dry Cooling for Power Plants*. in *Parabolic Trough Technology Workshop*. 2006. Incline Village, NV: NREL.

12. Boberg, J., *Liquid assets: how demographic changes and water management policies affect freshwater resources*. 2005, Santa Monica, CA: Rand Corporation.

13. Drbal, L., et al., eds. *Power Plant Engineering- Design and Construction*. 1996, Chapman & Hall: New York.

14. Veil, J.A., J.M. Kupar, and M.G. Puder, *Use of Mine Pool Water for Power Plant Cooling*. 2003, Argonne National Laboratory.

15. APS. *About APS*. 2009 [cited March 13, 2009]; Available from: http://www.aps.com/general_info/AboutAPS_18.html.

16. GAO, *Energy-Water Nexus: Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use*, in *Report to the Chairman, Committee on Science and Technology, House of Representatives*. 2009: Washington DC.

17. NETL, *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements*. 2008.

18. Feeley III, T.J., et al., *Water: A critical resource in the thermoelectric power industry.* Energy, 2008. **33**.

19. Torcellini, P., N. Long, and R. Judkoff, *Consumptive Water Use for U.S. Power Production*. 2003, NREL: Golden, CO.

20. EPRI, *Assessment of Waterpower Potential and Development Needs* 2007: Palo Alto, CA.

21. DOE, *Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants*. 2006, Idaho National Laboratory: Washington, DC.

22. CRS, *H.R. 2454: American Clean Energy and Security Act of 2009 Summary*. 2009, CRS: Washington, DC.

23. DOE, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*. 2008, DOE: Washington, DC.

24. DOE. *Office of Energy Efficiency and Renewable Energy's Concentrated Solar Power Program, Thermal Storage* 2009 [cited July 20, 2009]; Available from: http://www1.eere.energy.gov/solar/thermal_storage.html.

25. DOE, *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation*. 2009, DOE: Washington, DC.

26. NOAA, *Global Climate Change Impacts in the United States*, U.S.G.C.R. Program, Editor. 2009.

27. USGS, *Substantial Power Generation from Domestic Geothermal Resources*. 2008: Reston, VA.

28. DOE, *How an Enhanced Geothermal System Works*. 2006: Washington, DC

29. Green, B.D. and G. Nix, *Geothermal - Energy Under Our Feet*. 2008, NREL: Golden, CO.

30. Larson, D., et al., *California's Energy-Water Nexus: Water Use in Electricity Generation.* Southwest Hydrology, 2007.

31. Leitner, A., ed. *Fuel from the Sky: Solar Power's Potential for Western Energy Supply*. 2002, NREL: Boulder, CO.

32. AP, *Drought could shut down nuclear power plants*, in *MSNBC*.

33. J. Manuel, *Drought in the Southeast: Lessons for Water Management.* Environmental Health Perspectives, 2008. **116**(4).

34. EPRI, *A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation*, R. Goldstein, Editor. 2003, EPRI: Palo Alto, CA.

35. NRC. *A Short History of Nuclear Regulation*. 2009 [cited; Available from: http://www.nrc.gov/about-nrc/short-history.html.

36. Hightower, M. and S.A. Pierce, *The energy challenge.* Nature, 2008. **452**(7185): p. pp. 285-286.

37. Barnett, T.P., *Impacts of a warming climate on water availability in snow-dominated regions.* Nature, 2009.

38. Pimentel, D., et al., *Reducing energy inputs in the food system.* Human Ecology, 2008. **36**: p. 459-471.

39. Zhou, H. and D.W. Smith, *Advanced technologies in water and wastewater treatment.* Can. J. Civ. Eng., 2001. **28**(1): p. 49-66.

40. *US Population Projections*. 2005, U.S. Census Bureau: Washington, DC.

41. UN, *World Population Prospects: The 2008 Revision*. 2008, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat.

42. EPRI, *Water and Sustainability (Volume 2): An Assessment of Water Demand, Supply, and Quality in the U.S.—The Next Half Century*. 2002, EPRI: Palo Alto, CA.

43. Newell, R., *Annual Energy Outlook 2010: Reference Case*. 2009, EIA: Washington, DC.

44. King, C.W. and M. Webber, *Water Intensity of Transportation.* Environ. Sci. Technol., 2008. **42**(21): p. 7866 - 7872.

45. King, C.W., M.E. Webber, and I.J. Duncan, *The Water Needs for LDV Transportation in the United States.* Energy Policy, 2009. **38**(2): p. 1157-1167.

46. RFA, *RFS Schedule under the Energy Independence and Security Act of 2007*. 2009, Renewable Fuels Association: Washington, DC.

47. GAO, *Energy-Water Nexus: Many Uncertainties Remain about National and Regional Effects of Increased Biofuel Production on Water Resources*, U.S.G.A. Office, Editor. 2009.

48. RFA, *Historic and Projected US Fuel Ethanol Production*. 2009, Renewable Fuels Association: Washington, DC.

49. Simpson, T.W., et al., *The New Gold Rush: Fueling Ethanol Production while Protecting Water Quality.* J Environ Qual, 2008. **37**(2): p. 318-324.

50. Mitsch, W.J., et al., *Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem.* BioScience, 2001. **51**(5): p. 373-388.

51. Rabalais, N.N., R.E. Turner, and D. Scavia, *Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River.* BioScience, 2002. **52**(2): p. 129-142.

52. Hill, J., et al., *Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels.* PNAS, 2006. **103**(30): p. 11206-11210.

53. Donner, S.D. and C.J. Kucharik, *Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River.* PNAS, 2008. **105**(11): p. 4513-4518.

54. Hill, J., et al., *Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels.* PNAS, 2006. **103**(30): p. 11206–11210.

55. Morgan, M.G. and V. Dale, *Hypoxia in the Northern Gulf of Mexico: An Update by the EPA Science Advisory Board*. 2007, USEPA Science Advisory Board: Washington, DC.

56. Alexander, R., et al., *Differences in Phosphorus and Nitrogen Delivery to The Gulf of Mexico from the Mississippi River Basin.* Environ. Sci. Technol. , 2008(42): p. 822-830.

57. Donner, S.D. and C.J. Kucharik, *Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River.* PNAS, 2008. **105**(11): p. 4513–4518.

58. Costello, C., et al., *Impact of Biofuel Crop Production on the Formation of Hypoxia in the Gulf of Mexico.* Environ. Sci. Technol., 2009. **43**: p. 7985–7991.

59. Elobeid, A., et al., *The Long-Run Impact of Corn-Based Ethanol on the Grain, Oilseed, and Livestock Sectors: A Preliminary Asessment*. 2006, Center for Agricultural and Rural Development: Ames, Iowa.

60. NREL, *A Preliminary Examination of the Supply and Demand Balance for Renewable Electricity*. 2007, NREL: Golden, CO.

61. EPA, *National Primary Drinking Water Regulations*. 2009, EPA: Washington, DC.

62. Ward, M.H., et al., *Workgroup Report: Drinking-Water Nitrate and Health—Recent Findings and Research Needs.* Environ Health Perspect., 2005. **113**(11): p. 1607–1614.

63. EPA. *Regulation of Oil and Gas Construction Activities* National Pollutant Discharge Elimination System (NPDES) 2009 [cited April 1, 2010; Available from: http://cfpub.epa.gov/NPDES/stormwater/oilgas.cfm

64. NETL, *State Oil and Natural Gas Regulations Designed to Protect Water Resources*, U. DOE, Editor. 2009, US DOE: Washington, DC.

65. EPA. *Introduction to the Clean Water Act: Glossary*. 2009 [cited April 1, 2010; Available from: http://www.epa.gov/watertrain/cwa/glossary.htm#ps.

66. EPA, *Agriculture* in *National Pollutant Discharge Elimination System (NPDES)* 2009, EPA: Washington, DC.

67. McLaughlin, S.B. and M.E. Walsh, *Evaluating Environmental Consequences of Producing Herbaceous Crops for Bioenergy.* Biomass and Bioenergy, 1997. **14**(4): p. 317-324.

68. Donner, S., *The impact of cropland cover on river nutrient levels in the Mississippi River Basin.* Global Ecology & Biogeography, 2003. **12**: p. 341–355.

69. Schenk, P.M., et al., *Second Generation Biofuels: High Efficiency Microalgae for Biodiesel Production.* Bioenergy Resources, 2008(1): p. 20-43.

70. EPRI, *Water and Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply and Treatment - The Next Half Century*. 2002, EPRI: Palo Alto, CA.

71. Dale, L., *Electricity price and Southern California's water supply options.* Resources, Conservation and Recycling, 2004. **42**: p. 337-350.

72. Koparal, A.S. and U.B. Ogutveren, *Removal of nitrate from water by electroreduction and electrocoagulation.* Journal of Hazardous Materials, 2001. **B89**: p. 83-92.

73. Wilf, M., *Seawater Desalination: Meeting the Needs of California's Coastal Communities.* From Seawater Desalination: Meeting the Needs of California's Coastal Communities. Seminar held by the University of California, Santa Barbara (UCSB) Extension, February 14, 1991.

74. Crittenden, J., et al., *Water Treatment: Principles and Design, Second Edition*. 2005, Hoboken, New Jersey: John Wiley & Sons.

75. Mahler, R., A. Colter, and R. Hirnyck. *Nitrate and Groundwater*. University of Idaho Extension 2007 [cited May 2, 2009]; CIS: 872]. Available from: http://info.ag.uidaho.edu/pdf/CIS/CIS0872.pdf.

76. Soares, M.I.M., *Biological Denitrification of Groundwater* Water, Air, & Soil Pollution, 2004. **123**(1-4).

77. Guter, G.A., *Removal of Nitrate from Contaminated Water Supplies for Public Use*. 1981, USEPA: Cincinnati, Ohio.

78. Noble, R.D. and S.A. Stern, *Membrane separations technology: principles and applications*. 3 ed. Volume 2 of Membrane science and technology series. 1995: Elsevier.

79. Cruver, J.E. and I. Nusbaum, *Application of Reverse Osmosis to Wastewater Treatment.* Water Pollution Control Federation, 1974. **46**(2): p. 301-311.

80. Haller, L., et al., *Nitrate Pollution of Groundwater,* . 1996, Alpha Water Systems Inc. : Montague, NJ

81. Congress, H.R.-.-t.U., *Energy Independence and Security Act of 2007*, in *GovTrack.us* 2007: Washington D.C. .

82. USDOE, *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water*. 2006, USDOE: Washington D.C. . p. 1-73.

83. Nolan, B.T., et al., *Risk of Nitrate in Groundwaters of the United States - A National Perspective.* Environmental Science & Technology, 1997. **31**: p. 2229-2236.

84. Group, E.W., *National Tap Water Quality Database*. 2005, Environmental Working Group: Washington, DC.

85. *Water Conservation Implementation Task Force: Report to the 79th Legislature*. 2004, Texas Water Development Board: Austin, TX.

86. *Residential End Uses of Water study*. 1999 Aquacraft, Inc. and American Water Works Association Research Foundation: Denver, CO.

87. Lahlou, Z.M., *Ion Exchange and Demineralization*, in *Tech Brief: A National Drinking Water Clearinghouse Fact Sheet*, Z.M. Lahlou, Editor. 2003, National Drinking Water Clearinghouse at West Virginia University: Morgantown, WV.

88. Mueller, D.K. and N.E. Spahr, *Nutrients in streams and rivers across the nation - 1992-2001*. 2006, USGS: Reston, VA.

89. *The State of the Nation's Ecosystems: Measuring the lands, waters, and living resources of the United States*. 2005, The H. John Heinz III Center for Science, Economics, and the Environment: New York, NY.

90. Nolan, B., *Relating Nitrogen Sources and Aquifer Susceptibility to Nitrate in Shallow Ground Waters of the United States.* Ground Water, 2001. **39**(2): p. 290-299.

91. Bernard Nolan, K.H., *Vulnerability of Shallow Groundwater and Drinking-Water Wells to Nitrate in the United States.* Environ. Sci. Technol., 2006. **40**(24): p. 7834-7840.

92. Nolan, B.T., et al., *A National Look at Nitrate Contamination of Ground Water.* Water Conditioning and Purification, 1998. **39**(12): p. 76-79.

93. Nolan, B. and K. Hitt, *Vulnerability of Shallow Groundwater and Drinking-Water Wells to Nitrate in the United States.* Environ. Sci. Technol., 2006. **40**(24): p. 7834-7840.

94. Han, H., J.D. Allan, and D. Scavia, *Influence of Climate and Human Activities on the Relationship between Watershed Nitrogen Input and River Export.* Environmental Science & Technology, 2009. **43**(6): p. 1916-1922.

95. Rupert, M., *Decadal-Scale Changes of Nitrate in Ground Water of the United States, 1988–2004.* Journal of Environmental Quality, 2008. **37**: p. 240 - 248.

96. Manassaram, D.M., L.C. Backer, and D.M. Moll, *A Review of Nitrates in Drinking Water: Maternal Exposure and Adverse Reproductive and Developmental Outcomes.* Environmental Health Perspectives, 2006. **114**(3): p. 320-327.

Vita

Kelly Twomey was born in Washington D.C. in 1985. She received her Bachelor of Science in Bioengineering from The Pennsylvania State University in 2007 and is currently pursuing an MS and PhD at the University of Texas at Austin in the Department of Mechanical Engineering. A recipient of a National Science Foundation fellowship, Ms. Twomey conducts research within the Webber Energy Group under the supervision of Dr. Michael Webber, whose focus is to analyze energy problems at the intersection of science, engineering, and public policy. Her research interests include the nexus of energy, food and water.

Permanent address: 3406-A Tom Green St

Austin, Tx 78705

This thesis was typed by the author.