# Life-Cycle Water Impacts of U.S. Transportation Fuels

By

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# Abstract

## Life-Cycle Water Impacts of U.S. Transportation Fuels

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The connection between energy use and water scarcity is not well understood. The production of energy requires water and the supply of water requires energy. Water already plays a major role in stationary energy production; thermoelectric power generation is responsible for nearly half of total freshwater withdrawals in the United States. Current transportation fuels, which account for approximately one-third of U.S. energy consumption, are not nearly as reliant on freshwater given that petroleum fuel production makes up just a few percent of U.S. water use. If transportation were to become more reliant on water-intensive sectors such as power generation and agriculture, there would be major implications for water availability in the United States. As electricity and biofuels gain a larger share of the market, this is exactly the transition that is taking place.

Inconsistent water use metrics, inappropriate impact allocation practices, limited system boundaries due to lack the necessary tools and data, and the failure to quantify water resource availability and greenhouse gas (GHG) impacts are common pitfalls of existing assessments of transportation energy-related water use. To fill the knowledge gaps, this dissertation proposes a comprehensive life-cycle framework for assessing the water withdrawals and consumption of current and near-future U.S. transportation fuels — including gasoline, bio-based ethanol, and electricity. With this proposed framework for performing a life-cycle inventory and impact assessment, the following three questions are answered:

1. What is the life-cycle water footprint of current and near-future transportation fuel production in the United States?

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2. How might U.S. transportation fuel production pathways impact freshwater availability in the future?

3. What is the greenhouse gas-intensity of the water required for transportation fuel production, and how do these emissions impact the overall transportation fuel greenhouse gas footprints?

Understanding the impacts of water use on freshwater resources and GHG emissions requires knowledge of not only the fuel production pathways, but also how these pathways interact with other sectors in the economy. As new transportation fuels emerge, demand for some goods and services will increase while for others it will decrease, and each change has an effect on overall water demand. Quantifying the net system-wide impact of producing these new fuels is key to understanding the water implications of transportation energy-related policy decisions.

Furthermore, by geospatially disaggregating predicted water requirements for transportation fuel production pathways at the U.S. county-level, locations within the United States can be identified as vulnerable to local surface and groundwater shortages. These shortages may result in high water prices and the need for energy-intensive water supply methods such as desalination, importation, or wastewater recycling. Identifying regions with vulnerable water resources allows decision makers in industry and the public sector to guide burgeoning transportation fuel markets in ways that maximize their contributions to energy independence and greenhouse gas emissions reductions while avoiding negative impacts on water availability.

Results from the U.S. analysis show that indirect water use has a significant impact on total water use, particularly for withdrawals. In no other pathway is this as pronounced as it is for cellulosic ethanol production (in this case, corn stover and Miscanthus to ethanol). By using system expansion to account for the electricity generation displaced by cellulosic biorefineries' exports to the grid, total water consumption for those pathways drops considerably and total withdrawals actually becomes a net negative number. When the inventory is geospatially disaggregated and compared to drought and groundwater vulnerability data, the results show that biofuel production concentrated in the Midwest puts pressure on the already-overpumped High Plains Aquifer. Petroleum fuel production pathways result in water use concentrated in locations that are predicted to experience long-term drought, specifically California, Texas, and Wyoming. Electricity, in contrast, is more widely distributed throughout the U.S., but the high surface water consumption rates in the western half of the country may exacerbate future surface water shortages in those regions.

Gaining a better knowledge of how the production and consumption of fuels impacts freshwater resources is absolutely critical as humans attempt to transition into a more sustainable energy future. By making contributions to the methodologies required to assess the environmental impacts of water use, as well as knowledge about the potential water impacts of current and near-future U.S. transportation fuels, this dissertation provides U.S. decision makers with information necessary to create the most economical and sustainable

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transportation energy future possible while also providing future researchers with the tools to answer questions that have yet to be asked.

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# List of Acronyms and Abbreviations

| | |
|---|---|
| ASCC | Alaska Systems Coordinating Council |
| BEA | Bureau of Economic Analysis |
| BFW | Boiler Feed Water |
| BOD | Biological Oxygen Demand |
| C | Consumption |
| CAP | Criteria Air Pollutant |
| CARB | California Air Resources Board |
| CCS | Carbon Capture and Sequestration |
| CGF | Corn Gluten Feed |
| CGM | Corn Gluten Meal |
| CHP | Combined Heat and Power |
| COD | Chemical Oxygen Demand |
| CPC | Climate Prediction Center |
| CRA | Colorado River Aqueduct |
| CSS | Cyclic Steam Stimulation |
| CVP | Central Valley Project |
| DALY | Disability-Adjusted Life Year |
| DDGS | Dried Distillers' Grains and Solubles |
| DWR | Department of Water Resources |
| ED | Electrodialysis |
| EIA | Energy Information Agency |
| EIO-LCA | Economic Input-Output Life-Cycle Assessment |
| EOL | End-of-Life |
| EPA | Environmental Protection Agency |
| ET | Evapotranspiration |
| EtOH | Ethanol |
| FAO | United Nations Food and Agriculture Organization |
| FIPS | Federal Information Processing Standard |
| FRCC | Florida Reliability Coordinating Council |
| FRIS | Farm and Ranch Irrigation Survey |
| FWSE | Free Water Surface Evaporation |
| FY | Fiscal Year |
| GHG | Greenhouse Gas |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation |
| GTAP | Global Trade Analysis Project |
| GW | Groundwater |
| GWP | Global Warming Potential |
| HICC | Hawaiian Islands Coordinating Council |
| iLUC | Indirect Land Use Change |
| IPCC | Intergovernmental Panel on Climate Change |

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|---|---|
| ISO | International Organization for Standardization |
| LCA | Life-Cycle Assessment |
| LCFS | Low Carbon Fuel Standard |
| LCI | Life-Cycle Inventory |
| LP | Linear Programming |
| LPG | Liquefied Petroleum Gas |
| MED | Multi-Effect Distillation |
| MRO | Midwest Reliability Organization |
| MSF | Multi-Stage Flash |
| MTBE | Methyl Tertiary Butyl Ether |
| MWD | Metropolitan Water District of Southern California |
| MWDOC | Municipal Water District of Orange County |
| NAICS | North American Industry Classification System |
| NERC | North American Electric Reliability Corporation |
| NETL | National Energy Technology Laboratory |
| NOAA | National Oceanic and Atmospheric Administration |
| NPCC | Northeast Power Coordinating Council |
| NREL | National Renewable Energy Laboratory |
| PADD | Petroleum Administration for Defense District |
| PDI | Palmer Drought Index |
| ppm | Parts per Million |
| PV | Photovoltaic |
| PW | Produced Water |
| RFA | Renewable Fuels Association |
| RFC | Reliability*First* Corporation |
| RO | Reverse Osmosis |
| SAGD | Steam Assisted Gravity Drainage |
| SBM | Soybean Meal |
| SCO | Synthetic Crude Oil |
| SERC | SERC Reliability Corporation |
| SPP | Southwest Power Pool |
| SW | Surface Water |
| SWP | State Water Project |
| TDH | Total Dynamic Head |
| TDS | Total Dissolved Solids |
| TRE | Texas Regional Entity |
| TS&D | Transportation, Storage, and Distribution |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| VC | Vapor Compression |
| W | Withdrawals |
| WECC | Western Electricity Coordinating Council |
| WSI | Water Stress Index |

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| | |
|---|---|
| WTT | Well-to-Tank |
| WTW | Well-to-Wheels |

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In my years at Berkeley, I have come to learn just how fortunate I am to have Professor Arpad Horvath as my research adviser. Over the course of my research, I was given the respect and freedom normally afforded to a colleague, as well as the support and guidance required by a student. He was patient during those inevitable periods of time when I struggled to find direction and encouraging when I gained momentum. He pushed me to achieve more than I believed I was capable of. Despite juggling his many other responsibilities, Professor Horvath was also incredibly generous with his time, always making room in his schedule to do everything from editing my writing to giving me career advice. To have such an accomplished and supportive adviser is more than I ever could have asked for.

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# 1. Introduction and Problem Statement

## 1.1 Introduction

Providing energy for transportation introduces a number of unique engineering challenges: the fuels must be relatively cheap to produce, easy to transport and store (preferably using infrastructure that already exists), and their energy should be released via combustion or other means using engines, electric motors, etc. that are compact, mobile, and can be ramped up and down at the driver's request. In addition to those basic requirements, transportation fuels should not cause significant harm to the environment and human health. There are a wide variety of measures by which a fuel's impact can be determined, and often the first step in assessing the environmental "footprint" of a fuel is to identify the metrics that will be important. The environmental metrics of most importance may change depending on the particular fuel in question.

In the U.S. transportation sector, petroleum-based fuels have been the dominant energy source, and the impacts of most concern have been greenhouse gas (GHG) and criteria air pollutant (CAP) emissions (carbon monoxide, lead, nitrogen oxides, sulfur dioxide, particulate matter, and ozone); for example, CAPs and GHGs are the only environmental impacts included in GREET, an Excel-based model for assessing vehicles and transportation fuels (*1*). As the list of possible alternative transportation fuels expands to include electricity and biofuels, however, the framework for assessing their environmental impacts must also change. One example of a previous failure to make this adjustment is a fuel additive called methyl tertiary butyl ether (MTBE). Although MTBE is completely different from petroleum fuels (it is an oxygenate), its environmental impacts were assessed using the framework tailored to petroleum; in other words, policy makers assumed the only metrics that mattered were CAP and GHG emissions. Not long after its use became widespread, a number of states banned the use of this additive because it leaked from storage tanks into drinking water sources, resulting in an offensive taste and odor, as well as potential long-term human health effects (*2*). MTBE's impact on water resources was initially ignored, but resulted in its ultimate removal from the market. Having learned from such experiences, policy makers need a much more robust framework to evaluate possible alternative fuels in comparison to their petroleum counterparts.

As recent studies have shown, water impacts are important for some of the alternative fuels currently being considered, particularly biofuels (*3-5*). The water required to produce some biofuels can be up to three orders of magnitude higher than what is required to produce gasoline or diesel (*3*). Reference (*4*) estimates that for each $m^3$ of corn ethanol produced in the United States, over 780 $m^3$ of water are required on average, while corn grown in California requires 2,100 $m^3$ of water per $m^3$ of ethanol produced (*3*). Other alternative fuels can be very water-intensive as well; a $m^3$ of synthetic crude oil produced from oil sands requires between 2 and 4.5 $m^3$ of water for mining and upgrading (*6*), and closed-loop cooling for fossil fueled power plants consumes approximately 2.6 $m^3$ of water per kWh produced (*7*). The large water

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requirements for producing these alternative transportation fuels can cause more rapid depletion of underground aquifers, depletion of valuable surface water resources, and an increase in energy use for pumping and treating water.

Existing knowledge about the water impacts of transportation fuel production is limited, despite its potential importance. All but two Life-Cycle Assessment (LCA) studies make no attempt to quantify the indirect water use as a result of electricity, primary fuels, and materials along the supply chain of transportation fuels (*8, 9*). Furthermore, no studies have ventured beyond the inventory stage, which limits the usefulness of their results since water shortages are highly region-specific and water stress varies significantly by location even within the United States (*10, 11*). Given the existing knowledge gaps, the research presented in this dissertation seeks to answer three main questions:

1. What is the life-cycle water footprint of current and future transportation fuel production in the United States?

2. How might U.S. transportation fuel production pathways impact freshwater availability in the future?

3. What is the GHG-intensity of the water required for transportation fuel production and how do these emissions impact the overall transportation fuel GHG footprints?

This dissertation serves to answer these questions by performing a detailed life-cycle inventory of water consumption and water withdrawals for electricity, ethanol, and gasoline production, exploring the impacts of each fuel production pathway on groundwater (GW) and surface water (SW) resources in the United States, and quantifying the current and potential future GHG footprint of water supply.

## 1.2 Problem Statement

In today's global economy, water and energy are fundamentally connected. Compared to other substances abundant in the environment, water has a high specific heat capacity (approximately four times that of air), which makes it useful for transporting heat in power generation and industrial applications. Water is also a fundamental building block of life, which means it is essential for both human consumption and agriculture. If energy use is split into two categories: stationary and transportation, it is clear from the breakdown in Figure 1 that water already plays a major role in stationary energy production; thermoelectric power generation is responsible for approximately 49% of total freshwater withdrawals in the United States (*12*). As would be expected, agriculture and public supply also make up a large fraction of freshwater supply in the United States. Transportation energy, however, is not nearly as reliant on freshwater. Ninety five percent of transportation energy in the United States comes from petroleum fuels (*13*). Oil extraction and refining make up only a fraction of the mining and industrial sectors in Figure 1, which together are responsible for just 5% of total freshwater withdrawals (*12*). If transportation, which makes up approximately one-third of total U.S. energy consumption (*13*), were to become more reliant on water-intensive sectors such as

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power generation and agriculture, there could be significant implications for U.S. freshwater availability. Indeed, as electricity and biofuels gain a larger share of the transportation fuel market, this is exactly the transition that is taking place.

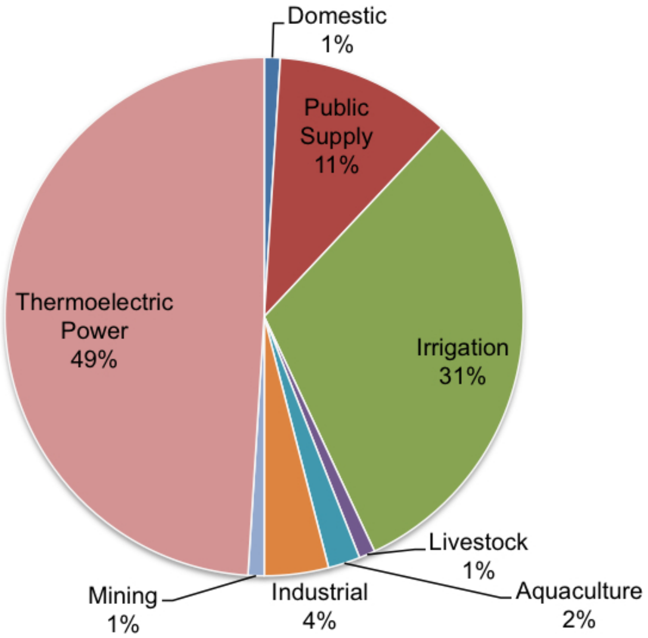

Figure 1: Estimated Freshwater Withdrawals in the United States in 2005 (Data Source: (*12*))

Increased use of freshwater resources carries with it a number of impacts. In developing nations, it can hamper sufficient access to potable water, thus increasing morbidity and mortality rates. In developed nations such as the United States, more likely near-term results include stricter regulations on water use and drought pricing of public water supplies, as well as an increase in the energy required to meet freshwater demand. Around the country, cities face increased prices for water during years with unusually low rainfall. Overpumping of underground aquifers can result in land subsidence and lowering of the water table, which in turn increases the amount of energy required to pump water to the surface. For example, the High Plains Aquifer level has dropped more than 18 m between 1980 and 1999 in New Mexico, Texas, and southwestern Kansas (*14*). When local resources can no longer support a population's needs, freshwater must be imported. California's State Water Project (SWP) and Colorado River Aqueduct (CRA) use electricity to pump water to Southern California, where local resources cannot support its large population and agricultural sector. The SWP is currently the largest single electricity consumer in all of California (*15*). Some communities may turn to desalination of saline or seawater instead, which can be twice as GHG-intensive as imported water (*16*). Finally, in both developing and developed nations alike, surface water resources serve as vital habitats for a variety of species and their depletion impacts local ecosystems.

Recent interest in the water requirements for energy production has resulted in a number of studies on water use for transportation fuel production (*3-5, 7-9, 17-21*). However, all but two

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of these studies do not go beyond the direct water impacts of feedstock extraction/production and fuel production/refining (as shown in Table 1). Impact assessment is also a critical step that has not been taken in existing studies. Because a liter of water used in already stressed areas such as Southern California is likely to cause more damage than a liter consumed in more water-rich parts of the country, a Life-Cycle Inventory (LCI) alone cannot reveal which fuels cause the greatest burden on freshwater resources. A comprehensive LCA should include not only the operational water requirements at each life-cycle phase, but water required for design, construction, operation and maintenance, and decommissioning of the infrastructure, as well as the water embodied in the material and energy inputs, or what is sometimes referred to as "virtual water" (*22*). This quantity of water should somehow translate into resulting stress on water resources. Last, these impacts should be properly allocated among the many co-products of fuel production systems.

| Fuel → | Gasoline | | Electricity | Ethanol | |
|---|---|---|---|---|---|
| Life-Cycle Phase ↓ | Conventional Crude Oil | Oil Sands | | Corn Grain | Corn Stover & Miscanthus |
| Feedstock Production/ Extraction & Pre-Processing | Exploration, drilling, extraction | Oil sands extraction, retorting, upgrading | Extraction and pre-processing of fuels used at power plant | Cultivation of crops | Establishment and cultivation of crops |
| Refining/ Fuel Production | Petroleum refining | Petroleum refining (of synthetic crude oil) | Electric power generation | Biorefining (conversion to ethanol) | Biorefining (conversion to ethanol) |
| Storage & Distribution | Transport of crude oil to refinery, transport and storage of gasoline after leaving the refinery | Transport of synthetic crude to the refinery, transport and storage of gasoline after leaving the refinery | Storage, transmission, and distribution of electric power | Transport of feedstock to the biorefinery, transport and storage of ethanol after leaving the biorefinery | Transport of feedstock to the biorefinery, transport and storage of ethanol after leaving the biorefinery |
| Combustion/ Use | Combustion of gasoline in spark-ignited ICE | Combustion of gasoline in spark-ignited ICE | Use of electric power in EVs or PHEVs | Combustion of ethanol in spark-ignited ICE | Combustion of ethanol in spark-ignited ICE |

Table 1: Fuel and Life-Cycle Phases within the Scope of this Dissertation

In this dissertation, the life-cycle water use, as well as resulting impacts on water resource availability and GHG emissions are quantified for gasoline, electricity, and fuel ethanol. By utilizing novel methodologies, the research produces LCI results that are substantially different than previous studies and serves as the only LCA to date of transportation fuels that goes beyond the inventory to assess water scarcity and GHG impacts. The chapters that follow lay out the methodologies used, input data, results, and discussion of the implications for transportation energy production as well as future studies.

Chapter 2 of this dissertation describes the methodologies used to develop a comprehensive LCI of freshwater withdrawals, consumption, and degradation, including engineering approaches to estimating water withdrawals, consumption, and wastewater discharge where

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no empirical data exist, proper allocation procedures, and the applicability of various LCA tools/approaches. The third chapter of this dissertation, employing the methodologies laid out in Chapter 2, presents an LCI for gasoline, ethanol, and electricity produced in the United States for passenger transportation. Chapter 4 translates these inventory results into impacts by disaggregating them to the county level and exploring the potential effects on surface and groundwater availability. Chapter 5 discusses the life-cycle energy and GHG impacts of water use, including local surface water, local groundwater, long-distance imports, desalination, and wastewater recycling. Chapter 6 presents an in-depth discussion of the national analysis results, explores uncertainty and sensitivity as applied to these results, and makes comparisons to existing studies to determine whether this research produces substantially different outcomes and, if so, why. Chapter 7 summarizes the main methodological contributions of this research as well as contributions to knowledge about the water impacts of U.S. transportation fuels, and outlines recommended future work.

The benefits of better understanding the life-cycle water impacts of fuel production are twofold. First, it allows policy makers to avoid incentivizing production of fuels that will ultimately have serious impacts on U.S. water supplies, and provides motivation to incorporate water consumption into energy legislation, as suggested by reference (*23*). Second, it can assist industry leaders in reducing their own impact on stressed water supplies in the most economically responsible manner possible.

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# 2. Methodology

## 2.1 Defining Water Use Metrics

### 2.1.1 Background

In order to understand why human water use is important, one must first grasp the natural processes that make up Earth's water cycle. Reference (*24*) describes the Earth's water cycle as a giant solar-powered machine that distills ocean water, and carries the evaporated freshwater over land where it falls as precipitation and serves the freshwater needs of life on land. Of all the water that is evaporated from the ocean, 91% of it returns directly to the ocean via rainfall. The remaining 9% is carried to land by wind patterns, where it ultimately condenses (*24*). This cycle is closed by surface runoff and groundwater seepage into the ocean, which replaces the ocean's 9% vapor "loss" to land. On land, an entire sub-cycle also operates, where water is lost to the atmosphere through plant evapotranspiration and free water surface evaporation (FWSE) from lakes and rivers and then condenses in the form of rain or snow. Rain and snow provide water that is absorbed by plants, replenishes surface water resources, and percolates down to recharge groundwater resources. The global water cycle and its sub-cycles maintain the equilibrium between oceans, groundwater, glaciers, lakes and rivers, soil moisture, and atmospheric vapor. However, human activities have a destabilizing effect by altering the natural water cycle, which will only become more significant as the world population grows and nations continue to industrialize. Even between countries that share no boundaries or climate similarities, there can be "virtual" flows of water when a production process that requires water occurs in one country to supply another (*22*). The question that follows is: how are humans altering this equilibrium between Earth's water resources, is it an unfavorable change, and if so, how should it be quantified?

Water use can be an ambiguous metric. Human activities do not chemically destroy water molecules in the same way that hydrocarbon fuels are consumed (oxidized) during combustion, so the result of water use is a temporary or permanent redistribution of freshwater resources. For example, the City of Los Angeles diverts large amounts of freshwater from the rivers that feed Mono Lake in California, resulting in a significant reduction in the lake's water level (*25*). Groundwater resources have also suffered from human withdrawals that have lowered the water table by more than 60 m in some areas (*26*). In contrast, some withdrawn water is immediately returned to its source, such as water cycled through open-loop cooling systems at thermoelectric power plants. While the former is often the only type of use that is tracked (*5, 7, 9*), one cannot assume that immediate return of freshwater to its original source has no negative impacts. If quality is degraded by contamination or other stressors, the water is less useful for other purposes. In the case of power plants, the return water comes at an elevated temperature, which has ecological impacts and limits the number of cooling systems that can withdraw from the same body of water.

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Water use can also be categorized as in-stream and off-stream. In-stream refers to a process that does not withdraw (remove) any water from its original source, but still somehow relies on that water to operate. A prime example of in-stream water use is hydroelectricity generation; although hydroelectric dams do not remove any water from the river, they do alter the flow in order to produce electricity. Some argue that, by altering the flow and hence the total surface area of water bodies, hydroelectricity does consume water by altering FWSE (*27*), but this will be discussed in more detail in Chapter 3. Off-stream water use refers to either temporary or permanent removal of water from its source; for example, thermoelectric power generation withdraws large volumes of water for cooling purposes. Irrigation and industrial process water also qualify as off-stream.

Another important method of categorizing water use comes from reference (*28*), which defines the "water footprint" of human activity as being made up of three components: blue water, green water, and grey water. The blue/green distinction is based on the water source, rather than type of use. Blue water refers to water that is withdrawn from surface or groundwater sources. Green water refers to water from rainfall that is used for human purposes, either through catchment systems or for direct absorption and evapotranspiration by crops. Grey water serves as an attempt to normalize water use and water resource degradation by translating degradation into units of water volume. It quantifies the amount of freshwater necessary to dilute water-borne pollutants to acceptable water quality standards. In general, the water footprint of any non-agricultural practices consist of only blue and grey water, whereas crops rely on rainfall (in addition to irrigation, if necessary), so the water footprint of agricultural products is made up of blue, grey, and green water.

There is one source-related water use distinction not made in reference (*22*), and that is between surface and groundwater. Although the two resources in natural environments interact, they also differ in terms of their quality (need for treatment) and availability. Groundwater resources, for example, can be depleted if the pump rate exceeds the recharge rate. Surface water resources are not limited in this way, but are more responsive to climatic variability. These differences are explored further in Section 2.4.

### 2.1.2 Framework for Quantifying Water Use

Establishing clear metrics for water use, the resulting GHG footprint, and potential impact on freshwater shortages is particularly important because different types of use have different environmental implications. LCA experts have not yet come to a consensus on how water use should be characterized, so most existing studies and datasets are plagued by inconsistencies and poor documentation. The first step in developing meaningful water LCAs is establishing a set of measures that can be implemented in a water use inventory.

This dissertation only deals with freshwater. The U.S. Geological Survey (USGS) categorizes water based on its salt content in the following manner, where 35,000 parts per million (ppm) approximates seawater (*29*):

Fresh Water: <1,000 ppm dissolved solids

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Slightly Saline Water: 1,000-3,000 ppm dissolved solids
Moderately Saline Water: 3,000-10,000 ppm dissolved solids
Highly Saline Water: 10,000-35,000 ppm dissolved solids

Freshwater is by far the most valuable water resource because, unlike saline water, it is fit for irrigation and human consumption. Many industrial processes also require freshwater. Desalination is possible and necessary in some areas, but is also very expensive and energy intensive, requiring between 10.8 and 25.2 MJ/$m^3$ for desalinating water through reverse osmosis (*30*). While saline water can be used directly for some purposes, such as thermoelectric cooling, this research will focus exclusively on tracking freshwater. Processes that rely solely on saline or seawater will be treated as having zero water use.

#### *2.1.2.1 Withdrawals*

The term "withdrawals" refers to the amount of water that is removed for any period of time from its source. In this dissertation, water withdrawals are tracked, separating surface withdrawals and groundwater withdrawals. Due to lack of sufficient data, these sources will not be further separated into specific bodies of water (rivers, lakes, aquifers, etc.). For some processes, particularly industrial facilities that practice water recycling and crops that are irrigated efficiently, withdrawals are equal to consumptive use. For others, such as thermoelectric power plants with open-loop cooling systems, withdrawals are very large, but much of that water is simply cycled through the facility and immediately returned to its source, with only a small fraction lost through evaporation or other means. Pumping such large volumes of water up from underground aquifers would require a great deal of energy, so open-loop cooling systems rely almost exclusively on surface water sources; groundwater makes up only 1% of total withdrawals for thermoelectric power generation (*12*). Aside from the ecosystem impacts associated with thermal and chemical pollution, which are not explored in this dissertation, this activity has very little impact on the availability of freshwater. Total withdrawals are nonetheless important because these facilities require that large amounts of freshwater be available, and one body of water can only withstand a limited amount of thermal pollution before the elevated ambient temperature becomes problematic. For this reason, closed-loop cooling is most common in areas with limited freshwater resources despite the fact that it actually evaporates more water per kWh of electricity produced than open-loop cooling (*31*). Additionally, tracking these withdrawals becomes necessary when calculating the GHG footprint of water supply, as all withdrawals require pumping energy.

In the case of groundwater, more energy is required to pump it up to the surface, but it also has the benefit of being cleaner than surface water due to the natural purification that occurs as the water percolates down through the soil. It is also less susceptible to fluctuations in rainfall and temperature (droughts, etc.). Underground aquifers can be confined, which means there is an impermeable or semi-permeable layer (rock, for example) between the aquifer and the surface that prevents the vertical infiltration of rainfall or surface water, or unconfined, in which case there is no such barrier (*32*). The permeability of material surrounding the aquifer plays a major role in determining its recharge rate. Many aquifers in the United States, including the High Plains Aquifer that underlies Colorado, Kansas, Nebraska, New Mexico,

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Oklahoma, South Dakota, Texas, and Wyoming, are being depleted over time because the rate at which water is pumped out for agricultural and municipal uses exceeds the recharge rate (*14*). Groundwater withdrawals are rarely returned directly to the source aquifer after use unless the water percolates down from irrigated crops or is returned through an artificial groundwater recharge system. This means that, for all practical purposes, groundwater withdrawals in the United States are equivalent to consumption.

#### *2.1.2.2 Consumptive Use*

Consumptive use refers to the amount of water that is evaporated, incorporated into a product, discharged to a body of water different from its source, or otherwise removed from its source without being immediately returned. As in the case of withdrawals, consumptive water use is tracked in this dissertation in terms of surface water consumption and groundwater consumption. Most often, water consumption occurs in the form of evaporation (through crop evapotranspiration or the release of water vapor through cooling towers, for example). Irrigated agriculture, thermoelectric power generation, and many industrial facilities withdraw freshwater from surface or groundwater sources, some or all of which is subsequently released as vapor through evapotranspiration, cooling processes, and other evaporative losses. Predicting the fate of this vapor is difficult; will it simply increase local precipitation, thus resulting in a net zero change in freshwater resources, or will wind patterns carry it elsewhere on land before it condenses? The answer is not easily determined, and varies by location. There is, however, evidence to suggest that in drier regions, an increase in evaporative losses means a net flux of freshwater out of the area. For example, the Arroyo Seco Watershed continues to operate at a net water loss of 6.9 million $m^3$ per year despite annual freshwater imports of 26 million $m^3$ of water (*33*). Forty eight percent of the watershed's total water outflow is due to evapotranspiration (*33*). Even if all evaporated water is ultimately returned to the same area, the temporary loss in water availability has its own negative impacts. Evaporative loss of river water reduces downstream flow rates; the Colorado River serves as a prime example, in which excessive water withdrawals for use in agriculture and other applications in the United States decreased downstream flow. This motivated a 1944 United States-Mexico treaty that guaranteed at least 1.9 billion $m^3$ of Colorado River water reach Mexico each year (*34*).

Another way that humans alter this cycle is by increasing the rate at which freshwater flows to the ocean, the likely result being an increase in ocean water volume and decrease in freshwater resources on land. A common example of this would be a municipal utility or industrial facility located near the coast that withdraws its water from a freshwater source on land, and discharges its wastewater into the ocean.

Finally, water can be incorporated into products. For example, agricultural products have varying moisture content, bottled water uses water as an integral part of its product, and chemicals will frequently be diluted with water. This is considered to be consumption because many of these products will be shipped to locations outside of the watershed in which they were produced. Thus, the products result in a net flux of water out of the immediate area.

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#### *2.1.2.3 Water Metrics Excluded from this Research*

A number of water use metrics have been excluded from the framework laid out in the previous section. First, saline and ocean water use are not included. This decision is based on the usefulness and abundance of these sources relative to freshwater. The total dissolved solids (TDS) in saline and ocean water makes them unfit for the majority of human uses, with the exception of open-loop thermoelectric power plant cooling systems. They can only be converted to freshwater through desalination, which can require more than three times the amount of energy typically required to provide municipal freshwater (*16*). The other important characteristic of saline and ocean water is abundance. Given that the ocean makes up 95% of the world's water (*24*), one would be hard pressed to argue that seawater is a constrained resource. Saline groundwater is the second largest component of Earth's hydrosphere at 3.9% of all water (94% of all groundwater is saline) (*24*). In contrast, total freshwater excluding glaciers makes up only 0.3% of the hydrosphere (*24*).

In addition to saline and ocean water, there are two freshwater use metrics that will not be included in the final results of this research: green and grey. As previously mentioned, one of the most popular schemes for categorizing water use comes from references (*22, 28*), in which the water footprint is split into three parts: blue water, green water, and grey water. So-called blue water is the focus of this dissertation. Green water consumption, although potentially a useful metric, does not account for the fact that preexisting vegetation would also consume rainwater and soil moisture. Therefore, in a consequential LCA, one would need to compare the relevant crop's green water consumption to that of native vegetation or whatever existed in the area before the crop of interest was planted (*35*). This practice is wrought with considerable uncertainty, so green water consumption via evapotranspiration will be discussed in this dissertation, but left out of the final results.

Evapotranspiration rates do differ greatly depending on the type of vegetation. For example, an acre of corn gives off approximately 11 to 15 $m^3$ of water per day, while one large oak tree may transpire 150 $m^3$ in a year (*36*), implying that forestland results in significantly higher green water consumption than corn crops. High-yield biomass, such as *Miscanthus x Giganteus* and switchgrass results in lower evapotranspiration than forestland, but higher than corn grain on a water volume per land area basis (*20*). Too often, green water use is compared on a per land area basis, ignoring the important fact that ethanol yields per unit of land also vary by crop (*37*). On the basis of water transpired per unit of ethanol ultimately produced, high yield biomass consumes only 60% of the green water required to produce ethanol from corn grain (*20*). If biomass crops like perennial grasses and other high-yield crops replace land that is currently used to grow corn for ethanol production, holding total ethanol production levels constant, one could argue that in fact the net effect on green water consumption is negative.

In an attempt to help mitigate potential land-use-change-related impacts, though, it is predicted that biomass crops will be grown on fallow land (cropland that is not seeded during the growing season) so as not to create competition between food and fuel crops. The baseline for comparison then becomes whatever biomass (if any) is allowed to grow on fallow cropland. If this biomass is, for example, low-yield like grassy fodder crops, reference (*20*) estimates that

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replacing this low-yield biomass with a high-yield biomass crop would almost double the evapotranspiration rate on that plot of land. This leads to another question: will biomass crops actually be planted on fallow land, and would this fallow land have remained unused or would it have eventually been seeded with some other crop? Although considered less desirable than crop rotation, fallowing can be used as a temporary method of enriching the soil and accumulating moisture, thus making it more productive for future seasons. This implies that much of the United States' fallow land will not remain inactive in the long term. The amount of fallow land that is actually available for cultivation of new crops, and the long-term intentions of the farmers/owners of that land represents a major knowledge gap that limits land-use-related biofuels research.

The companion metric to green water that has been left out of the framework is grey water. Reference (*28*) defines grey water as the "volume of fresh water that is required to dilute pollutants to such an extent that the quality of water remains above agreed water quality standards." There are two major problems with this metric. The first issue is that, because it is based on policy, it is time and location-dependent. Water quality standards vary widely around the world and even within individual countries. Standards have also evolved over time and will continue to evolve as the supporting science advances. This also begs the question: if the United States is being analyzed as a whole, as is the case in this dissertation, should grey water be measured based on each state's water quality standards or should some uniform standard be established for the purposes of the research? The second and arguably more significant problem with the grey water metric is that it is a relatively arbitrary way of including water quality degradation in the overall footprint number. Different waterborne pollutants have very different human health and ecological implications. They also differ in terms of their impact on the usability of freshwater resources. For example, increasing the salt content of a water body can make treating it to potable (or industrial) standards much more energy-intensive, whereas increasing the biological oxygen demand (BOD) or chemical oxygen demand (COD) content may not be as problematic. Also, if the release is a pulse rather than a constant flow, some pollutants will break down over time, thus restoring the water body to its original quality whereas other pollutants will persist for long periods of time. For these reasons, and because the focus of this dissertation is on water use rather than water degradation, grey water is not included in the analysis.

## 2.2 Life-Cycle Assessment

The research described in this dissertation uses a life-cycle assessment approach to determine the supply chain water impacts of transportation fuels. The term "life-cycle assessment" (LCA) is used to describe the study of a product or process from raw material extraction to decommissioning/end of life. As shown in Table 1, the life cycle of transportation fuels can be split into four major phases: feedstock production/extraction and preprocessing, fuel production/refining, fuel transportation and distribution, and combustion. All of the phases except combustion are often referred to as upstream or well-to-tank (WTT). Well-to-wheels (WTW) includes the upstream phases plus the use phase (combustion). After accounting for all of the direct impacts from each of these four life-cycle phases, the next step is to follow the life

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cycle of the inputs for those phases. For example, petroleum refineries require large amounts of electricity, and electricity generation has water impacts that should be accounted for; electricity generation also requires fuels such as coal, uranium, and natural gas whose life cycles have their own set of water impacts. Circular effects also occur: electricity is required to refine petroleum products, but petroleum products are used to generate electricity. Following this reasoning, it quickly becomes evident that LCA is both complex and infinite in nature. There are three different methods that help engineers to approach LCA in a systematic way: process-based, economic input-output, and hybrid.

### 2.2.1 Process-Based Life-Cycle Assessment

Process-based LCA refers to the practice of accounting for every process within the supply chain for the product or service of interest, and compiling their inputs and outputs to determine the life-cycle environmental impacts of the entire supply chain. As previously mentioned, LCA is inherently infinite, so reasonable boundaries must be drawn in order to make process-based LCA possible. Reference (*38*) outlines the four main steps necessary to perform a complete process-based LCA:

1. Goal/Scope Definition

   A product or service of interest, functional unit for comparison, impact(s) of interest (climate change, human health impacts, biodiversity impacts, etc.), and boundaries for analysis should be chosen during this step. Defining boundaries may require an initial educated guess as to what will or will not be important, given the impact(s) of interest, and will be refined later on.
2. Inventory Analysis

   The first step in quantifying an impact, such as human health, is to collect data on the process inputs and outputs that will contribute to the chosen impact. Typically, these data are taken from other sources rather than being collected directly from the field. Assessing the quality of these data is an essential step and any associated uncertainty should be addressed. Sensitivity analysis and external validation can help to ensure that the results are reliable.
3. Impact Analysis

   Translating inventory data into final impacts on human health and the environment is arguably the most difficult step. A wide variety of metrics can be used, depending on which are most relevant to the system in question. Human health impacts are often measured in disability-adjusted life years (DALYs), whereas ecosystem impacts can be measured in eutrophication, acidification, or a number of other metrics. A simple example how impact assessment can be performed is greenhouse gas normalization by their effects on radiative forcing. According to the IPCC, methane is approximately 23 times more potent than $CO_2$ as a greenhouse gas; this means that emitting 23 Mg of $CO_2$ has roughly the same impact on climate change as one Mg of methane (*39*). However, even this seemingly simple conversion has embedded assumptions. Global warming potential (GWP, measured in $CO_2$-equivalent) is dependent on the time horizon because different gases remain in the atmosphere for different lengths of time. The GWP for

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methane cited above (23) uses a 100-year time horizon, but a shorter horizon would result in a much higher GWP and a longer one would result in a smaller GWP. These assumptions can be somewhat arbitrary; there is no obvious reason for using a 100-year horizon instead of 50, 150, or even 300. Despite its challenges, however, impact analysis is extremely important, as it is the only way to understand and compare the full environmental impacts of products and services.

4. Improvement Analysis

   After the impact analysis is complete, recommendations should be made as to how negative impacts can be reduced. This could involve choosing one product or service over another, altering the supply chain of a product/service, or even relocating certain production processes. The improvement analysis should be guided by the initial question to be answered, whether it is as simple as paper vs. plastic grocery bags, or as complicated as where and how a new transportation fuel should be produced.

### 2.2.2 Economic Input-Output Analysis-Based Life-Cycle Assessment

Economic input-output LCA takes a very different approach than the previously described process-based method; it utilizes economic input-output data combined along with impact per dollar output factors ($CO_2$ emitted per dollar's worth of output, for example) to calculate the supply-chain environmental footprint. It should be noted that EIO-LCA does not include the use or EOL phases, so these must be calculated using process-based methods.

Economic input-output analysis was developed by Nobel Laureate and economist, Wassily Leontief. It begins with a matrix that displays the economic transactions between sectors, as shown in Table 2. This is known as the direct requirements table. As shown in the table, $D_{12}$ represents the dollar value of products or services that sector 2 requires from sector 1 as an input to its own production processes, per dollar of output from sector 2 (for every dollar of output produced by sector 2, $D_{12}$ dollars are required as inputs from sector 1). All of the other elements will be less than 1 because it would not make sense for the value of any of the inputs to be greater than the value of the product (there would be no point in producing a car worth $10,000 if the engine alone is worth $15,000). In addition to the products traded among sectors, each sector sells a portion of its output directly to consumers, and this is known as final demand (F). Therefore, the total output from any given sector should be equal to the amount sold to other sectors, plus the final demand. In equation form, where D represents the direct requirements matrix, X represents the total output vector, and F represents the final demand vector, this becomes (see Equation 1):

$$X = DX + F$$

Equation 1: Relationship Between Direct Requirements, Total Requirements, and Final Demand

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| Output from | Input to | | | | Final Demand |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | n | |
| 1 | $D_{11}$ | $D_{12}$ | $D_{13}$ | $D_{1n}$ | $F_1$ |
| 2 | $D_{21}$ | $D_{22}$ | $D_{23}$ | $D_{2n}$ | $F_2$ |
| 3 | $D_{31}$ | $D_{32}$ | $D_{33}$ | $D_{3n}$ | $F_3$ |
| n | $D_{n1}$ | $D_{n2}$ | $D_{n3}$ | $D_{nn}$ | $F_n$ |

Table 2: Sample Direct Requirements Table

Of course, the goal of economic input-output analysis is to go far beyond just the direct requirements for a given sector. To determine the 2nd level requirements (indirect, one level up in the supply chain), D must simply be squared, for the third level, D is cubed, etc. Equation 2 shows how to calculate the total requirements matrix (T) using the direct requirements matrix (D) and the identity matrix (I) with the same dimensions as D. I is used to indicate that, for a sector to produce $1 of product, it requires one dollar's-worth of production from itself, plus whatever additional demand exists.

$$T = I + D + D^2 + D^3 + D^4 \ldots$$

Equation 2: Total Requirement Matrix Calculated from the Direct Requirements

Revisiting Equation 1, it can be rearranged to produce Equation 3:

$$X = (I - D)^{-1} F$$

Equation 3: Total Output Calculated from the Direct Requirements and Final Demand

$(I - D)^{-1}$ is known as the Leontief Inverse, and is equivalent to Equation 2. Thus, T can be substituted in to produce Equation 4:

$$X = TF$$

Equation 4: Total Output Calculated from the Total Requirements and Final Demand

Recall that X represents the total output vector, and F represents the consumer demand for each sector. In economic input-output analysis, the typical question is: given a certain consumer demand for one or more products, what is the total economic activity (production) generated in every sector of the economy? To answer this, one would enter the desired economic demand as F, and multiply it by T to get X, or the total economic activity.

Reference (*40*) used economic input-output analysis to build a model for assessing environmental impacts by developing impact per dollar of economic activity vectors for each sector of the economy. The Economic Input-Output Life-Cycle Assessment Model (EIO-LCA) allows the user to enter an economic input for one or more sectors, and calculate a variety of life-cycle environmental effects (such as GHG emissions, CAP emissions, or toxic releases to soil, water, and air). Unlike process-based LCA, there is no need to define system boundaries; EIO-LCA's boundaries are infinitely large. It is also a very quick and simple method for performing an LCA. There are, however, a number of limitations. First and foremost, collecting the transactions data and producing the direct and total requirements matrices is a major task. The U.S. Bureau of Economic Analysis (BEA) publishes these data for the United States, but it only

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collects new data every five years and there is a five-year lag between collection and publication, so the 2002 data were just released in 2007. This means that emerging industries, such as biofuels, are often not included for many years. Another limitation is the aggregation of different production processes within sectors. The BEA releases data in terms of North American Industry Classification System (NAICS) codes and some of the sectors include multiple industries that are likely to each have quite different environmental impacts per dollar. For example, the 1997 model combined all power plant types in one sector: power generation and supply, rather than splitting it into nuclear, coal-fired plants, hydroelectricity, etc. In regards to the environmental impact vectors, the source data are of varying quality, depending on the impact and sector in question. There are usually little or no data for more obscure sectors, such as beet sugar manufacturing (NAICS code 311313), so assumptions must be made about their similarity to other sectors for which there are data available. Lastly, the EIO-LCA method is incapable of accounting for differences between average and marginal impacts; it can only provide averages.

### 2.2.3 Hybrid Life-Cycle Assessment

The positive and negative aspects of process-based and economic input-output methods for LCA have been discussed in detail and it is clear that neither method is always better than the other. Each has its benefits and drawbacks. EIO-LCA is quick to run and can provide a sense for the magnitude of life-cycle environmental impacts. It also serves as a screening tool to pinpoint which processes within the supply chain of a particular good or service are major contributors to the overall impacts. EIO-LCA only captures the average unit, however, so it is inherently attributional in nature (see Section 2.2.4 for further discussion of attributional LCA). It also excludes any economic activity outside of the United States and aggregates industries into economic sectors, which can skew the results for an analysis that is focused on a very specific product or service. Conversely, process-based LCA is entirely within the researcher’s control, so the geographic boundaries, distinction between the marginal and average unit, level of industry aggregation, and all other factors can be altered to meet the specific goals of the analysis. The downside of the process-based approach is that it is time-consuming and the researcher must establish boundaries for the analysis, meaning that only a fraction of the product or service’s supply chain is actually accounted for.

Hybrid LCA attempts to combine the best aspects of both methods by using the process-based approach initially, following the most important supply chains for the first few levels, and then using EIO-LCA to calculate the remaining effects. As discussed in reference (*41*), the boundary limitations of using only a process-based approach results in an underestimation of environmental impacts, referred to as cutoff error, but the use of EIO-LCA on its own results in aggregation, geographic, and temporal error. In addition to avoiding cutoff error, EIO-LCA can also be used initially to judge which products and services are most important and should be analyzed through process-based LCA.

Figure 2 illustrates an example of hybrid LCA as applied to groundwater pumping using an electric motor. There are other inputs to groundwater pumping, such as the materials and

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energy used to manufacture the pump itself, but this figure focuses on the electricity used to power the pump. Groundwater pumping is not its own sector in EIO-LCA, but rather is contained within the "water, sewage, and other systems" sector, which means the results will be an average of all water supply and wastewater treatment processes (*42*). To avoid this aggregation, the researcher will collect data on the amount of electricity required per unit of water pumped from the groundwater source of interest. Suppose the goal of the analysis is to calculate the life-cycle GHG emissions of groundwater pumping. A quick run of EIO-LCA for the "power generation and supply" sector shows that 94% of the total life-cycle GHG emissions come from the "power generation and supply" sector itself (in other words, power plants) (*42*). The results indicate that most of the researcher's effort should be spent accurately quantifying the GHG emissions from the production of electric power that ultimately supplies the groundwater pump, taking into account the geographic location of the pump and whether the analysis calls for the average mix or marginal electricity mix. Once the GHG footprint of electricity production is calculated, EIO-LCA can be used to eliminate cutoff error by estimating processes further down the supply chain, such as coal, natural gas, uranium, and other fuel supply. This is reflected in Figure 2, where the dotted line indicates the point at which process-based LCA ceases and EIO-LCA is used.

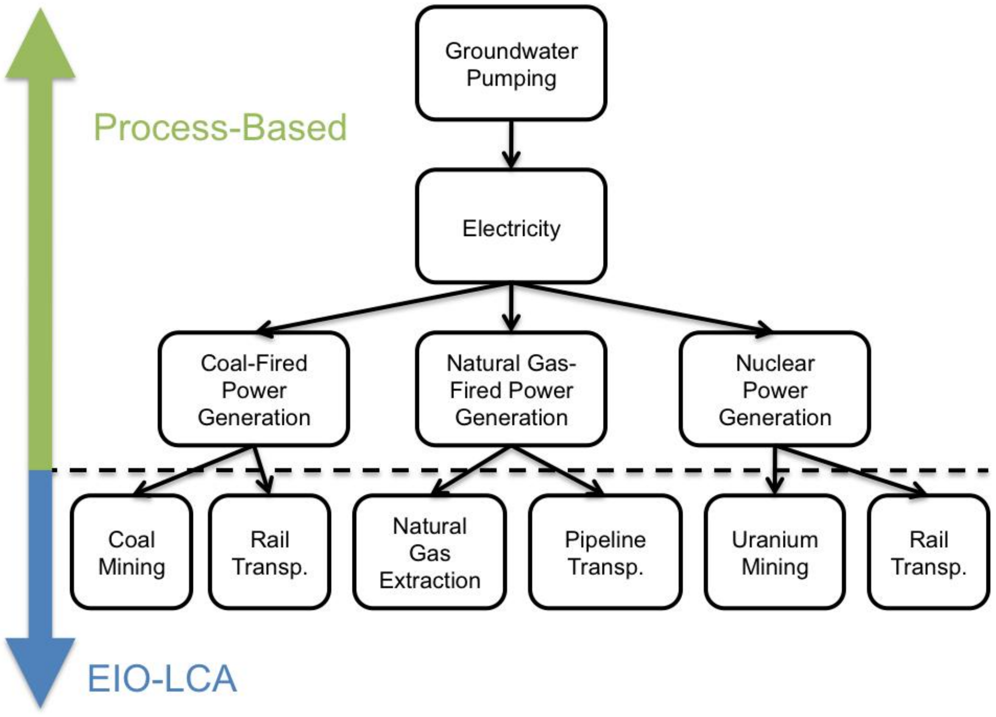

Figure 2: Hybrid LCA Example

### 2.2.4 Consequential versus Attributional LCA

As shown in Section 2.2.3, there are a number of different methods available for answering the same question. In contrast, consequential and attributional LCAs are distinguished from one another by the type of question being asked. As the name might suggest, consequential LCAs

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aim to answer the question: what are the consequences of providing some additional amount of a good or service? An attributional LCA aims to answer the question: what are the average impacts of the existing production of a good or service?

Electricity serves as a simple example to demonstrate how the choice between attributional and consequential LCAs can affect a study's results. To perform an attributional LCA of electricity consumption in the United States, one would use the average generation mix of coal, hydroelectricity, natural gas, nuclear, etc. to calculate the environmental impacts. However, a consequential LCA would require that a marginal mix be calculated (in other words, fuels that would be used to generate an additional unit of electricity). In the case of electricity, most coal and nuclear power plants operate near capacity, so these would not be ramped up to meet additional demand. Rather, natural gas, petroleum, and sometimes hydroelectricity, make up the marginal unit of electricity.

The choice between consequential and attributional LCA has significant implications for calculating water use as well. For example, crude oil extraction generally requires more water as a well is depleted, so as the easy-to-extract oil becomes less abundant, the marginal unit of crude oil is likely to become increasingly water-intensive (*5*). For biofuels, the difference between the average and marginal unit can be even more pronounced. Irrigation water required for corn grain production varies greatly depending on where the corn is grown (*3*). If the marginal unit is grown in areas with enough rainfall that little or no irrigation is required, the water footprint of corn ethanol production will be on the same order of magnitude as gasoline. If the marginal unit of corn is grown in areas that require significant irrigation, such as Nebraska, the water footprint will be multiple orders of magnitude higher than petroleum fuels (*8*). Finally, the consequential/attributional choice dictates which impact allocation methods are most appropriate for a given study, the implications of which are discussed further in Section 2.3. Ultimately, the choice comes down to what the study is attempting to quantify, and how the results will be used.

When the goal of an LCA is to inform policy decisions that will impact future production of goods and services, consequential LCA is generally a more appropriate choice, which is why this research takes a consequential approach. Yet another distinction can be made within consequential LCA between marginal and incremental analysis (*43*). Marginal refers to the impacts of producing an additional, infinitesimally small unit of good or service. Incremental analysis refers to a larger increase (for example, one could run a scenario in which U.S. electricity production must increase by 10%, and calculate which energy sources would supply that additional 10%). Performing an incremental analysis can often be more challenging because it requires assumptions about future investments in additional capital, such as industrial facilities, power plants, or other infrastructure. In some industries, the distinction may make little or no difference, while in others, it may be absolutely critical. For example, the incremental unit of freshwater supplied to residents of Southern California could come from desalinated seawater or brackish water, recycled wastewater, or additional imports, depending on which infrastructure systems are built/expanded. Such decisions are based on a multitude of legal, political, economic, and environmental considerations.

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### 2.2.5 Direct versus Indirect Economic Impacts

Traditionally, the term “direct”, as used in the LCA community, refers to inputs that are directly required for the provision of the good or service in question; for example, electricity is a direct requirement for auto manufacturing because electric energy is used to run the machinery, provide lighting in the factory, etc. Conversely, “indirect” is traditionally used to describe inputs that are required upstream in the supply chain; for example, coal is indirectly required for auto manufacturing because coal is used to generate the electricity that the plant uses. However, with the publication of reference (*44*), an entirely new type of indirect impact has been introduced as important. Reference (*44*) shows that market signals resulting from production of a good or service can cause additional environmental impacts beyond the supply-chain effects usually characterized in LCAs. The specific case on which the paper focuses is indirect land use change (abbreviated as iLUC) resulting from increased biofuel production. Put simply, conversion of agricultural land from food production to biofuel feedstock production means a decrease in food supply, which then raises the global price of food, providing farmers with an incentive to bring additional land into production. Reference (*44*) calculates that the largest fraction of this new land cultivation will occur in Brazil, followed by India and China, and lastly, the United States. Clearing forestland for cultivation results in a release of soil carbon and carbon previously stored in vegetation into the atmosphere, which has been shown to contribute significantly to the overall carbon footprint of biofuels (*44*). Although it has not been quantified, iLUC also has implications for water use. Suppose corn that had previously been grown for food is now used to produce fuel ethanol in the United States, thus resulting in new corn production elsewhere. From a consequential perspective, the water footprint of the additional unit of corn ethanol is equal to the net change in water use as a result of the change in land use.

The emergence of iLUC also highlights a larger issue: the importance of setting appropriate geographical system boundaries in consequential LCAs. For products that are net imports or are neither exported nor imported, determining the marginal unit is more straightforward. In the former case, whichever country supplies a greater quantity in response to increased demand is the supplier of the marginal unit. In the latter case, the marginal unit comes from increased supply within the country. For a product that is a net export, although additional local demand for that good will likely be supplied by local production, the result is a reduction in total exports of that good, which in turn raises global prices and incentivizes an increase in production. Economic models can be used to determine which countries will likely provide this additional supply; for example, reference (*44*) calculates that, when U.S. corn from 12.8 million ha of land is no longer exported, 10.8 million ha of additional land will be brought into production globally, including 2.2 million ha in the United States, 2.8 million ha in Brazil, and 2.3 million ha in China and India. From an environmental perspective, identifying which countries will provide marginal units of the good in question can be crucial since the impacts of production can vary greatly depending on the strictness of a country’s environmental regulations.

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While the existence of indirect economic impacts is essentially universally accepted, the question of how they should be treated in environmental regulations remains a point of contention.  The California Low Carbon Fuel Standard (LCFS) iLUC impact estimates are performed as part of corn ethanol's carbon footprint (*45*).  The argument for such inclusion is a reasonable and pragmatic one: if regulators are aware that the production of corn ethanol results in iLUC and, hence, increased GHG emissions, an iLUC GHG factor should be included in order to disincentivize corn ethanol production.  Reference (*46*) makes this argument in support of the decision to include iLUC factors in the LCFS, while reference (*47*) asserts that iLUC should not be included in biofuels regulation.  The reasoning for excluding indirect economic impacts has to do with the principles of externality management.  Corn ethanol producers should not be held responsible their impact on land use change because they have no direct control over global grain prices or decisions made by farmers in foreign countries (*47*).  Additionally, actual GHG emissions attributable to iLUC are highly variable and uncertain (*47*).

The assertion that including iLUC-related GHG emissions violates basic principles of externality management is an interesting one.  Assuming that ethanol producers are each locked into a particular feedstock, such that corn ethanol producers are only capable of processing corn grain, the argument holds true.  However, if one assumes that future biorefineries will be hybrids, capable of processing a variety of sugar, starch, or biomass feedstocks, the problem becomes more complex.  In this case, while ethanol producers have no control over the iLUC impacts of corn, they do have the ability to choose other feedstocks that do not cause iLUC. iLUC becomes similar to any other indirect environmental impact included in life-cycle-based standards.  For example, biofuel producers have no direct control over the environmental impacts of manufacturing the chemicals they purchase, but they can choose to purchase these chemicals from companies that minimize their carbon emissions and other environmental impacts.

Still, one could argue that in the case of chemical manufacturing, power generation, or any other activity along the life cycle, some party does exercise control over the associated externalities.  Chemical manufacturers can take steps to minimize emissions, waste generation, and resource consumption; the owners of power plants can install emissions controls or implement carbon capture and sequestration (CCS).  In the case of iLUC associated with corn ethanol, the only method by which corn farmers could minimize their iLUC impact would be to increase yields, and thus total corn production.  Unfortunately, the way in which iLUC is currently treated in the California LCFS does not account for potential yield increases.  Whether this lack of control is sufficient grounds for ignoring iLUC altogether remains unclear.

## 2.3 Impact Allocation

Allocation is a methodological problem that is ubiquitous in LCA.  The selected allocation method can have a profound impact on LCA results.  Unfortunately, these choices are often arbitrary and, even more frequently, poorly documented.  Some allocation problems have objectively correct solutions, while others can be more subjective.  By breaking these problems down according to some key characteristics, one can begin to develop a guide for how best to

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allocate the impacts of any system. There are two main types: multi-output production systems and open-loop recycling. The former refers to any process that results in multiple outputs with some market value. In this case, the inputs and environmental impacts of the process must somehow be attributed to each output. Open-loop recycling refers to any good that, at the end of life (EOL), can be somehow reused outside the immediate system from which it originated. Some examples of open-loop recycling are steel, aluminum, paper, and some plastics, all of which can be collected, processed, and used in the production of new goods. Questions arise about when to include credits for avoiding virgin material consumption by using recycled materials, and credits for intentionally producing a good that can easily be recycled at the end of its life.

### 2.3.1 Allocation from the Perspective of Consequential and Attributional LCA

Researchers in LCA frequently make attempts at establishing both general and process-specific frameworks for choosing the most appropriate allocation method (*48-53*). These frameworks are presented as applicable for any LCA when in fact they ignore one critical piece of information: the distinction between consequential and attributional LCA. As discussed in Section 2.2, this choice is critical and should be dictated by the ultimate purpose of the study in question. The choice also determines how allocation problems should be dealt with, despite the fact that literature published until this point treat allocation as independent of the consequential/attributional choice.

A prime example of this oversight in LCA is the ISO 14044 standards, which recommends that, where a production process cannot be subdivided to avoid allocation altogether, system expansion be used (*54*). System expansion simply refers to quantifying the net impact of introducing a co-product into the market. For example, to determine how much GHG emissions should be allocated to the electricity produced at a combined head and power (CHP) plant, one could subtract off the emissions avoided as a result of the plant’s heat supply. System expansion is discussed in more detail in Section 2.3.2. This practice is inherently consequential because it involves estimating the total change as a result of increased production. This is further evidenced by the fact that, if the production that the co-product displaces has a larger environmental footprint than the total production process in question, the net result of system expansion can be negative. Such is the case for the total life-cycle withdrawals in cellulosic ethanol fuel production pathways, as shown in Section 3.4. Because attributional LCA is essentially an accounting method, the total impact of a process should never be negative. This dissertation assesses both co-product and open-loop recycling impact allocation methods from a consequential perspective, so any methods that are inherently consequential are prioritized in relation to attributional methods.

### 2.3.2 Multi-Output Production Systems

Even within multi-output production systems, there are two types of allocation that must take place: allocation of operational inputs and impacts (such as energy consumption, water consumption, air emissions, etc.), and allocation of infrastructure/capital inputs and impacts

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(such as production facility construction, maintenance, and material inputs, as well as storage and distribution infrastructure like pipelines, roads, etc.). Both are discussed in detail in this Section. However, because allocation of operational inputs and impacts is the more difficult of the two, and often has a much greater influence on the overall results of an LCA, the vast majority of literature focuses on operational allocation.

### *2.3.2.1 Literature Review*

A natural first step in dealing with allocation in multi-output production systems is to consult the ISO guidelines, which establish general best practices for LCA. They define multi-output production system allocation as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (*54*). The guidelines are reproduced below:

(*54*): *ISO 14044 Guidelines for Allocation in LCA*
*a) Step 1: Wherever possible, allocation should be avoided by*

> *1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or*
> *2) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.*

*b) Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.*
*c) Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products. Some outputs may be partly co-products and partly waste. In such cases, it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only. Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system. The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.*

As described in ISO 14044 (*54*), there are steps that should be taken (division into sub-processes or system expansion) to ensure that allocation is only performed when absolutely necessary. However, if those alternatives have been exhausted, allocation based on physical relationships between the inputs and outputs should be used, and failing that, one can base the allocation on market values, energy content, or some other unit by which the outputs can be

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normalized. The following studies discuss system expansion, as well as various allocation methods. Most offer insight as a product of case study applications.

(*48*): *Wang et al. (2004)*
*System of interest*: petroleum refineries
*Allocation methods assessed/presented*: mass-based, energy content-based, and market value-based
*Summary*: First, the authors assert that it is important to divide the system into sub-processes whenever possible, rather than treating the larger system as a black box. Many of the most energy-intensive processes such as hydrocracking and hydrotreating are used exclusively to produce lighter products, and their impacts should thus be allocated primarily to those lighter products. In terms of mass vs. energy content vs. market value allocation, it is shown that the choice can lead to different results, particularly for diesel fuels, LPG and naphtha, but no conclusion is made about which allocation method(s) is preferable.

(*55*): *Kim and Dale (2005)*
*System of interest*: ethanol from corn grain and corn stover, soybean biodiesel (agriculture and fuel production phases)
*Allocation methods assessed/presented*: system expansion
*Summary*: The authors assert that, for corn oil, corn gluten meal, corn gluten feed, soybean meal, glycerin, and surplus electricity, there are alternative product systems that either result in the same product or one that is functionally the same. Thus, system expansion can be used to allocate impacts to these co-products. This builds from reference (*49*), which discusses displacement ratios for co-products in the corn grain-to-ethanol conversion process. The focus is, however, entirely on biorefinery impact allocation, and does not offer any insight as to how the impacts of cultivating corn and soybean crops should be treated.

(*50*): *Weidema (2000)*
*System of interest*: no specific system
*Allocation methods assessed/presented*: system expansion
*Summary*: The author makes the argument that allocation by mass/energy content/market value/etc. is never necessary in prospective LCAs (looking at future production, as opposed to retrospective LCAs that examine past production). He states that, for systems where the output quantities of each output can be varied independently of one another (called combined production), the impact that should be assigned to each product is equal to the marginal impact of increasing the output of that product by one unit. In the ISO guidelines, this is referred to as allocation by physical relationships and is summarized in "step 2". For processes where the ratio of products to one another is fixed (termed joint production), the author asserts that a product that is comparable to the co-product can always be found such that system expansion is possible; in other words, allocation is never necessary for joint production processes. Built into this assertion is the assumption that price elasticity is zero and demand is constant over time. If this were the case, any change in production of a good or service would be displacing some functionally equivalent good or service and indeed, system expansion would always be

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applicable.  However, these are not appropriate assumptions when dealing with transportation fuels, which is why other studies have been forced to use alternative methods of allocation (such as mass, energy, and market value-based) (*48*).

(*52*): *Ekvall and Finnveden (2001)*
*System of interest*: no specific system
*Allocation methods assessed/presented*: ISO 14041 allocation guidelines
*Summary*: The authors point out that, while ISO 14041 stresses that system expansion be used whenever possible, often the appropriate data are not available or difficult to obtain. Sophisticated economic modeling is required to determine the actual impact of an increase in production of a product on the supply of other products within the economy.  This is a very valid point, and should be taken into account when deciding whether to use system expansion or the simpler market value or physical characteristic-based allocation methods.  The authors also assert that subdivision (drilling down to the lowest level of sub-processes possible before performing allocation) should also be performed with caution because while some sub-processes may appear independent of one another, they may be physically or economically linked.

(*56*): *Pierru (2007)*
*System of interest*: petroleum refineries
*Allocation methods assessed/presented*: cost-based allocation via linear programming
*Summary*: Pierru shows that Aumann-Shapley prices, derived through linear programming can be used to allocate impacts from a refinery to the various outputs.  Building from work by references (*57*) and (*58*), this method has the advantage of being able to incorporate policy-related costs, such as carbon pricing, into the optimization.  Unfortunately, the cost information required to perform this analysis is not typically publically available, which makes this method less useful for large-scale analysis.  Other papers that present linear programming approaches include (*59-61*).

(*62*): *AERI (2009)*
*System of interest*: petroleum refineries
*Allocation methods assessed/presented*: physical relationship-based allocation via linear programming
*Summary*: In this report, commissioned by the Alberta Energy Research Institute and completed by MathPro, Inc., a proprietary linear programming (LP) model developed by MathPro, Inc. was used to analyze the marginal change in environmental impacts resulting from a 1% decrease in each refinery output while holding all other outputs and inputs constant.  For an average U.S. refinery, they report that gasoline is responsible for the lion's share of energy consumption, at 928 MJ per barrel of gasoline, followed by 517 MJ per barrel of jet fuel, and finally 348 MJ per barrel of diesel.  All other refinery outputs are essentially zero.  The fact that the model and its assumptions are kept private makes assessing sensitivity and uncertainty infeasible, but the general methodology laid out in this report is defensible.

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(*63*): *Guinée et al. (2004)*
*System of interest*: none
*Allocation methods assessed/presented*: economic allocation (market value-based)
*Summary*: The authors provide a more detailed guide to performing market value-based allocation of impacts. They list 17 common problems associated with market-based allocation, and provide recommended solutions for each. For the most part, the solutions are reasonable, although some may result in distorted results due to poor-quality data. For example, when dealing with market values that are distorted by regulations, it is suggested that the user "accept prices as they are, use value or cost of close alternative for missing market prices" (*63*). The question remains: at what point are the data so distorted or incomplete that using market prices is no longer the preferable option? As of now, the only viable option is for the user to perform sensitivity analyses on a case-by-case basis. The authors follow this discussion with a case study: co-production of caustic soda, chlorine, and hydrogen.

(*64*): *Frischknecht (2000)*
*System of interest*: general discussion with case study
*Allocation methods assessed/presented*: market value-based, physical property-based, system expansion
*Summary*: The author takes a management sciences approach to allocation in LCA. He provides a qualitative discussion about aligning allocation methods with motivation for production, acknowledging that the choice is always subjective and subject to case-by-case judgment. He uses the simple example of combined heat and power (CHP). The ratios are listed for allocation by energy content, exergy content, market value, and "motivation" (all allocated to heat, or all allocated to electricity). In this case, it becomes clear that energy content is not appropriate since it vastly overvalues heat. The author also discusses system expansion, making the assertion that it should be considered an allocation method, rather than a means of avoiding allocation.

(*65*): *Cederberg and Stadig (2003)*
*System of interest*: milk and beef production
*Allocation methods assessed/presented*: economic (market value-based) allocation, cause-effect physical (biological) allocation, system expansion
*Summary*: For the most part, this paper is simply a case study using methods that have already been described above. However, one method that has yet to be discussed is cause-effect physical (biological) allocation. The context in which it is presented is a cow as the production facility, with inputs being feed and outputs being milk, calves, and meat. Because there is a cause-and-effect relationship between different feed elements and production of milk, calves, and meat, ratios for allocation can be derived by examining what happens to production as quantities of the feed mixture ingredients are varied. In regards to biofuels, this method can be applied to crops, where fertilizer, water, and other inputs may have varied effects on different outputs (corn grain versus stover, etc.). It should be noted that attempting to model living organisms in the same manner as man-made production systems can be risky; the relation

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between inputs and outputs is typically non-linear and difficult to predict due to the multitude of external factors that play a role in output levels.

### *2.3.2.2 Methodology*

As shown in the review of allocation literature, a number of options for allocating impacts and inputs in a multi-output production system exist. In this section, existing methods are critically evaluated and a process for determining the proper allocation for any system is laid out.

Multi-output production system allocation is broken down into two main categories: infrastructure allocation and operational allocation. The impacts associated with constructing, maintaining, and decommissioning infrastructure must be allocated among its users; this is referred to as infrastructure allocation, and includes any capital being used to produce goods or provide services. For example, in an LCA of transportation, roads are used by many different parties, both passenger and freight, and the impacts of that road system should be allocated accordingly. Another example explored in reference (*66*) deals with the use of airplanes for the transport of passengers, as well as mail and other freight.

*Infrastructure Allocation:*

Typically, the life-cycle impacts of construction, maintenance, and decommissioning are summed, and then divided over the total service provided over the expected life of the infrastructure. This simple calculation method is shown in Equation 5, where I equals the impacts of construction, maintenance, and decommissioning activities, L equals the lifetime of the infrastructure system, S equals the quantity of the service provided by the infrastructure over its lifetime, and $S_x$ equals the quantity of service demanded by user X.

$$\text{Simple Life-Cycle Infrastructure Impacts of “User X”} = \frac{\sum_L I}{\sum_L S} \bullet S_x$$

Equation 5: Simple Formula for Infrastructure-Related Impacts of Providing a Service

Over the lifetime of an infrastructure system, its use will result in depreciation, requiring maintenance and perhaps, eventually a complete replacement. These are the only ways in which users can alter the environmental impact of infrastructure. Thus, infrastructure impacts should be allocated to multiple users, not based on the total quantity of a service that each one receives, but the impact that these users have on maintenance needs and the system’s overall lifetime. For example, service provided by roads could be measured in vehicle-miles (or passenger-miles), but it is well known that heavier vehicles such as freight trucks and large passenger buses do significantly more damage to roads over time than do lighter vehicles (*67*). Therefore, a greater fraction of the impacts of building and maintaining roads should be allocated to these heavy vehicles. The same is true for any capital for which some users/products cause greater damage than others. Equation 6 shows the adjusted formula, allocating infrastructure impacts by contribution to maintenance/replacement needs rather than total use. ∆L represents the change in lifetime (L) of the infrastructure system or

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particular component as a result of User X. For example, suppose that a stretch of paved road will last 50 years if 500,000 identical freight trucks pass through per year. This means that, per truck, the road ages 50 years divided by 500,000 trucks/year * 50 years, which comes out to 2 x $10^{-6}$ years (1.05 minutes) per truck. Hence, the infrastructure impact of one truck on that particular stretch of road would be 2 x $10^{-6}$ years divided by 50 years, multiplied by the overall impacts of building and maintaining the infrastructure over its lifetime. This comes out to be:

$$(4 \times 10^{-8})\sum_{L} I$$

The general equation is shown in Equation 6.

$$\text{Adjusted Life-Cycle Infrastructure Impacts of "User X"} = \sum_{L} I \bullet \frac{\sum_{\Delta L} S}{\sum_{L} S}$$

Equation 6: Adjusted Formula for Infrastructure-Related Impacts of Providing a Service

Certainly, this more accurate method of allocating capital/infrastructure impacts requires information that may not be readily available, such as how a particular piece of equipment typically fails and which users/products contribute most to that failure. There are also instances where various users do not directly contribute to infrastructure depreciation. For example, a stoplight does not wear out more quickly if more cars utilize that particular intersection (ignoring the possibility that some fraction of those cars accidentally strike the pole with their vehicles). Still, when a major disparity exists between the wear and tear resulting from different users/products, using even a very basic estimate is better than utilizing the simple formula shown as Equation 5.

Unfortunately, even in theory, it is not always possible to use Equation 6 to allocate infrastructure impacts. Consider a steel tank in which a chemical reaction takes place and one of the ingredients for the reaction is corrosive. After some period of time, the tank will become so corroded that it needs to be replaced. If the chemical reaction produces multiple outputs, it is not immediately clear how the impacts of manufacturing, installing, maintaining and eventually disposing of the steel tank should be allocated. Because the corrosive ingredient (an operational input) is the determining factor for the tank's lifetime, the corrosive ingredient and its resulting environmental impacts should be allocated based on operational allocation methods, and then the tank's life-cycle impacts should be allocated in an identical fashion. This example illustrates the fact that sometimes infrastructure allocation and operational allocation are sometimes closely tied. Compared to the infrastructure allocation methods outlined above, operation allocation can be far more complicated, and often relies on choices that are subjective in nature.

*Operational Allocation:*

Assuming subdivision of processes in order to eliminate any need for allocation is not possible, ISO 14044 lists three main strategies: system expansion, physical relationship-based allocation,

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and allocation by functional unit. An important first step in establishing proper allocation practices is to evaluate these existing methods and their ability to be applied practically with a critical eye.

System expansion, where possible, is preferable to other operational allocation methods. In fact, ISO 14044 (*54*) does not consider it to be allocation, but rather a method of avoiding allocation (similar to dividing a larger production system into sub-processes that each only have one output). It can be used whenever a co-product is displacing another identical or comparable product (in economic terms, a perfect substitute). The impacts per functional unit of producing this comparable product are subtracted from the total impacts of the process in question to determine the impacts that should be allocated to the product being studied. A simple representation is shown in Figure 3, where the focus of the study is Process 1 and the production that is being displaced is Process 2 (used to create Product B).

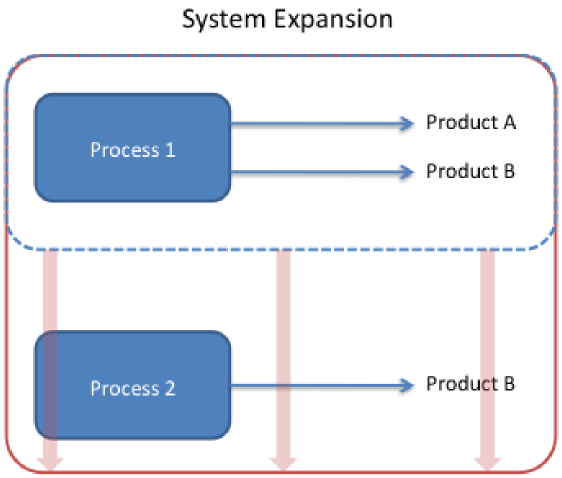

Figure 3: System Expansion Example

To determine the impacts from Process 1 that should be allocated to Product A, Equation 7 can be used, where:

$I_{1A}$ = Impacts from Process 1 allocated to Product A, per unit output of Product A

$I_1$ = Total impacts from Process 1

$O_{1A}$ = Total output from Product A from Process 1

$I_2$ = Total impacts from Process 2

$O_{2B}$ = Total output of Product B from Process 2

$O_{1B}$ = Total output of Product B from Process 1

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$$I_{1A} = \frac{I_1}{O_{1A}} - \frac{I_2}{O_{2B}} \times \frac{O_{1B}}{O_{1A}}$$

Equation 7: Impact Allocation via System Expansion

One major assumption made in performing system expansion is that demand for the displaced product (in the example above, Product B) is perfectly inelastic. If demand is not perfectly inelastic, the substitution ratio would not be 1:1 because adding more of the good (or its functional equivalent) would result in an increase in total demand. Determining the actual price elasticity of the product in question may be infeasible, but it is important to, at a minimum, acknowledge this assumption and address whether it is realistic for the particular good or service in question.

Where system expansion is infeasible, or poor data quality makes it an undesirable choice, other strategies must be employed. Physical relationship-based allocation can be a useful alternative. For a production system in which the outputs can be varied independently of one another and no constraints exist, allocation by physical relationships is a straightforward task. Consider a hypothetical process in which two outputs (A and B) are produced from feedstock F, with resulting energy consumption E and environmental impacts I (see Figure 4). One can increase production of A infinitesimally while holding B constant to determine the marginal environmental impact (I), energy use (E), and feedstock input (F) for A. The same can be done for B, while holding A constant, these marginal factors for A and B can be multiplied by their respective output, and the ratio between them is the ratio by which F, E, and I should be allocated. Equation 8 demonstrates this process for allocating F (an identical process can be used for E and I).

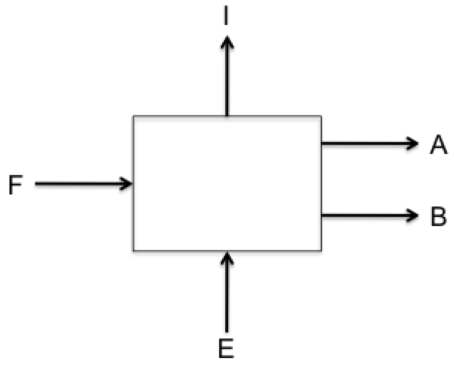

Figure 4: Hypothetical Co-Product System

$$\frac{\frac{\partial F}{\partial A} \bullet A}{\frac{\partial F}{\partial B} \bullet B} = \text{Feedstock Allocated to Output A / Feedstock Allocated to Output B}$$

Equation 8: Allocation of Input F between Outputs A and B by Physical Relationship

In many systems, this is not possible because the output ratios are fixed; for example, the amount of glycerin that is produced alongside biodiesel is governed by chemical reactions and cannot be increased or decreased without also increasing or decreasing biodiesel output. Any

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production system in which the output quantities are interdependent in some way complicates the allocation process significantly. Petroleum refineries are a prime example of a system in which outputs, for the most part, cannot be varied independently of one another, although unlike the biodiesel/glycerin example, the ratio between output quantities is not fixed. Holding the feedstock composition constant, the quantity produced of each product can be adjusted by increasing or decreasing the use of such processes as catalytic cracking (a process by which heavier products are converted to lighter, higher-value products). In order to optimize profit for these complex production systems, companies use linear programming (LP) to determine, within the capacity constraints of the refinery and given a particular crude input, how much of each fuel/product should be produced. If the emissions, energy use, water use, etc. for each sub-process within the refinery as a function of production are known, then LP can be used to determine how the total environmental impacts of the refinery change if one additional L of gasoline, for example, is produced.

As previously mentioned, one petroleum refinery output cannot be increased without altering the output levels of other products. This means that, if crude input is held constant, increasing gasoline production comes at the expense of heavier products and, if crude input is allowed to increase, increasing gasoline production will likely be accompanied by an increase in production of other outputs. Therefore, attributing the change in total refinery energy use, water use, and emissions solely to the marginal increase in gasoline output is incorrect. In fact, if this method is attempted for heavier products, such as bitumen, the result is a negative number, since increasing bitumen production means diversion of heavy products that would otherwise be cracked to produce lighter products (a very energy-intensive process). This reasoning is echoed by reference (*60*), whose authors deem LP an inappropriate allocation tool for any system in which the outputs cannot be varied independently. Another, more practical issue with using LP models for allocation is that they are very data-intensive, relying on market prices and detailed operating cost information that is not available in the public domain. For this reason, although such models are used in a number of reports and journal publications, the input data cannot be published, making sensitivity analysis and uncertainty analysis near impossible.

Still, LP is used in petroleum refinery allocation. In a report by MathPro Inc. for the Alberta Energy Research Institute (*62*), LP is used, but rather than measuring the change in impacts as a result of marginal production increases, they measure the result of a 1% *decrease* in production of each output while holding all other inputs and outputs constant (*62*). If the total quantity produced of one output is decreased while holding all other outputs and inputs constant, conservation of mass indicates that some petroleum products that would otherwise have been processed and sold will likely be burned within the refinery to provide process heat instead, although theoretically they could also be discarded as waste. If the LP model used for optimization assumes any extra fuel products are burned for process heat instead, displacing natural gas combustion, this will have some unintended impacts on the results: carbon emissions from process heat production will increase (because any refinery-produced fuel will be more carbon-intensive than methane), and criteria pollutant and toxic emissions may also increase. Despite the drawbacks, this type of marginal analysis is the least flawed or arbitrary of all the available allocation methods and should be used when the necessary data is available.

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It has been shown that using marginal decreases in production is an acceptable method of determining physical relationships between a system's outputs and its impacts, given interdependent output quantities, but one question still remains: how should the input(s) be allocated among the system outputs? Equation 8 is not applicable because the outputs cannot be varied independently of one another. Using an LP model with marginal production increases should not be used because all other outputs and inputs cannot be held constant, as previously explained. The method described in the previous paragraph (LP with marginal output decreases) cannot be used because, with the exception of the output of interest, all inputs and outputs must be constant. Going back to the petroleum refinery example, if one were to attempt to hold all other outputs constant and measure how much additional crude oil would be needed to produce one more liter of gasoline, only a fraction of crude oil can be converted to gasoline, so much of the oil would be wasted (or burned for process heat). Clearly, this is not an accurate picture of how input would change given additional demand for gasoline. Having exhausted all options utilizing physical relationships, the best remaining method is to estimate the increase in each output in terms of market price, given a marginal increase in the input(s), and allocate input based on the ratio between market values of the resulting outputs.

As specified in ISO 14044 (*54*), allocation by some functional unit (typically mass, energy content, or market value) should be a last-resort because it is a relatively arbitrary means of allocating impacts to multiple products. The method itself is self-explanatory; impacts are assumed to be constant per unit of output (measured in mass, energy content, dollar of output, etc.). For example, using mass-based allocation for a process that results in 1 kg of Product 1, 4 kg of Product 2, and emits 10 kg of $CO_2$ would be allocated in the following way: 2 kg of $CO_2$ emitted to produce Product 1 and 8 kg of $CO_2$ emitted to produce Product 2 (both assigned an emission factor of 2 kg $CO_2$ per kg of output). The decision as to which output measure to use (mass, energy content, or market value) is largely left to the judgment of those performing the study. The output measure should serve as an indication of outputs' functional value and contribution to the overall motivation for using the production process in question. By this logic, market value is preferable because any production process is generally motivated the value of its products. However, there are some drawbacks to allocation by market value. First, the market value of some products fluctuates significantly over time and across different countries (steel or petroleum products, for example), so the reader must pay close attention to what prices were used for the study. Second, if an overall process is broken down into the smallest sub-processes, some of the outputs of intermediate processes may not have an established market value because they only serve as inputs to other processes within the production facility, and thus are never actually purchased or sold. Dummy prices must be assigned to these intermediates in order to allow for market value-based allocation at the sub-process level. For these reasons, mass-based allocation (example: reference (*68*)) and energy content-based allocation (example: GREET model (*69*)) are sometimes used.

Up to this point, studies on allocation and any models or other analyses that utilize some form of multi-product allocation have focused on the individual system in the short term and the (infinitesimally small) margin. However, it should be acknowledged that this is not the only possible approach. One can apply the concept of marginal versus incremental presented in

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reference (*43*) to multi-output production systems by examining the impact of incremental, rather than marginal, changes. In fact, the activities of certain industries in the long term may provide greater insight into how impacts should be allocated in multi-product systems. Again, petroleum refineries can be used as an example. If they are operating in the inelastic section of their supply curve, as petroleum refineries often are, increasing demand for gasoline will raise prices, but may have little to no impact on production (*70*). It is far more interesting to examine how the petroleum industry will change its practices over a period of ten or twenty years. The industry may choose to build more petroleum refineries to meet increased gasoline demand, allowing prices for its less valued co-products such as bunker fuel and asphalt to drop. If this occurs, the total change resulting from an increase in gasoline demand is actually equal to the change in overall production because the change in gasoline demand was the sole driving factor. If the demand for gasoline continued to increase while holding demand for all other petroleum refinery products constant, the price would continue to drop until these other products essentially become waste. In theory, this long-term economic analysis could be run for each co-product and the ratio of the impacts of scaling up each co-product to meet rising demand while holding all other demand constant could serve as a non-arbitrary allocation method that attempts to reflect real-world responses to changes in demand, and hence, production.

Ultimately, each of the multi-output production system impact allocation methods has limitations, both in their ease of application and robustness of results. However, it is possible to establish a hierarchy of preferred methods for guidance in future analyses that is more thorough and specific than those laid out in previous literature. Table 3 shows possible allocation methods, along with positives and negatives as well as a ranking for each method based on their desirability for use in this research.

| Method | Pros | Cons | Priority Ranking |
|---|---|---|---|
| System Expansion | -Measures actual system-wide change in production impacts<br>-Does not require large amounts of data | -Typically does not capture non-zero price elasticity of demand<br>-Not applicable if no alternative production process exists for the good in question | 1 |
| Physical Relationships | -Measures realistic short-run changes in production impacts | -Only applicable if outputs can be varied independently | 2 |
| Long-Term Economic Modeling | -Measures realistic long-run changes in production impacts | -Requires complex economic modeling<br>-Relies on price information that may not remain constant over time | 3 |
| Market Value-Based | -Allocates impacts based on reasonable estimates for which products are the economic drivers of the process<br>-Can be calculated using publicly available data | -Relies on price information that may not remain constant over time<br>-Requires dummy prices for intermediate products when performed at the sub-process level | 4 |
| Functional Unit-Based (e.g. Energy Content, Mass) | -Requires very little data, all of which is publicly available and constant over time | -Essentially arbitrary<br>-Ceases to be useful in systems with products that do not have common functional units | 5 |

Table 3: Multi-Output Impact Allocation Methods

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## 2.3.3 Open-Loop Recycling

Open-loop recycling refers to any instance where goods reach their EOL phase and rather than being disposed of, they are somehow put to use outside of the immediate system from which they originated. Prior to reuse, the material typically requires additional energy, labor, and other inputs in order to prepare it. For example, plastic bottles can be collected, melted down and processed, and used to produce plastic bags. Plastic, steel, aluminum, and paper are all materials that commonly undergo open-loop recycling. The problem is as follows: using recycled materials offsets virgin material production and should therefore be granted a credit, and if a company or consumer ensures that their waste materials are recycled, this practice eventually offsets virgin material production and should be credited. However, granting credits for both of these activities results in double counting: the waste materials are credited as they enter the recycling process, and then credited again when they are purchased in the form of recycled materials. There is also a question of how large the credit should be since frequently the recycled material has different, and perhaps less desirable, properties than its virgin equivalent. For example, recycled steel must be mixed with large quantities of virgin steel to achieve the "drawability" necessary to manufacture products such as soup cans, pails, and drums (*71*). For these reasons, choosing a method for allocating the avoided emissions resulting from open-loop recycling is subjective, and is heavily dependent on how the study in question's results are intended to be used.

### *2.3.3.1 Literature Review*

A number of studies have explored possible ways of dealing with open-loop recycling allocation. None claim to have developed a universally applicable "correct" method, but rather assess the relative merits of existing methods. In order to develop a better understanding of the state of the art for open-loop recycling impact allocation, five representative papers are summarized here.

(*72*): *Klöpffer (1996)*
*System of interest*: none
*Allocation methods assessed/presented*: 50:50 allocation, arbitrary attribution
*Summary*: The author provides a literature review in which two specific methods for allocating impacts in open-loop recycling systems are assessed. The first method, referred to here as 50:50 allocation requires that the cumulative impacts of producing the virgin material, and recycling the material to produce secondary goods be split equally between the goods with virgin material and the goods with recycled material (of course, this only works if the primary goods are recycled to produce only one product). The second method, referred to as arbitrary attribution, as its name suggests, allocates parts of the material's life cycle to the virgin material and recycled material arbitrarily: the credit for avoided waste goes to the virgin material that is recycled, the bonus for avoided virgin content goes to the recycled material, and the impacts of the recycling process are attributed to the recycled material. The author is quick to point out that both of these methods are arbitrary, but claims this to be necessary because no scientifically satisfying methods exist.

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(*73*): *Ekvall (2000)*
*System of interest*: none
*Allocation methods assessed/presented*: system expansion, 50:50 allocation
*Summary*: The author highlights the same issue that is discussed for co-product allocation via system expansion: the elasticities of supply and demand should not be ignored. If the market for recycled steel, for example, is saturated, additional supply of recycled steel may replace other recycled steel rather than virgin steel. The author lists default estimates of price elasticities of supply and demand for various paper products, glass, metals, and plastics and demonstrates system expansion with supply and demand elasticities through two case studies: corrugated board and newsprint. However, it should be mentioned that with any materials for which the market is unstable, this approach becomes treacherous. Because virgin steel prices are very volatile, and this volatility extends to scrap prices as well (*74*), attempting to accurately predict the impacts of additional recycled steel supply on total steel consumption may prove very difficult. In cases where elasticity information is unavailable or unreliable, the author recommends the arbitrary assumption that, for every unit of recycled material that enters the market, 50% displaces virgin material and the remaining 50% displaces other recycled material. Built in is the assumption that additional supply of recycled material does not change the total amount of material (recycled plus virgin) demanded.

(*51*): *Vieira and Horvath (2008)*
*System of interest*: buildings
*Allocation methods assessed/presented*: decision-based attribution
*Summary*: The authors discuss allocation, among other issues, in the context of buildings' EOL phase. Ultimately, they claim that allocation methods should be chosen in such a way that the study sends the correct signals to all stakeholders, rewarding choices that will decrease the environmental impact of the project in question. They argue that crediting producers (in this case, those involved in the design and construction phase) for including recyclable materials in the building causes two problems: first, there is uncertainty as to whether the materials will indeed be recycled at the building's EOL, and second, the current state of technology is used to estimate this credit despite the fact that the material will likely be recycled many decades later. To avoid this problem, the authors recommend that the impact of EOL activities (deconstruction of the building) be allocated to the original building/materials, and all other recycling activities as well as credit for offsetting virgin material production be allocated to the new building/materials (utilizing the recycled materials). They claim that this methodology incentivizes designers to use recycled or reused materials only when they reduce the building's overall impact with respect to virgin materials, while also signaling the owner to deconstruct and manage waste in the most sustainable manner possible.

(*75*): *Frees (2008)*
*System of interest*: aluminum
*Allocation methods assessed/presented*: system expansion

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*Summary*: Although the author does not advocate for particular system(s) one can allocate recycling credits, he echoes Ekvall (*73*) in highlighting the importance of price elasticity of demand and supply when estimating what recycling credits. Through collection of data on primary and scrap aluminum prices and consumption, he recommends that scrap aluminum be treated as inelastic, thus recycled aluminum always displaces primary aluminum.

(*76*): *Kim et al. (1997)*
*System of interest*: none
*Allocation methods assessed/presented*: quality index for recycled materials
*Summary*: The authors emphasize that as materials are recycled, their quality is degraded (for example, recycled steel lacks some of the desirable characteristics of virgin steel). They propose that this reduction in quality be quantified in relation to the virgin material, such that the quality index for the virgin material is equal to one, and inferior, recycled material has an index somewhere between zero and one.

#### *2.3.3.2 Methodology*

Open-loop recycling allocation inherently results in a conflict between two goals of LCA: the support and encouragement of environmentally optimal decisions and the accurate representation of human activity impacts on the environment. To advocate the recycling of a material as well as the use of that recycled material, it seems logical to credit both the party who chooses to recycle their used material and the party who chooses to use recycled material in their product. From a decision support standpoint, this practice makes sense. However, it also does not accurately reflect the environmental benefits of recycling because, from a system-wide perspective, the benefits have been double counted. In light of this issue, reference (*51*) can be justified in postulating that the users of recyclable materials are not guaranteed to actually recycle them at their EOL, and the users of recycled materials should be granted all credit. This implies that consumers of virgin steel, for example, would be assigned the impacts of ore extraction, smelting, and shaping, while the consumers of recycled steel would only be assigned the smelting and shaping of the recycled steel.

Choosing the most defensible open-loop recycling allocation method ultimately comes down to whether the LCA is consequential or attributional, and how the system boundaries are defined. If the LCA is consequential, as is the case in this dissertation, allocation becomes unnecessary. For example, consider the LCA of a building that uses recycled steel in its construction, and also recycles some portion of its steel in the EOL phase. The owners avoid the impacts of producing virgin steel by choosing to use recycled steel instead, so they should be granted credit equal to the difference between the environmental impacts of producing virgin steel and recycling used steel. Similarly, when the owners choose to recycle their used steel at the building's EOL, they offset virgin steel production by feeding recycled steel into the market, thus meeting demand that would otherwise be met with virgin steel (provided the market for recycled steel is not saturated). Just as using recycled steel results in a net decrease in environmental impacts equal to the difference between producing virgin steel and recycling used steel, this practice also results in the exactly the same impact reduction and should also be credited. The problem with

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crediting the building owners twice in an attributional LCA is the following: attributional LCAs are supposed to be additive and crediting each system that both uses and produces recycled material twice results in a double-counting of the credit. To address this concern, an alternative method that can be used in attributional LCAs is put forth below.

For attributional LCAs where the material is only recycled once and is then discarded after its second use, it is clear that the user of virgin material should be assigned somewhere between 0 and 50% of the credit for recycling. If recycling were guaranteed after the first use and the quality of recycled and virgin material were indistinguishable, 50% would be a reasonable allocation, but as mentioned before, this is not necessarily the case. Recycled material is often of a lower quality than its virgin counterpart. Hence, there should be some measure of quality integrated into the allocation. As is often the case, market value is the best available single measure of quality/desirability. Equation 9 uses relative market values to adjust the credits between 0 and 50% for virgin material users and between 50 and 100% for the users of recycled materials, where $P_R$ is equal to the price of the recycled material and $P_V$ is equal to the price of the virgin material.

$$\text{Fraction of Recycling Credit Allocated to Virgin Material User} = \frac{0.5P_R}{P_V}$$

Equation 9: Fraction of Recycling Credit Allocated to Virgin Material User

In the case of downcycling, where a product is recycled and used to substitute for a lesser-quality product, Equation 9 is still valid. Pavement serves as an illustrative example: asphalt can be recycled at the end of a road's life by undergoing crushing and use as an aggregate. Recycled asphalt is a better aggregate than virgin aggregate because of its binding properties. The key point is that the price of virgin material used in Equation 9 should still be the price of virgin asphalt, not virgin aggregate. The recycling credit, however, should be equal to the difference between the environmental impacts of producing virgin aggregate and the impacts of the asphalt recycling process.

### 2.3.4 Allocation Applications for Transportation Fuels

However robust a framework for dealing with allocation may be, it is ultimately an applied problem, and no framework is capable of capturing all of the potential nuances in engineered systems. This is why, in addition to discussing allocation in the abstract, it is also necessary to explore the specific systems that are relevant to transportation fuel production. Petroleum and gas extraction, petroleum refining, agricultural systems, biorefining, and power generation are all analyzed in detail here.

#### *2.3.4.1 Oil, Gas, and Coal Extraction*

Crude oil, natural gas, and coal are all vital energy sources in the United States. All three are fossil fuels, although non-fossil methane (the primary component in natural gas) can be produced in the short term through anaerobic decomposition of biomass, as is the case for

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landfill gas. Oil, gas, and coal are all contained in large underground reserves, from which they must be extracted, and then processed and transported to consumers. Allocation comes into play during the extraction process because, although dedicated natural gas fields exist, natural gas is also a co-product of both oil and coal extraction. When extracted separately from oil, it is referred to as non-associated gas (*77*). When dissolved in oil, it is called associated gas, and natural gas that is recovered during coal mining is called coalbed methane (*77*). Natural gas can also be extracted from oil shale, known as shale gas, but this pathway will not be discussed because it contributes a relatively small fraction of U.S. natural gas production (*77*). Although the initial composition differs, all three natural gas products are processed such that they yield the same product.

Oil and natural gas extraction are fundamentally intertwined. Not only is natural gas often dissolved in oil (and can subsequently be separated out and sold), pure natural gas reserves are frequently located alongside oil reserves. In 2008, U.S.-estimated wet non-associated natural gas production was 539.89 billion $m^3$, and 2008 estimated production of wet associated natural gas was 66.52 billion $m^3$ (*78*). In countries where oil production is the main focus, such as Saudi Arabia, a much larger fraction of their local natural gas supply is associated gas or gas that is found alongside oil reserves (*79*). There are five different scenarios for oil and gas fields:

1. Oil only (no allocation required)
2. Non-associated gas only (no allocation required)
3. Oil and associated gas
4. Oil and non-associated gas
5. Oil, associated gas, and non-associated gas

As stated above, scenarios 1 and 2 require no allocation. Scenario 3 involves a field that primarily produces crude oil, but has some concentration of dissolved natural gas contained in its crude. This gas is separated, processed, and sold. Holding demand for all else constant, the marginal unit of natural gas would be supplied through extraction of non-associated gas. This means that in scenario 3, oil is the primary product and impacts can be allocated to natural gas via system expansion, assuming that the production of associated gas displaces production of non-associated gas. According to reference (*7*), the amount of water required to extract non-associated natural gas is negligible, which implies that all water required for the extraction of oil with associated gas should be attributed to the oil. However, it should be noted that the relatively new practice of hydraulic fracturing or “fracking” for natural gas extraction does require significant amounts of water. Fracturing of a vertical well may use 4500 $m^3$ of water and a horizontal well requires up to twice that (*80*). Most of this water is returned as highly mineralized “flowback” that is not generally recycled because its TDS level results in scaling and groundwater contamination problems (*81*). Because the amount of water required is determined based on the well type and is not closely correlated with the amount of natural gas that is ultimately produced over the lifetime of the well, estimating the water use per unit of natural gas is problematic and the results can be highly variable. Reference (*81*) uses water consumption for shale gas extraction as a proxy for that of hydraulic fracturing, estimating consumption over the lifetime of a well to be 0.000418 L of water per MJ of natural gas

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produced. For perspective, the water use during processing and distribution of natural gas is calculated by reference (*7*) to be three orders of magnitude higher than this and even the next smallest water-using life-cycle phase requires an order of magnitude more than hydraulic fracturing. This means that even when accounting for this new "water-intensive" extraction technique, the water use during natural gas extraction is negligible, and hence there is no need for system expansion to be performed; all water impacts can be allocated to oil in scenario 3. There may be valid concerns about short-term water shortages because hydraulic fracturing uses a large volume of water all at once, rather than spreading the use out over the lifetime of the well. However, the issue of time-dependence is not within the scope of this dissertation.

Having established the allocation (or lack thereof) necessary for associated gas, scenarios 4 and 5 are straightforward. In scenario 4, an oil and gas field exists where gas is not recovered from the oil itself, but exists in reserves that are very nearby or connected to oil reserves. The gas and oil can be extracted separately, which means the only allocation necessary deals with capital inputs to the extraction process, such as rigs, roads, and other equipment. These inputs (steel, concrete, asphalt, etc.) are all inconsequential from a water perspective when compared to operational water use, so no allocation is performed. In the case of scenario 5, where associated and non-associated gas exist, no allocation is necessary for non-associated gas and, because of natural gas' minor water requirements during the extraction process, all impacts from oil plus associated gas extraction should be attributed to oil.

#### *2.3.4.2 Petroleum Refineries*

Petroleum refineries serve as one of the classic examples of allocation issues in LCA. Refineries are made up of many interconnected processes that result in the production of a variety of gaseous and liquid fuels, as well as non-fuels such as asphalt, waxes, and lube oils. A process flow diagram of a typical petroleum refinery can be found in Appendix A. There are two primary reasons for why petroleum refineries are especially challenging from an allocation perspective. First, the fact that the outputs serve many different purposes means there is not one functional unit; measuring asphalt's usefulness by its energy content makes no sense because its energy content has no impact on its ability to function as pavement, in contrast to the many fuel outputs that are ultimately combusted to release energy. Additionally, system expansion cannot be used because petroleum refining is the primary, and often sole, production pathway for most of its outputs. As discussed in detail in the Literature Review for operational allocation, a number of studies use linear programming to estimate the marginal impacts of increasing production of a particular product. However, because such techniques require detailed process and cost data that is not publicly available, they will not be used here. Instead, a sub-process-level market value allocation method is used. Market values are taken from reference (*48*) and the resulting allocation breakdown is shown in Table 4. This method is far from perfect because prices vary over time and space. Diesel is likely to have a higher market value in European countries at any given time, while gasoline will have a higher price in the United States due to difference in prevailing passenger vehicle engine technologies.

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| Product | Mass Output (kg/kg crude oil input) | % of Inputs/Impacts Allocated to Product |
|---|---|---|
| Residual Oil | 0.044 | 0.9% |
| Diesel | 0.094 | 8.2% |
| Kerosene | 0.137 | 6.8% |
| Gasoline | 0.465 | 58.7% |
| LPG | 0.058 | 3.0% |
| Other Products | 0.212 | 22.3% |

Table 4: Petroleum Refinery Allocation (Data Source (*48*))

### *2.3.4.3 Agricultural Systems*

There are two instances in which allocation becomes an issue for agricultural systems: crop rotations and multiple products originating from the same crop. Reference (*82*) emphasizes the importance of specifying crop rotations when performing an LCA of agricultural systems. In this case, the operational inputs such as fertilizer, pesticides, herbicides, irrigation, and fuel for farm equipment can all be easily assigned to the individual crops that they support. There can be subtleties, for example, different uptake rates for certain applied nutrients like phosphate and potassium. Reference (*82*) asserts that these uptake rates are in fact the proper measure by which nutrient application should be allocated. However, for the sake of simplicity and transparency, allocation of operational agricultural inputs will be performed based on application rates for the purposes of this research. Capital inputs are also not straightforward. In this case, the recommended course of action is to utilize the infrastructure allocation method as described in Section 2.3.2. For the purposes of this dissertation, the water embodied in steel and rubber used in farm equipment was allocated in this way, approximating the impact that each unit of harvested output had on the lifetime of the equipment.

The allocation problem associated with multiple products originating from the same crop can take one of two forms. In the first, the crop is split into different products during harvest. For example, corn could be separated into grain to be processed into food products and stover to be used for cellulosic ethanol production. In the second form, all useable (non-waste) portions of the crop are transported to the same processing/manufacturing facility, at which point they are converted into multiple products. The latter will be dealt with separately in Section 2.3.2 because it is seen as a biorefinery allocation problem rather than an agricultural one. The former has not been dealt with in U.S.-focused biofuels studies. However, with the possibility of converting agricultural residue, it is possible if not likely that the biomass will be separated out and sent to a facility entirely separate from facilities that process food and other traditional agricultural products. The question is then how, if at all, should the impacts of crop production be allocated between the residue and the food?

While there have been some preliminary efforts to estimate a price for crop residues, as reference (*83*) does for corn stover, there is not yet a market for these residues because cellulosic EtOH production technology is not commercially viable at the present time. If one were to allocate the current (2010) impacts of growing corn, all inputs and emissions should be attributed to the grain because it is the only portion of the crop that is used, and is the sole economic driver for the crop's existence. Some fraction of crop residues must be left on the field and are important to maintaining soil quality, but any additional residue (which is the fraction that could be converted to biofuels) is still a waste product. Any marginal unit of

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irrigation water, fertilizer, or other input is driven exclusively by the desire to maximize corn grain production. This will continue to be true until the demand for biomass approaches the practical supply. The “practical” qualifier is used because some waste biomass is so dispersed and expensive to collect and transport that it is not likely to be utilized for biofuel production in the foreseeable future. The amount of usable waste biomass in the United States is large. According to reference (*84*), there are 68 Mg tons of corn stover available each year, 10 Mg of wheat straw, 5 Mg of small grain residues, and 47 Mg of other residues. Corn stover is the largest resource, with an average yield of 7.8 dry Mg of biomass per hectare of land per year. Using ethanol yields from corn stover as an approximation for all crop residues, this amount of biomass would result in 1.3 TJ of ethanol per year, or roughly 10% of U.S. gasoline consumption. Here, we will assume that cellulosic ethanol production will not reach this level in the near term, so crop residues are considered a waste product. The only impacts that should be assigned to residues are those directly associated with the collection and processing of the residue itself, for example, operation of farm equipment used to gather corn stover from the field.

| System | Co-Products | Method |
|---|---|---|
| Corn Agriculture | Corn Grain, Corn Stover | All Impacts Allocated to Corn Grain Except those Directly Associated to Stover Harvesting |
| Petroleum Extraction | Crude Oil, Natural Gas | System Expansion |
| Corn Stover or Miscanthus Biorefinery | Ethanol, Electricity | System Expansion |
| Petroleum Refinery | Gasoline, Diesel, Residual Oil, Kerosene, LPG, Other Products | Market Value |
| Corn Grain Biorefinery | Ethanol, DDGS | System Expansion |
| Electricity Generation: CHP | Electricity, Heat | System Expansion |
| Steel Recycling | Recycled Steel | All Virgin Steel Production Impacts Allocated to User of Virgin Steel |

Table 5: Allocation Methods Applied in this Dissertation

### *2.3.4.4 Biorefineries*

All ethanol plants currently produce more than one output. Ethanol is the primary output of the process, but the ability to sell its co-products does contribute to its economic viability. In dry milling corn ethanol facilities, there are two products: fuel ethanol and dried distillers’ grains and solubles (DDGS), as shown in Table 5. In wet milling corn ethanol facilities, corn gluten meal (CGM), corn gluten feed (CGF), and corn oil are all produced in addition to ethanol. According to the Renewable Fuels Association (RFA), dry mill facilities make up 88% of existing ethanol production capacity (*85*). Wet milling is analogous to petroleum refining, where the feedstock (in this case, corn) is used to produce a suite of useful products. However, if the goal is to increase ethanol production only, dry milling is a much more efficient way to achieve that target. Hence, dry milling can be considered the sole source of marginal ethanol production in the United States and the only process worth analyzing here. This perspective is echoed by reference (*5*), which limits its analysis to dry corn milling as well.

DDGS replaces animal feed, which means system expansion is the preferred allocation method (*49*). It displaces both corn and soybean meal. According to reference (*49*), each kg of DDGS replaces 1.2 kg (dry) of soybean meal (SBM) and 0.93 kg (dry) of corn. For each kg of ethanol produced, 0.92 kg of DDGS are also produced and sold. To adjust for the corn displaced by

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DDGS production, Equation 10 can be used to develop a co-product-adjusted corn input per MJ of ethanol produced. The result is an almost 30% reduction in corn input when the DDGS co-product is properly credited.

Adjusted Corn Input for Ethanol Production (kg corn/MJ EtOH) = (0.109 kg corn/MJ EtOH) - (0.92 kg DDGS/1 kg EtOH) x (0.034 kg EtOH/MJ EtOH) x (0.93 kg corn) x (0.109 kg corn/MJ EtOH) = 0.080 kg corn input/MJ EtOH output

Equation 10: Method for Adjusting Corn Input for Ethanol Production

For SBM, there is no shortcut, as is the case with corn. The impacts of producing it are simply calculated and subtracted from the total impacts of producing corn ethanol.

Cellulosic ethanol biorefineries do not produce DDGS, but rather electricity and heat by burning the fraction of biomass that cannot be converted to fuel, known as lignin (see Table 5). This is a common practice in Brazil, where the entire sugarcane bagasse is burned for the electricity and process heat that can be used at the biorefinery. Based on pilot cellulosic plants and process models, enough lignin exists to not only meet the biorefinery's need for electricity, but also generate excess power that can be exported to the grid. The amount of excess electricity produced is largely dependent on the fraction of the input biomass that is lignin. The two biomass feedstocks, corn stover and Miscanthus, are similar in this regard because they are both herbaceous feedstocks. Dry corn stover contains approximately 18% lignin by mass and Miscanthus contains 22% (*86, 87*). Woody biomass usually contains more lignin. Using the Engineering Suite from AspenTech$^{TM}$, researchers at the Energy Biosciences Institute at UC Berkeley developed a process model for simultaneous saccharification and co-fermentation. By varying the input biomass makeup (fractions of hemicellulose, cellulose, lignin, etc.), feedstock-specific outputs are produced (*88*). The model is based on the National Renewable Energy Laboratory (NREL) pilot plant described in reference (*86*), updated to reflect advancements in technology. Although the model is not publicly available, the results are used in this dissertation because they are of a higher quality than other published data on cellulosic biorefineries.

The biorefinery process model yields net electricity exports that are very similar for corn stover and Miscanthus. The Miscanthus-to-ethanol conversion results in net electricity production of 0.075 MJ of electricity per MJ of ethanol output. Corn stover produces 0.077 MJ of electricity for every MJ of ethanol. System expansion can be used in this case to estimate the net change in environmental impacts. As excess electricity from biorefineries is fed on to the grid, other sources are ramped down. As is typically the case with system expansion, the price elasticity of demand is assumed to be negligible, so additional power supply has no ultimate impact on total demand.

In reality, the mix of electricity that will be displaced is not equal to the average mix, but rather a marginal mix. The marginal mix is partially driven by operating costs and partially driven by the technical feasibility of ramping a particular type of power plant up and down. For example, coal and nuclear power plants cannot respond quickly to changes in demand, whereas natural gas-fired power plants are easy to ramp up and down. Power plants that fit the former's profile (difficult to ramp up and down) are considered baseload plants, while those similar to the latter

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are categorized as "peaker" plants. Hydroelectricity, while very cheap to generate, is also easy to adjust on short notice, so it can be considered baseload unless demand dips so low that hydro is the only source that can feasibly be reduced.

The U.S. EPA eGRID database (*89*) has been used in the past to provide hourly, plant-level data on electricity generation that could be used to estimate the marginal electricity mix at any given time. Now that these data are no longer available, the marginal mix is much more difficult to assess. Models for individual North American Electric Reliability Corporation (NERC) regions do exist, but are not available for every NERC region and are not publicly available. For these reasons, the average NERC region-specific mixes are used in place of marginal mixes.

### *2.3.4.5 Electric Energy Generation*

There are two cases in electric energy generation for which allocation decisions come into play. The first involves the use of what was previously a waste product, for example, fly ash from coal plants as a substitute for cement (*90*). Fly ash is typically considered to be a waste product based on the same reasoning put forth in the agricultural residue discussion, but this ignores its actual net impact, which is the displacement of cement production. Therefore, in a consequential LCA, system expansion should be used by determining how much cement production is avoided per unit of coal-fired electricity due to fly ash. Because this dissertation focuses on water impacts and cement production has negligible water impacts compared to other components of the transportation fuel life cycle, system expansion is assumed to be unnecessary here. However, for future studies that account for GHG emissions, CAP emissions, or other impacts, system expansion should be used.

The second is a much more widely discussed topic: combined heat and power (CHP), also known as cogeneration (*91*). Because thermoelectric power plants only convert roughly one third of the fuel input's energy content into electricity, a great deal of waste heat is generated. This waste heat in fact drives water consumption and withdrawals because cooling systems require water to absorb and remove this waste heat from the power plant. However, thermal energy does have value if it can be transported to facilities that require it, such as industrial facilities, commercial buildings, and even district heating systems. CHP plants take advantage of this fact, locating themselves sufficiently close to industrial, commercial, municipal, or other facilities that can make use of their waste heat.

The most common topic of discussion is how air emissions and fuel input should be allocated between the electricity and useable heat output; in the eGRID database, emissions are allocated based on energy content, weighting the energy content of electricity as twice that of heat to reflect the relative usefulness of each energy form (*92*). Using this method for water withdrawals/consumption accounting becomes problematic. This is because the total water use for a power plant that practices cogeneration actually decreases when waste heat is used because water is no longer required in such great quantities for cooling. Steam or liquid water is almost certainly used to transport waste heat from the power plant to its consumer, but this water use should be attributed to the consumer rather than the power plant unless more water is required to deliver CHP heat than would otherwise be used for conventional heat

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transfer/conveyance in the industrial/commercial/municipal system. The waste heat also displaces whatever fuel would have otherwise been used to produce heat for the facilities that purchase it, so system expansion can be used to estimate the embodied water in those fuels and subtract it from the CHP plant's total water use. To date, no studies have attempted to quantify the amount of cooling water required for CHP plants as compared to their regular counterparts or the amount of additional water that is needed to transport heat from the CHP plant to the receiving facility. In the absence of these data, allocation is performed by assuming cooling water use at CHP facilities is identical to their non-CHP counterparts and utilizing system expansion based on the water use embodied in natural gas as a fuel for heating (see Table 5).

#### *2.3.4.5 Steel Recycling*

Steel is ubiquitous in infrastructure, used in everything from rebar in concrete structures to tanks in petroleum refineries. Recycling steel is common practice, and helps keep the price of virgin steel lower than it would otherwise be. It is also a classic open-loop allocation problem in LCA. As discussed in Section 2.3.1, a consequential LCA should award credit anytime a system either uses recycled steel or provides recycled steel. However, it is unclear whether the infrastructure analyzed in this dissertation will produce recycled steel and, if so, how much. Thus, the method put forth by reference (*51*) that calls for 100% allocation of recycling credit to the user of recycled steel is used and no steel is assumed to be recycled at the EOL (see Table 5).

## 2.4 Water Resource and Climate Impact Assessment

To understand the water impacts of a particularly policy, there must first be geospatial disaggregation. Water resource scarcity (also referred to as water resource stress) is inherently a local problem, so the inventory of water use carries little meaning unless it is broken into relevant regions. Second, the GHG emissions associated with the water requirements must be quantified and included in the overall climate impacts of the policy. Ideally, the long-run marginal GHG-intensity of water should be calculated. If building a new industrial facility or cultivating additional crops will ultimately lead to new water importation projects or the construction of desalination capacity, the marginal unit of water will have much greater climate impacts than the average unit of water. Determining where the marginal unit of water will come from requires many assumptions about state and local government decisions. Rather than trying to identify the marginal source of water, drought vulnerability and underground aquifer depletion are used in this dissertation to identify areas within the United States where local water resources are currently, or are projected to be, stressed.

Freshwater use can result in a number of different impacts, including increased GHG emissions from pumping and treatment; economic impacts due to insufficient supply for industrial, energy-producing, and agricultural activities; human health effects resulting from shortages of potable water; and damage or loss of aquatic habitats. Reference (*10*) explores a number of watershed-level impact metrics, including the water stress index, water resource damage, ecosystem quality damage, human health impacts, as well as an aggregated damage factor that encompasses resource, ecosystem, and human health damage. However, the data intensity of

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this type of analysis is such that it becomes difficult to apply at the level of resolution needed in many studies, such as county-level resolution.

In this dissertation, a new and simpler, less data-intensive approach is taken, aimed at quantifying GHG emissions from the supply of freshwater and identifying the fraction of water use that occurs in areas where surface and groundwater stress may be exacerbated. The approach used here for gauging relative impacts on surface and groundwater stress can be considered analogous to the splitting of criteria pollutant emissions into urban and non-urban categories as is performed in GREET (*69*). Because an impact assessment with high fidelity to reality is difficult and wrought with uncertainty, many studies simply choose to stop at an LCI. The only study that does perform impact assessment uses a complex, data-intensive methodology that produces results in “damage factors” that only have meaning relative to one another (*10*). The assertion made here is that performing even a simple and transparent impact assessment is favorable to omitting the step altogether. Also, because the impact assessment framework put forth here produces results in physical units rather than intangible damage factors, it is more comprehensible to decision makers and the general public (*93*).

## 2.4.1 GHG-Intensity of Freshwater Supply

It is well known that climate change can and will impact freshwater resources (*94*), but less frequently acknowledged is the impact of freshwater use on climate change. Raw water pumping from ground or surface water sources, treatment, and distribution all require energy. The GHG-intensity of water varies depending on how far the raw water must be pumped, as well as the extensiveness of treatment and distribution requirements. Agricultural water, for example, is very GHG-intensive in parts of California where water is imported; this dissertation calculates that Kern County, CA averages 0.33 g of $CO_2$-equivalent emitted per L of irrigation water supplied (see Chapter 5). In counties that use local freshwater, the GHG-intensity is one to two orders of magnitude lower. Because it is assumed that most industrial water, mining/oil extraction water, and power generation cooling water do not require significant treatment, the GHG-intensity is similar to that of agricultural water, altered somewhat by differences in pump efficiencies and fuel types. Public water supply is by far the most energy and GHG-intensive because it must be treated to achieve potable standards and pumped through a distribution system to various customers. In Los Angeles and San Diego Counties, CA, where water is imported over long distances, the GHG-intensity is approximately 1 g $CO_2$e/L water supplied (*16*), whereas this dissertation estimates that most of the public water supply in the United States results in approximately 0.5 g $CO_2$e/L (see Chapter 5). Desalination projects in El Paso County, TX and Hillsborough County, FL also result in an average GHG-intensity of approximately 1 g $CO_2$e/L, according to Chapter 5 of this dissertation. Figure 5 shows a U.S. county-level map of annual Mg of $CO_2$e emitted as a result of pumping and treating water for human use, normalized by land area. The data used to develop this map are discussed in Chapter 5. Figure 5 shows that California is the major contributor, but population centers in TX, IL, FL, and the Northeast also contribute significantly to GHG emissions.

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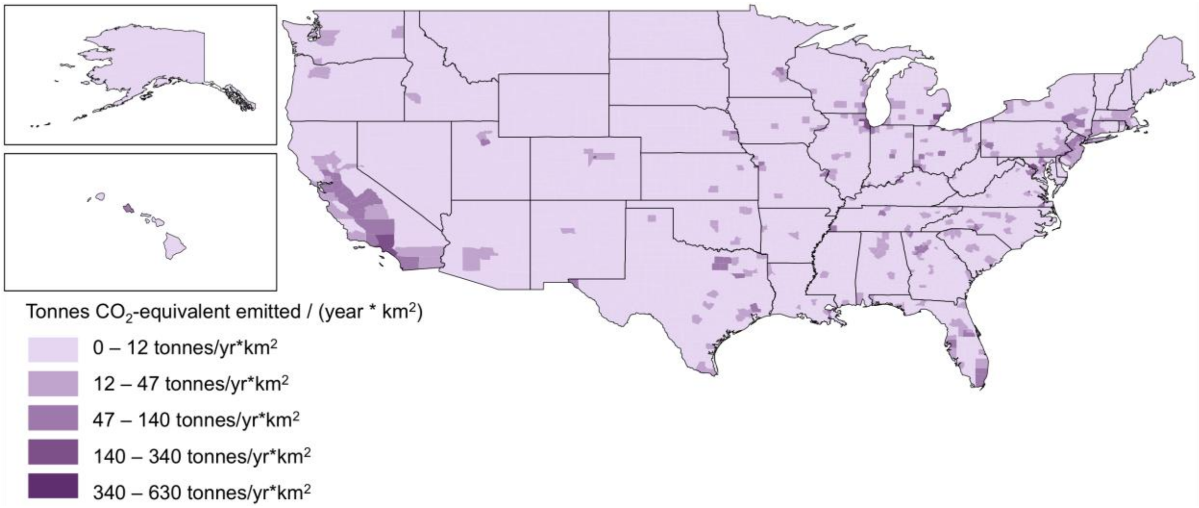

Figure 5: Annual GHG Emissions from Water Supply by County as Calculated in Chapter 5

### 2.4.2 Surface Water Impacts

Surface water, although easily accessed and typically requiring less pumping energy than groundwater, is a vulnerable resource. For example, a period of low or no rainfall can significantly reduce surface water availability. Soil moisture, stream flow, and precipitation all inform drought measurements. The Palmer Drought Severity Index (PDSI) is a common measure of drought severity, which the U.S. Drought Monitor has used to develop five categories: D0: Abnormally Dry, D1: Moderate Drought, D2: Severe Drought, D3: Extreme Drought, and D4: Exceptional Drought (*95*). A map of drought incidence in the United States is shown in Figure 6. Further details about this rating system are provided in Chapter 4. Although water shortages are typically associated with the arid west, over half of the United States has spent at least 10% of the last 100 years in severe, extreme, or exceptional drought (*95*). For the purposes of this research, areas experiencing drought categorized as D2 or worse for more than 10% of the last one hundred years are considered to have elevated drought risk. Drought incidence data is collected by National Oceanic & Atmospheric Administration (NOAA) climate divisions, which the NOAA then maps to U.S. counties. This county-level data is matched up with county-level surface water withdrawals and consumption LCI data to determine how much surface water is used within drought-prone areas.

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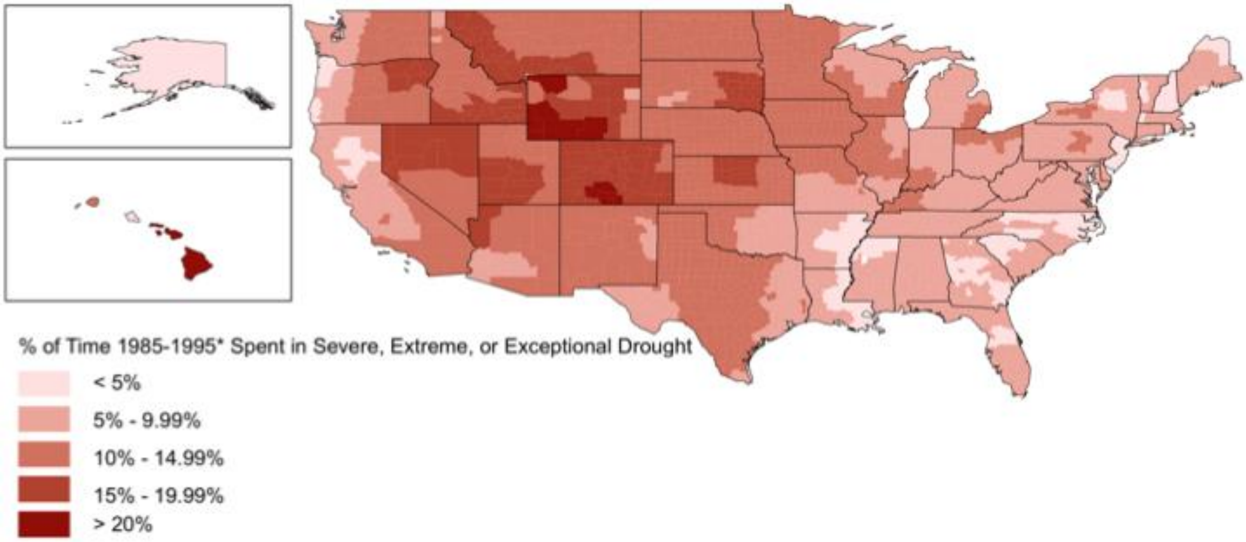

Figure 6: U.S. Drought Incidence Defined by PDSI (Data Source: (*95*))

### 2.4.3 Groundwater Impacts

One asset of groundwater resources is that they are not as vulnerable to climatic fluctuations as surface water. However, groundwater availability is limited by the recharge rate. If the pump rate exceeds the recharge rate, the aquifer will ultimately be depleted. Additionally, as the water level in unconsolidated aquifers drops, land subsidence can occur. More than 44,000 $km^2$ of land in the United States are directly affected by subsidence. Approximately 80% is caused by pumping of subsurface water (*96*). No comprehensive national groundwater monitoring system exists (*26*), so mapping groundwater impacts at a local level for the entire United States is not possible. Instead, it is more reliable and useful to focus on more susceptible areas that have better monitoring. The following 27 states have been identified as suffering either significant decline in aquifer levels, subsidence, or both, based on information from references (*26*) and (*96*): AR, AZ, CA, CO, DE, FL, GA, ID, IL, KS, KY, LA, MA, MS, NE, NJ, NM, NV, NY, OR, SC, TN, TX, UT, VA, WA, WI, as shown in Figure 7. A list of impacts experienced in each state is included in Table 36. Although the state itself does not experience significant groundwater overpumping impacts, Nebraska is included here because its excessive withdrawals seriously affect groundwater levels in Kansas (*97*).

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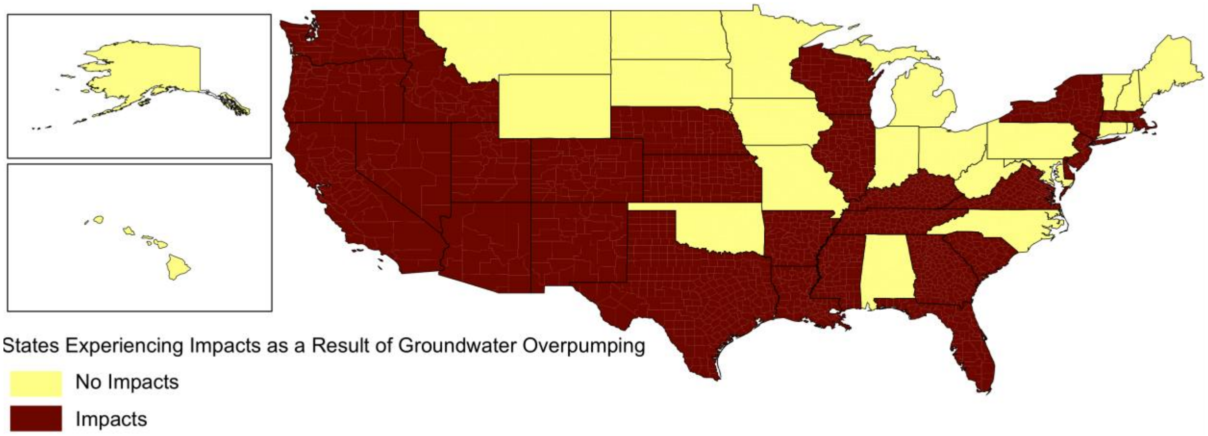

Figure 7: GW Overpumping Incidence in the United States

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# 3. Life-Cycle Water Footprint of U.S. Transportation Fuels

As noted in Chapter 2, reference (*38*) lists the four critical steps that make up an LCA: goal/scope definition, inventory analysis, impact analysis, and improvement analysis. In this chapter, the goal/scope is defined and the inventory is laid out. Chapter 4 presents the impact analysis, and Chapter 7 discusses opportunities for reducing negative human impacts on water resources.

## 3.1 Goal and Scope

The goal of this research is to support decisions made about the future of transportation fuels from a water-resource perspective. Policy makers currently have a much firmer grasp on the GHG implications of passenger transportation fuel options than on other environmental impacts. This dissertation seeks to help fill that gap by providing detailed information about the water requirements of producing different transportation fuels so that water issues can be incorporated into future decision-making.

### 3.1.1 Importance of Transportation Fuels

Transportation energy use was chosen for two major reasons: first, it makes up a significant fraction of total U.S. energy consumption, and second, there are fewer feasible options for replacing existing fossil transportation fuels than there are for replacing fossil fuels used for heat or electricity generation. Transportation fuels account for almost one-third of total U.S. energy consumption and 95% of that demand is met with petroleum (*13*). The fraction of highway transportation (excluding modes such as pipeline, etc.) energy use supplied by petroleum fuels is even higher, as shown in Figure 8.

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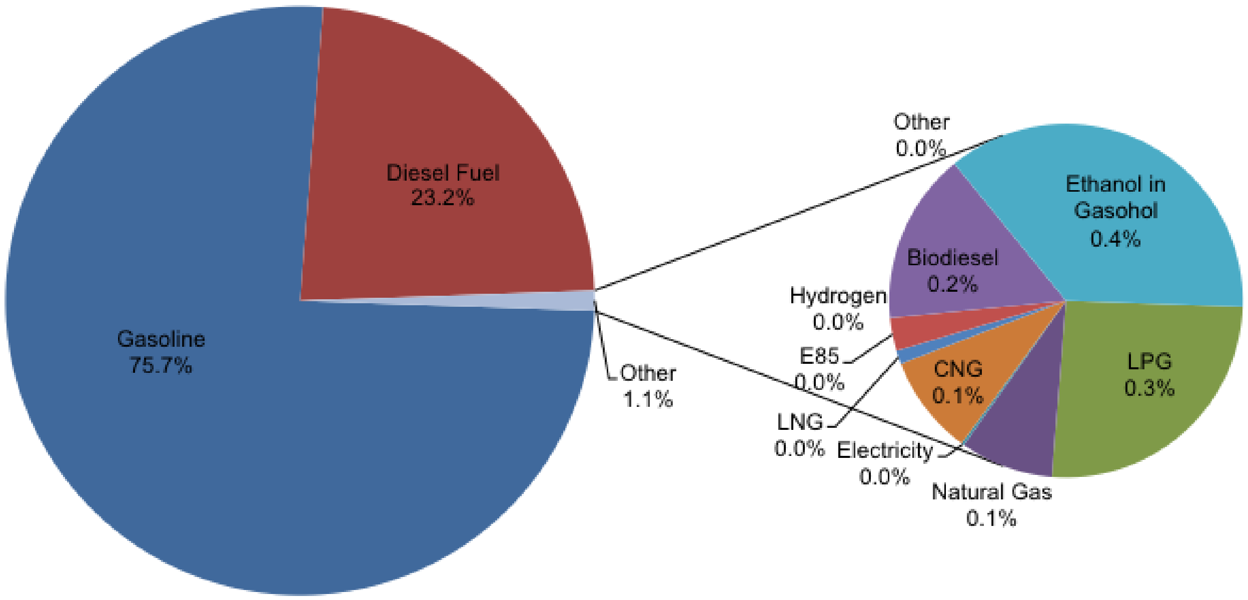

Figure 8: 2008 Highway Transportation Energy Use in the United States (Data Source: (*98*))

Petroleum fuel consumption has been steadily increasing since approximately 1950, as shown in Figure 9. Because of concerns about climate change and dependence on oil imports from politically unstable countries, President Obama and many U.S. presidents before him have called for a reduction in petroleum consumption and increase in alternative fuel production. Non-petroleum fuels have thus far been successfully used as fuel additives in gasoline to promote complete combustion. Ethanol in gasohol serves this purpose; its share of the transportation fuel market is shown in Figure 8. However, legislation such as the EPA's Renewable Fuel Standard (RFS) program seeks to increase non-petroleum fuel production significantly. Figure 9 shows that U.S. ethanol has sharply increased in the last 10 years thanks to a subsidy for domestic production, although it still represents a very small fraction of total transportation energy consumption. Other alternative fuels, such as compressed natural gas (CNG) and electricity also maintain a small share of the transportation energy market and stand to gain larger shares over time (*99*).

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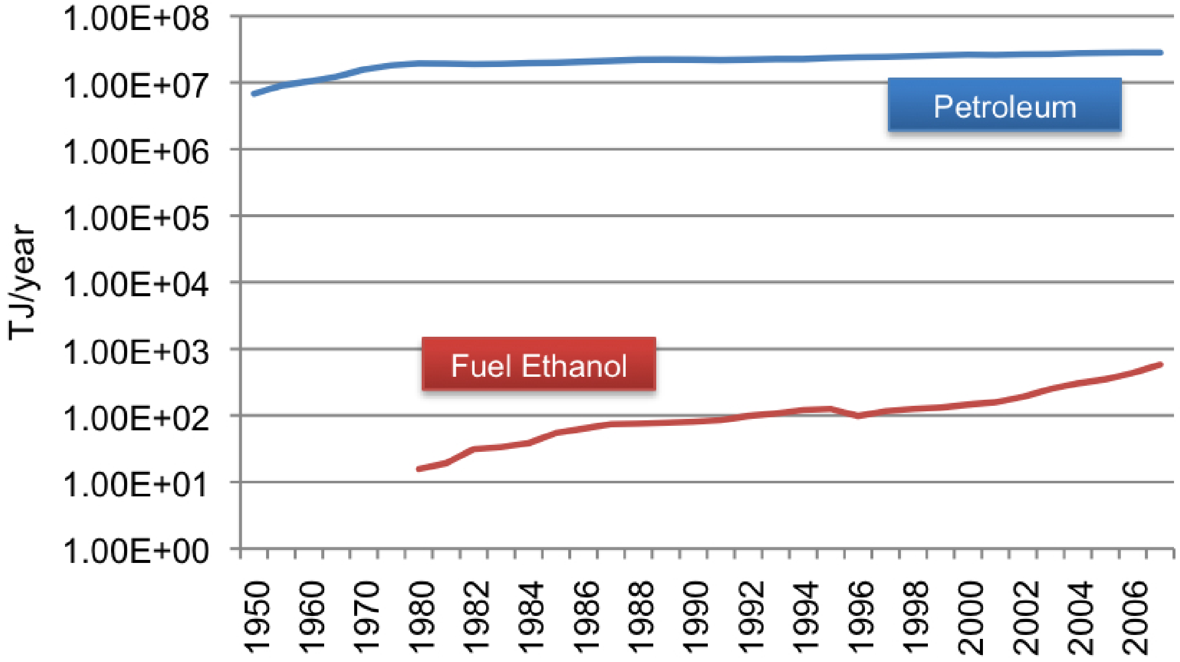

Figure 9: Oil and Ethanol Consumption for U.S. Transportation (Data Sources: (*13, 85*))

Given that the goal of this research is to inform decisions affecting the future of transportation fuels, a consequential LCA approach is taken (see Chapter 2 for more details). The purpose is to predict the impact of increasing or decreasing production of a particular transportation fuel. In the case of emerging alternative transportation fuels, this means that they're likely to displace (or prevent an increase in) consumption of existing fuels. Hence, the fuels chosen for this dissertation fall into two categories: emerging fuels and baseline fuels. The latter serves as a basis for comparison, so if some quantity of emerging fuel displaces a baseline fuel, the net impact can be determined. Table 6 lists two baseline fuels: gasoline and diesel along with potential replacements for each. Some fuels make more sense as a replacement for one in particular (for example, ethanol would replace gasoline in spark-ignited engines while biodiesel can replace diesel in compression-ignited engines). Others, such as electricity, CNG, and hydrogen require completely different vehicles and infrastructure than both gasoline and diesel, so they can be considered replacements for either fuel.

As shown in Figure 8, gasoline dominates the U.S. transportation fuel market, so this dissertation focuses only on gasoline and its potential replacements. Of those, ethanol has the most near-term potential for success because it requires only minor vehicle alterations and can be more economically produced than its bio-based alcohol counterpart, butanol, which is still in the research phase (*100*). Butanol and hydrogen are both excluded based on their inability to gain any medium-term market share due to cost and infrastructure limitations. The remaining fuels are CNG and electricity, both of which face the issue of vehicle technology limitations. Until automakers sell significant numbers of electric and CNG vehicles, there will not be demand for the fuels. Of the two, electric vehicles are believed to have more long-term

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potential because they could theoretically be independent of fossil fuels if electricity generation becomes reliant on renewable sources only, whereas CNG vehicles will continue to rely on a finite supply of natural gas. Electricity is chosen for analysis in this dissertation on the basis of its long-term potential, and CNG is excluded.

| Baseline Fuel | Emerging Fuel | Vehicle/Infrastructure Compatibility | Included in This Analysis? |
|---|---|---|---|
| Gasoline | Ethanol | -Minor vehicle alterations necessary<br>-Incompatible with petroleum pipelines | Yes |
|  | Butanol | -Compatible with current vehicles<br>-Compatible with petroleum infrastructure | No |
|  | CNG | -Requires new vehicles<br>-Compatible with natural gas infrastructure | No |
|  | Electricity | -Requires new vehicles<br>-Requires improvements to existing electricity infrastructure | Yes |
|  | Hydrogen | -Requires new vehicles<br>-Requires completely new infrastructure | No |
| Diesel | Biodiesel | -Compatible with current vehicles<br>-Incompatible with petroleum pipelines | No |
|  | Renewable Diesel | -Compatible with current vehicles<br>-Compatible with petroleum infrastructure | No |
|  | CNG | -Requires new vehicles<br>-Compatible with natural gas infrastructure | No |
|  | Electricity | -Requires new vehicles<br>-Requires improvements to existing electricity infrastructure | Yes |
|  | Hydrogen | -Requires new vehicles<br>-Requires completely new infrastructure | No |

Table 6: Baseline and Emerging Transportation Fuels in the United States

### 3.1.2 Water Use Metrics

As discussed in Chapter 2, there are a number of potential water use metrics that attempt to quantify resource depletion as well as resource quality degradation. For the sake of simplicity and feasibility, this dissertation will focus only on the former and to that end, freshwater withdrawals and consumptive use will be the two metrics that are reported in this inventory. For more details about how these metrics are defined and why they were chosen above others, see Chapter 2.

## 3.2 Literature Review

Researchers in the United States began publishing on the water impacts of transportation fuel production in the 1970s, after the first oil crisis began in 1973 (*101-105*). Petroleum shortages spurred a discussion about potential alternatives that could be produced domestically. One of the most promising alternatives was oil shale, a bituminous material known as kerogen that is contained in sedimentary rock located in Colorado, Utah, Wyoming, Kentucky, Ohio, and Indiana, totaling an estimated 2.0 trillion barrels of oil equivalent, as compared to current U.S. crude oil production of 7.2 million barrels per day (*98, 106*). Because production of synthetic crude oil (SCO) from oil shale is more water-intensive than crude oil extraction, and the U.S. oil shale reserves are located in areas already experiencing water stress, a series of reports and journal papers were published on the water impacts of SCO production from oil shale (*7, 101, 103, 104, 107, 108*). A smaller number of publications also looked into the water requirements of refining conventional crude oil (*7, 109-111*). While none of these studies quantified anything

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beyond the direct impacts of fuel extraction, pre-processing, and refining, they provided the first data on water requirements for transportation fuel production.

The interest in water impacts of transportation fuels that this early research sparked is recently renewed due to a rapidly growing biofuels industry. Corn ethanol has been the first to gain significant momentum, with production in 2008 at more than 50 times 1980 levels, and 5.5 times production levels in 2000 (*112*). Initially, the corn ethanol debate focused on its fossil energy and climate impacts, but references (*3-5, 113*) and others helped attract attention to water issues as well. While estimates of transportation fuel water impacts have become more sophisticated by differentiating between different types of water ("blue", "green", "grey" or "dilution water", etc.) (*17*) and including rough estimates of indirect water use for materials and construction (*9*), large gaps in the literature still remain. To identify these gaps, a framework for assessing each study has been developed by establishing four main life-cycle phases. Life-cycle inventories of transportation fuels are broken into four phases: feedstock production/extraction and pre-processing, fuel production/refining, storage and distribution, and use/combustion (see Table 1).

Table 1 also includes a description of which activities fit into each life-cycle phase for each fuel analyzed in this research. These activities are then used to determine inputs and outputs for each phase. True life-cycle inventories of water use are rarely done. There are two likely reasons for this: the first being that data on water consumption are far less abundant than greenhouse gas (GHG), energy use, criteria pollutant, and even toxic releases data. The second reason is that the environmental research community is only recently making an effort to establish universal guidelines for quantifying water use. In previous years, confusion over whether "water use" referred to total withdrawals or consumptive use, and further confusion about what consumptive use entails, made including water in life-cycle inventories a difficult task and treacherous task. For these reasons, most assessments of water consumption for transportation fuel production consider only the direct water requirements for two phases: feedstock production/extraction and pre-processing, and refining/fuel production. Table 7 shows how existing literature on water consumption for transportation fuel production is distributed amongst the different life-cycle phases and fuel pathways. As shown in the table, all studies to date ignore the transportation, storage, and distribution phase. Combustion/use is not included because no freshwater is consumed during this phase (in fact, water vapor is produced when gasoline and ethanol are combusted but should not be included for reasons discussed in Section 3.3.13). Following Table 7 are more in-depth summaries of four selected studies.

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| Study | Fuel | | | | Life-Cycle Phase | | | | | Measures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gasoline | Starch/ Sugar Ethanol | Cellulosic Ethanol | Electricity | Feedstock | Ref/ Prod | TS&D | Use | Indirect Effects | W | C | GHG | WSI |
| (*3*) | | X | | | X | X | | | | | X | | |
| (*18*) | | X | | | X | | | | | X | X | | |
| (*31*) | | | | X | | X | | | | X | X | | |
| (*21*) | | | | X | X | X | | | | X | X | | |
| (*19*) | X | | | | X | | | | | X | | | |
| (*17*) | | X | | | X | | | | | X | | | |
| (7) | X | | | X | X | X | | | | | X | X | |
| (*9*) | X | X | X | X | X | X | X | | X | | X | | |
| (*8*) | X | X | X | X | X | X | | | X | X | X | | |
| (*114*) | | | | X | | X | | | | X | X | | |
| (*4*) | | X | X | | X | X | | | | | X | | |
| (*27*) | | | | X | | X | X | | | | X | | |
| (*5*) | X | X | X | | X | X | | | | | X | | |

Table 7: Water Life-Cycle Assessment Literature Review

Notes: Ref/Prod: Refining/Fuel Production; TS&D: Transportation, Storage & Distribution; W: Withdrawals; C: Consumption; WSI: Water Stress Index

*(7): Gleick (1994)*

The author's report on water and energy, despite being more than fifteen years old, is still one of the most widely cited studies on the energy-water connection. It provides point estimates or ranges for consumptive water use of a variety of fuels' extraction/production, and electricity generation technologies. Biofuel production is not included in the scope of this study.

*(9): Harto et al. (2010)*

This is the only study that utilizes a hybrid LCA technique. The authors use water consumption data from recent literature to estimate the direct water requirements for each life-cycle phase, and then used industry data on material, infrastructure, and energy inputs to plug into the Economic Input-Output Analysis-based Life-Cycle Assessment (EIO-LCA) model in order to obtain indirect water consumption results. This strategy is known as hybrid life-cycle assessment; more information on EIO-LCA, as well as hybrid LCA can be found in Chapter 2. In theory, the method employed by the authors is sound, but the water data within the 1992 EIO-LCA that they used is acknowledged as being out-of-date and incomplete. The water impact vector is calculated using a U.S. Census Bureau report on water use for manufacturing sectors (*115*), which means water use for non-manufacturing sectors is assume to be zero, despite the fact that agriculture and power generation are known to be major water users. For this reason, the 1992 version of EIO-LCA is not an appropriate tool for estimating life-cycle water consumption. Very recently, water data were added to the 2002 EIO-LCA tool, which will be discussed further in Section 3.3.12.

*(5): Wu et al. (2009)*

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The Argonne National Lab report served as one of the first studies to quantify water consumption for each life-cycle phase of not only corn ethanol, but cellulosic ethanol and petroleum gasoline as well. For agriculture, they assumed that cellulosic crops such as prairie grasses require no irrigation and for corn, they took a production-weighted average of irrigation needs for the three primary corn-producing USDA regions. This is a very basic analysis compared to other studies that employ evapotranspiration models, use smaller spatial resolutions, and differentiate between ground and surface water withdrawals. For the biorefining/fuel production phase, the authors provide rough approximations of water use in corn ethanol and cellulosic ethanol plants (3 L/L EtOH and 10 L/L EtOH, respectively). Although these numbers are on par with other estimates, it is very unlikely that they involve any co-product allocation of impacts. Transportation and storage of ethanol is assumed to require negligible amounts of water. On the petroleum side, the authors provide a much more thorough analysis than comparable publications. They outline the various crude oil extraction techniques and corresponding water demands, and account for how average produced water (PW) volumes in each Petroleum Administration for Defense District (PADD) impact those water demands. This study also explores Saudi Arabian crude and synthetic crude oil (SCO) from Canadian oil sands. Finally, water withdrawals and consumption for crude oil refining are broken down by process. In summary, while the authors do not attempt a true life-cycle assessment, they do provide important insight, particularly for crude oil/oil sands extraction and refining.

*(3): Chiu et al. (2009)*

This paper focuses exclusively on corn ethanol, exploring the direct water requirements for corn growing and biorefining. It served an important purpose by highlighting the states that currently bear the brunt of corn's water needs, and separating groundwater withdrawals from surface water withdrawals. Finally, the authors clearly show that irrigation water requirements vary greatly by state, so future researchers in the area of water should exercise great caution when applying U.S. average water consumption values.

## 3.3 Life-Cycle Inventory Components

Because conventional LCA tools such as EIO-LCA do not contain reliable, up-to-date data on water consumption, this LCI of water use must be primarily process-based. Additionally, because the resulting stress on freshwater resources is heavily location-dependent, it is essential that water consumption estimates are tied to geospatial data. In order to make this task manageable, a subset of industries that comprise the majority of water consumption in the United States are identified and then tracked throughout the life cycle of gasoline, ethanol, and electricity. As shown in Figure 1, U.S. water withdrawals are dominated by agriculture, thermoelectric power generation, and secondarily, public supply, with industrial sectors making up around 5% and mining constituting only 1% of withdrawals. However, if only consumptive water use is counted, a very different picture emerges (see Figure 10). Irrigation makes up by far the largest share of water consumption, followed by public supply. It should be noted that public supply provides water for industrial and commercial sectors in addition to residences,

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with 56% going to domestic uses, 17% to commercial uses, 12% to industry, and 15% to public use/loss (*116*).

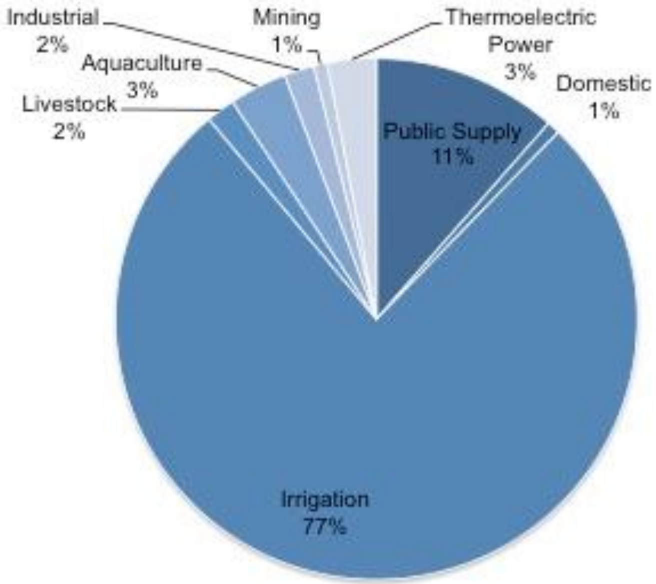

Figure 10: Consumptive Water Use in the United States (Data Sources (*12, 116*))

Quantifying consumptive use rather than withdrawals provides a more accurate portrayal of the impact that human activities have on freshwater resources. This is one of the major shortcomings of the 2002 EIO-LCA water use data; only withdrawals are included (*117*). However, as discussed in Chapter 2, even total consumptive use is not sufficient because a unit of water consumed in an area where water is scarce has a significantly greater impact than water consumed in an area with abundant resources. Power generation, industrial, mining, construction, and transportation activities, although they appear to make up a small share of total U.S. water consumption, are included in this life-cycle inventory because they could potentially have a far more significant contribution to overall water stress. The geographical distribution of these industries ultimately plays a large role in how they interact with freshwater resources, so all inventory data is collected on a county-level basis for use in the impact assessment presented in Chapter 4.

A complete list of factors included in this water use inventory is shown in Table 8. It should be noted that, while oil shale is discussed above for the purpose of context, it is not included in this research because large-scale U.S. production of oil shale has yet to be realized.

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| Pathway | Direct | Electricity Consumption | Primary Fossil Fuels | Chemicals | Construction & Materials | Supply-Chain Agriculture | Supply-Chain Services |
|---|---|---|---|---|---|---|---|
| Crude Oil to Gasoline | • Injection water<br>• Refinery process/cooling/ other water | • Electricity for extraction, transportation, storage, & distribution, & refining | • Crude oil<br>• Residual oil<br>• Diesel<br>• Gasoline<br>• Natural gas<br>• Coal | • Biocide<br>• Surfactant<br>• NaOH<br>• Neutralizer<br>• Inhibitor | • Steel<br>• Concrete<br>• Dust control | • All indirect agricultural NAICS sectors | • All service NAICS sectors |
| Oil Sands to Gasoline | • Injection & other mining water<br>• Refinery process/cooling/ other water | • Electricity for extraction, transportation, storage, & distribution, & refining | • Residual oil<br>• Diesel<br>• Gasoline<br>• Natural gas<br>• Coal | • NaOH<br>• Neutralizer<br>• Inhibitor | • Steel<br>• Concrete<br>• Dust control | • All indirect agricultural NAICS sectors | • All service NAICS sectors |
| Corn Stover to Ethanol | • Refinery process/cooling/ other water | • Electricity for transportation, storage, & distribution, & net input/output for biorefining | • Residual oil<br>• Diesel<br>• Gasoline<br>• Natural gas<br>• Propane | • Fertilizers<br>• Sulfuric acid<br>• Lime<br>• Corn steel liquor<br>• Cellulase<br>• Diammonium phosphate<br>• Ammonia<br>• Cooling water chemicals<br>• WWT chemicals | • Steel<br>• Rubber<br>• Concrete<br>• Dust control | • All indirect agricultural NAICS sectors | • All service NAICS sectors |
| Miscanthus to Ethanol | • Irrigation water ("high" case only)<br>• Refinery process/cooling/ other water | • Electricity for transportation, storage, & distribution, & net input/output for biorefining | • Residual oil<br>• Diesel<br>• Gasoline<br>• Natural gas<br>• Propane | • Fertilizers<br>• Glyphosate<br>• Sulfuric acid<br>• Lime<br>• Corn steel liquor<br>• Cellulase<br>• Diammonium phosphate<br>• Ammonia<br>• Cooling water chemicals<br>• WWT chemicals | • Steel<br>• Rubber<br>• Concrete<br>• Dust control | • All indirect agricultural NAICS sectors | • All service NAICS sectors |
| Corn Grain to Ethanol | • Irrigation water<br>• Refinery process/cooling/ other water | • Electricity for farming, transportation, storage, & distribution, & biorefining | • Residual oil<br>• Diesel<br>• Gasoline<br>• Natural gas<br>• Coal<br>• LPG | • Fertilizers<br>• Pesticides<br>• Herbicides<br>• Sulfuric Acid<br>• Lime<br>• Ammonia<br>• Alpha-Amylase & Glucoamylase<br>• Cooling water chemicals<br>• WWT chemicals | • Steel<br>• Rubber<br>• Concrete<br>• Dust control | • All indirect agricultural NAICS sectors | • All service NAICS sectors |
| Electricity | • Cooling water<br>• Other plant operations water | • Electricity transmission & distribution line losses | • Diesel<br>• Natural gas<br>• Coal<br>• Uranium* | N/A | • Steel<br>• Rubber<br>• Concrete<br>• Glass<br>• Sand<br>• Silicon<br>• Primary fossil fuels | • All indirect agricultural NAICS sectors | • All service NAICS sectors |

Table 8: Processes Included in Water Use LCI

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The life-cycle inventory components appearing in Table 8 were chosen based on expectations about their contribution to the overall results. Sector-specific data from reference (*12*) highlight the importance of agricultural production and thermoelectric power generation. This is echoed in results from the EIO-LCA tool, which show grain farming and power generation as significant contributors to the water footprint of most products and services, regardless of how far down in the supply chain or how miniscule the consumption is. For example, grain farming and power generation are the third and first largest contributors to the life-cycle water withdrawals for petroleum refining, respectively (*42*). More generally, the energy-water connection has long been acknowledged as an important one (*7, 31*), so the water footprints of electricity and primary fuels are tracked carefully through the LCI. Some contributors such as chemical manufacturing, steel production, and mining play a smaller role in total U.S. water use (*12*), but references (*118, 119*) prove that per unit of product, these sectors can be water-intensive and are worth including in a water use inventory. Other small industries are known to require large quantities of water, even though their contribution to total U.S. water use is small; the classic example is silicon production for solar photovoltaic panels (*120*). Finally, there are some processes that have never been studied in the context of freshwater environmental impacts: concrete production and dust control during construction. These construction-related impacts were included because they can have significant short-term, local impacts on freshwater resources and their overall significance has never before been estimated (*121*).

The following sections describe how water use was calculated for each of the major contributing inputs/processes.

### 3.3.1 Agricultural Systems

In agricultural systems, irrigation is the dominant consumer of water. Although crops receive water from precipitation, rainfall can be unpredictable and may fall short of providing enough water to optimize crop yields or even allow the crop to survive. For this reason, irrigation is vital to the success of agriculture. Irrigation needs vary greatly not only amongst different crops, but also by the location in which crops are grown. Water consumption by crops can be measured by the moisture content of the harvested biomass plus evapotranspiration (ET), a term that refers to the sum of plant transpiration (release of water vapor through pores called stomata) and evaporation from the surrounding soil. Figure 11 shows the major inflows and outflows of freshwater in a cropping system.

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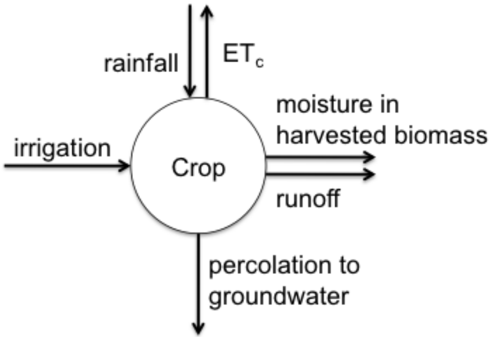

Figure 11: Flow of Water in Agricultural Systems

The water footprint of agriculture is made up of the direct requirements for crop growth and the water embedded into other inputs, such as primary fuels, equipment, chemicals, and electricity. The direct portion of the water footprint includes irrigation water, often referred to as blue water, as well as water from rainfall that is consumed through $ET_c$, which is referred to as green water.

### *3.3.1.1 Direct Crop Requirements*

If a farmer irrigates efficiently, runoff and percolation to groundwater sources should be minimized since these are both the result of excess irrigation water. The amount of moisture contained in the harvested biomass is relatively small compared to the other water flows in agricultural systems, which means crop irrigation should be roughly equal to $ET_c$ minus rainfall. ET rates depend on environmental factors such as temperature, wind speed, humidity, and solar radiation. Although there are multiple equations available for estimating ET, the equation recommended by the United Nations Food and Agriculture Organization (FAO) is the Penman-Monteith equation (*122*). The version of the Penman-Monteith equation used by the FAO is described in Appendix B.

Until now, all consumptive use has been treated equally. However, as pointed out in Chapter 2, green (from rainfall) and blue (withdrawn from surface or groundwater sources) water have different implications for water resource availability. Green water use represents consumption of water from rainfall that would otherwise meet a variety of fates, including absorption and ET by native plants, percolation into groundwater, or runoff into surface water sources. Because this dissertation takes a consequential LCA approach, the ultimate question is whether the cultivation of a biofuel crop results in a net change in green water consumption. Even soil without any vegetation results in some ET, so the only instance in which the entire green water footprint should be added to the total footprint in a consequential LCA is if the land in question were paved or otherwise covered such that no ET could take place. The assertion is made in Section 2.1.2 that there is too much uncertainty associated with the net change in green water consumption for this element to be included in the final life-cycle results. Additionally, publicly available data do not contain the necessary parameters to estimate ET from new biofuel crops such as Miscanthus. Studies that quantify ET for such biomass typically use grassy fodder crop

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data as a proxy (*20*). For illustrative purposes, green water use is modeled for U.S. corn production and presented here, compared side-by-side with irrigation inputs.

While using weather and land use data to estimate ET, along with plant moisture content, is the most accurate method for predicting agricultural consumptive water use, creating a national or global-scale model is beyond the scope of this research. CropWat is a software package based on the Penman-Monteith Equation that can be used to model ET and predict the resulting irrigation needs by location for a variety of crops (*123*). The default FAO input parameters are shown in Appendix B.

Location-specific climate input data required to run CropWat can be obtained by ClimWat (*124*). ClimWat obtains (and reports) its information from weather monitoring stations. Hence, for each state, one station, or some average of multiple stations, must be used to best represent the climate in the area where the crop in question is grown. To achieve this task, the USDA map of corn production is used (shown in Figure 12). Based on the geospatial distribution of each crop, representative climate stations are chosen. When there is no obvious choice, the station is selected whose data, when plugged into CropWat, produces irrigation data that most closely matches the USDA FRIS empirical data. The selected climate stations for each crop are shown in Appendix B. It should be noted that ClimWat climate data come from a small number of meteorological stations within each state that are typically located in or near cities, which means they may not always be representative of parts of the state where agriculture is concentrated.

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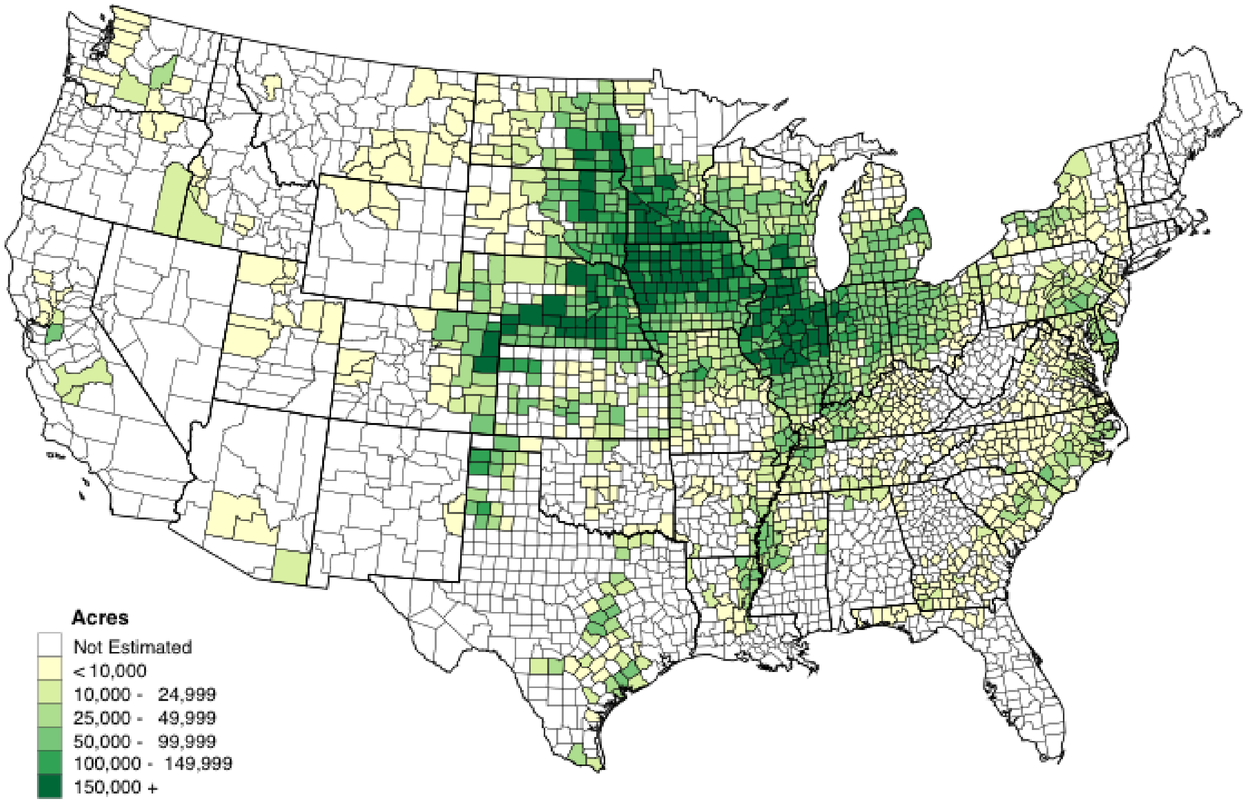

Figure 12: 2008 U.S. Corn Harvested Acres by County (Source: (*125*))

Empirical agricultural water use data for the United States is collected by the USDA in the form of total volume of irrigation water applied. Irrigation requirements by state for a wide array of crops grown in the United States are available in the USDA's 2003 Farm and Ranch Irrigation Survey (FRIS) (*126*). Table 28 of the FRIS includes state-level data on applied water per acre and bushel for potential biofuel feedstocks such as corn, sorghum, wheat, barley, soybeans, and sugar beets. Essentially all studies on lignocellulosic feedstocks, such as *Miscanthus x Giganteus* and switchgrass, assume that these grasses would only be produced in areas of the United States where no irrigation is required, so information on irrigation requirements for these grasses is limited. While the FRIS is a valuable data source, it ignores monthly variations in irrigation requirements, which are relevant when determining where potential water shortages may occur because of seasonal fluctuations in freshwater resources. This information would be vital for more sophisticated water consumption impact assessment modeling. However, for this research, only total annual consumption is used.

The USDA FRIS and CropWat data can be combined in a number of different ways to produce blue and green water consumption numbers. CropWat provides estimated evapotranspiration, rainfall, and required irrigation, while the FRIS only reports irrigation. Typically, the CropWat-estimated irrigation requirements are higher than those reported in the FRIS. In part, this could be due to the fact that irrigation inputs are flexible, and the farmer will make a decision based on marginal increased yield of his/her crop resulting from additional irrigation inputs versus the cost of water and fuel inputs to irrigation equipment. Therefore, farmers may be willing to

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settle for lower yields than are assumed in CropWat, and hence will irrigate less. The FRIS does provide irrigated and non-irrigated average yields for each crop, but translating bushel per acre yields into CropWat inputs is not a straightforward task. In future research, this should be explored as a method for improving model outputs.

Although CropWat ET estimates are also somewhat uncertain, they are assumed to be sufficiently accurate for the purposes of this research. Hence, blue water consumption is equal to the irrigation requirements reported by the FRIS, and green water consumption is calculated as the difference between CropWat-estimated ET and applied irrigation. Green water requirement results are shown in Figure 13.

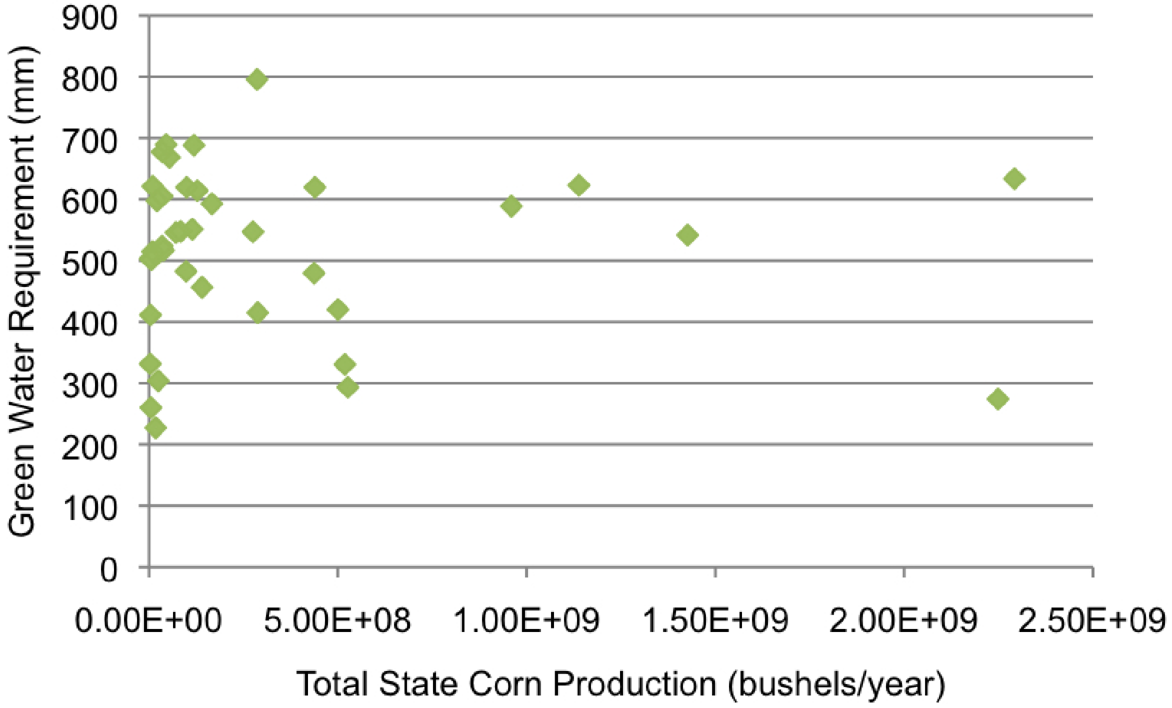

Figure 13: Green Water Consumption vs. State Corn Production (Data Sources: (*123, 126*))

Using the FRIS irrigation data combined with corn production data, county level irrigation inputs are developed, and are shown in Appendix B. State-level irrigation data are shown in Appendix B as well. The average irrigation water input for corn grain produced in the United States is 0.63 $m^3$/bushel. Figure 14 shows a scatter plot of irrigation inputs by total in-state corn production. It is clear that, while there are outliers that require huge amounts of irrigation, these states produce only a small fraction of the nation's corn. With the exception of Nebraska, the highest corn-producing states require very little water.

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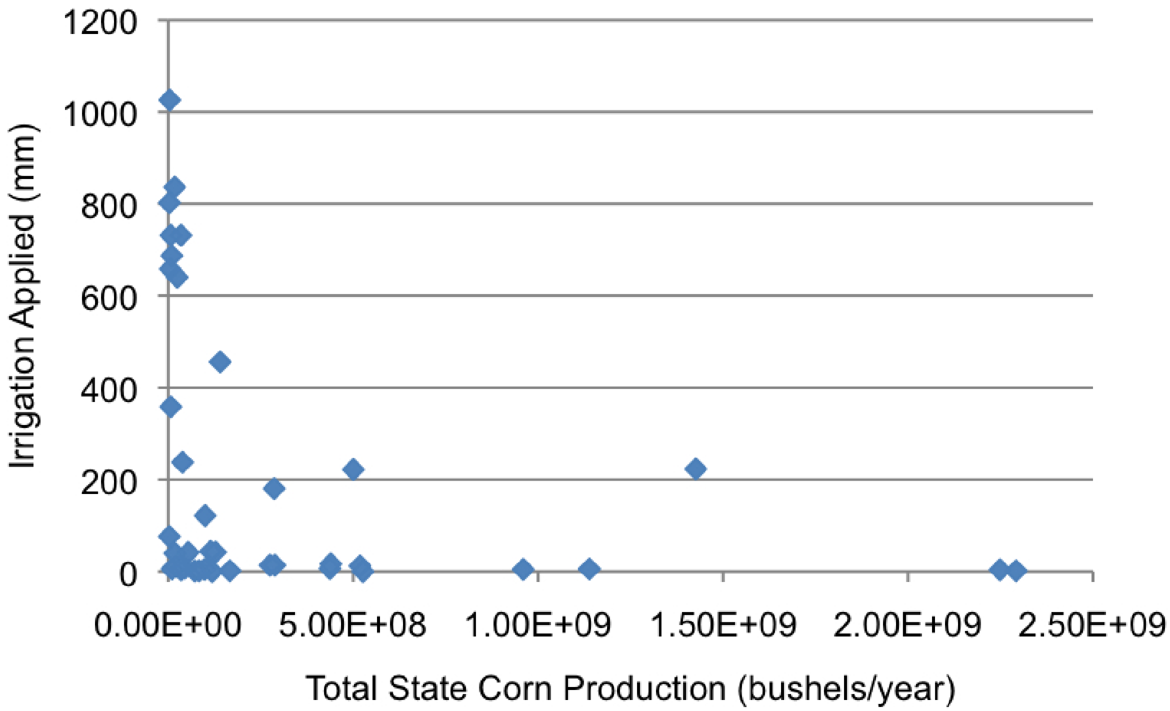

Figure 14: Irrigation Application vs. Corn Production by State (Data Sources: (*123, 126*))

In contrast, Figure 13 shows that Iowa, which produces the most corn, also has one of the largest green water footprints. The results for Minnesota, Nebraska, and Indiana are similar. The issue remains that the net change in green water use is ultimately a question of land use change; what land will be converted to biofuel crop production and what were the water needs for that land?

### *3.3.1.2 Indirect Land Use Change and Irrigation Needs*

Modeling iLUC and its resulting environmental impacts could fill one or more dissertations in itself, requiring knowledge of global general economic models as well as carbon fluxes for different ecosystems (see Chapter 2 for a description of iLUC). This research relies on the iLUC analysis produced by the California Air Resources Board (CARB) and the University of California, Berkeley for use in the LCFS emission factors, which employ the Global Trade Analysis Project (GTAP) model. The scenario used in this research was run for corn ethanol in the United States, with a baseline year of 2001 and baseline production of 6.62 billion L of corn ethanol, increasing to a final ethanol production volume of 56.8 billion L (*127*). As U.S. corn ethanol production is increased, additional cropland in a variety of countries is brought into production to make up for the reduction in U.S. corn exports in the food market. The breakdown of this additional cropland by location, as calculated by GTAP, is shown in Table 9.

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| Canada | Africa | Europe | Soviet Union | Latin America | North Africa & Middle East | Developed Pacific | China/India/ Pakistan | Southeast Asia | United States | Rest of World |
|---|---|---|---|---|---|---|---|---|---|---|
| 4.45% | 8.74% | 7.26% | 3.47% | 9.85% | 1.79% | 1.84% | 1.18% | 0.13% | 61.18% | 0.12% |

Table 9: GTAP iLUC Results (Data Source: (*127*))

iLUC occurs anytime land formerly used for food production is converted to biofuel crop production, even if the biofuel crop is not food itself. For example, corn ethanol plants are being expanded to add the capacity to process cellulosic feedstocks. Because corn ethanol plants are typically located in close proximity to corn crops, the result may be that land formerly used to grow corn is converted to cellulosic feedstock crops, such as switchgrass or Miscanthus. If this were to become widespread, LCA-based GHG regulatory frameworks that include iLUC, such as the LCFS (*128*), are equipped to penalize such practices on the basis of increased carbon emissions.

An increase in GHG emissions is not the only result of iLUC; there are potential freshwater consumption impacts as well. Depending on whether the new corn production occurs in areas that require more or less irrigation than U.S. corn, this will be either a negative or positive impact on total global freshwater needs. Because of the large uncertainty associated with iLUC calculations, and lack of information about the specific location and irrigation requirements for the land that will theoretically be brought into production, this dissertation leaves this as a qualitative discussion. However, further exploration of iLUC effects on total irrigation requirements would be valuable in future work.

### *3.3.1.3 Water Embodied in Energy and Material Inputs*

Yet to be quantified in any other process LCA is the water embodied in the energy and material inputs for agriculture. For an irrigated crop, these contributions may seem insignificant, but as society moves toward rain fed crops such as perennial grasses, this embodied water will become important.

Farms require fuels to power tractors and other equipment, some electricity for pumping, fertilizer, herbicide, pesticide, and the material inputs for the equipment itself, such as steel and rubber. Three agricultural products are considered here: corn grain, corn stover, and Miscanthus, as shown in Table 10. The latter is not a commercial crop yet, so data is based on academic studies and experimental data gathered from test plots in Illinois (*87*). Corn grain requires the most on-farm inputs because it must be replanted each year, as opposed to perennial grasses such as Miscanthus that have a lifetime of 15-20 years before they must be replanted (*129*). The energy and equipment use for Miscanthus is assumed to be the same as corn stover (on a dry Mg basis) because the most significant energy use comes from harvesting. Also, Miscanthus requires very little nutrient input. Reference (*87*) predicts that the only regular nutrient application will come in the form of recycled ash from cellulosic biorefineries, with purchased fertilizer application occurring during the establishment year. Estimating herbicide and pesticide application is difficult because, until large quantities of land are converted to Miscanthus production, it is difficult to predict which pests and weeds will be problematic (*87*). Conservative estimates are shown in Table 10. In contrast to Miscanthus,

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corn stover is already produced at commercial scale, although it is not currently used for biofuel production. As consistent with the multi-output allocation methodology put forth in Chapter 2, none of the impacts of growing corn for grain are allocated to the stover. However, there are additional inputs required when stover is harvested; fertilizer input goes up, and the energy and equipment needed to harvest and prepare the stover. All of these additional inputs are allocated entirely to corn stover, and are shown in Table 10. Lastly, the agricultural inputs have their own energy footprints, which in turn require water. The energy inputs for agricultural input manufacturing are shown in Table 11.

| **Input Type** | **Input** | **Corn Grain** | **Corn Stover** | **Miscanthus** | **Source** |
|---|---|---|---|---|---|
| Energy | Diesel (HHV) | 6.49 MJ/bushel | 295 MJ/dry Mg | 295 MJ/dry Mg | (*69*) |
| | Gasoline (HHV) | 2.63 MJ/bushel | N/A | N/A | (*69*) |
| | Natural Gas (HHV) | 1.93 MJ/bushel | N/A | N/A | (*69*) |
| | LPG (HHV) | 2.45 MJ/bushel | N/A | N/A | (*69*) |
| | Electricity | 0.707 MJ/bushel | N/A | N/A | (*69*) |
| Fertilizer | N | 420 g/bushel | 4940 g/dry Mg | 175 g/dry Mg | (*69, 87*) |
| | $P_2O_5$ | 149 g/bushel | 1790 g/dry Mg | 7.31 g/dry Mg | (*69, 87*) |
| | $K_2O$ | 174 g/bushel | 9170 g/dry Mg | 139 g/dry Mg | (*69, 87*) |
| Herbicide | Atrazine | 2.53 g/bushel | N/A | N/A | (*69, 87*) |
| | Metolachlor | 2.28 g/bushel | N/A | N/A | (*69, 87*) |
| | Acetochlor | 1.91 g/bushel | N/A | N/A | (*69, 87*) |
| | Cyanazine | 1.39 g/bushel | N/A | N/A | (*69, 87*) |
| | Glyphosate | N/A | N/A | 24.9 g/dry Mg | (*87*) |
| Pesticide | Generic | 0.68 g/bushel | | N/A | (*69, 87*) |
| Equipment (Assumed lifetime of 12 years) | Steel | 56.6 g/bushel | 0.574 g/dry Mg | 0.574 g/dry Mg | (*69*) |
| | Rubber | 7.68 g/bushel | 0.0794 g/dry Mg | 0.0794 g/dry Mg | (*69*) |

Table 10: Biofuel Crop Energy and Material Inputs

| **Input** | **Natural Gas** | **Electricity** | **Residual Fuel** | **Diesel** | **Coal** | **Source** |
|---|---|---|---|---|---|---|
| N | 37.2 MJ/kg | 1.58 MJ/kg | N/A | N/A | N/A | (*69*) |
| $P_2O_5$ | 4.85 MJ/kg | 1.30 MJ/kg | N/A | N/A | N/A | (*69*) |
| $K_2O$ | 1.22 MJ/kg | 1.30 MJ/kg | N/A | 1.41 MJ/kg | N/A | (*69*) |
| Atrazine | 37.3 MJ/kg | 27.5 MJ/kg | 48.6 MJ/kg | 48.6 MJ/kg | N/A | (*69*) |
| Metolachlor | 54.1 MJ/kg | 40.0 MJ/kg | 70.5 MJ/kg | 70.5 MJ/kg | N/A | (*69*) |
| Acetochlor | 54.5 MJ/kg | 40.3 MJ/kg | 71.1 MJ/kg | 71.1 MJ/kg | N/A | (*69*) |
| Cyanazine | 39.5 MJ/kg | 29.2 MJ/kg | 51.5 MJ/kg | 51.5 MJ/kg | N/A | (*69*) |
| Glyphosate | 46.3 MJ/kg | 34.2 MJ/kg | 60.4 MJ/kg | 60.4 MJ/kg | N/A | Calculated as average of herbicides |
| Pesticide | 53.1 MJ/kg | 41.9 MJ/kg | N/A | 139 MJ/kg | N/A | (*69*) |
| Steel | 6.76 MJ/kg | 4.20 MJ/kg | N/A | N/A | 0.686 MJ/kg | (*42, 130*) |

Table 11: Energy Intensity of Agricultural Inputs

Using the data in Table 10 and Table 11, combined with the water intensities in Table 32, the water footprint of agriculture can be calculated, as shown in Figure 15 and Figure 16. Clearly, irrigation water, if necessary, dominates the water footprint of agricultural systems. However, the withdrawals associated with chemicals can be very significant, and make up the majority of corn stover's water footprint. It is interesting to note that, even though very little electricity is used on farms relative to other fuels, water withdrawals for electricity are so high that it shows up as the third largest contributor to water withdrawals for corn grain production.

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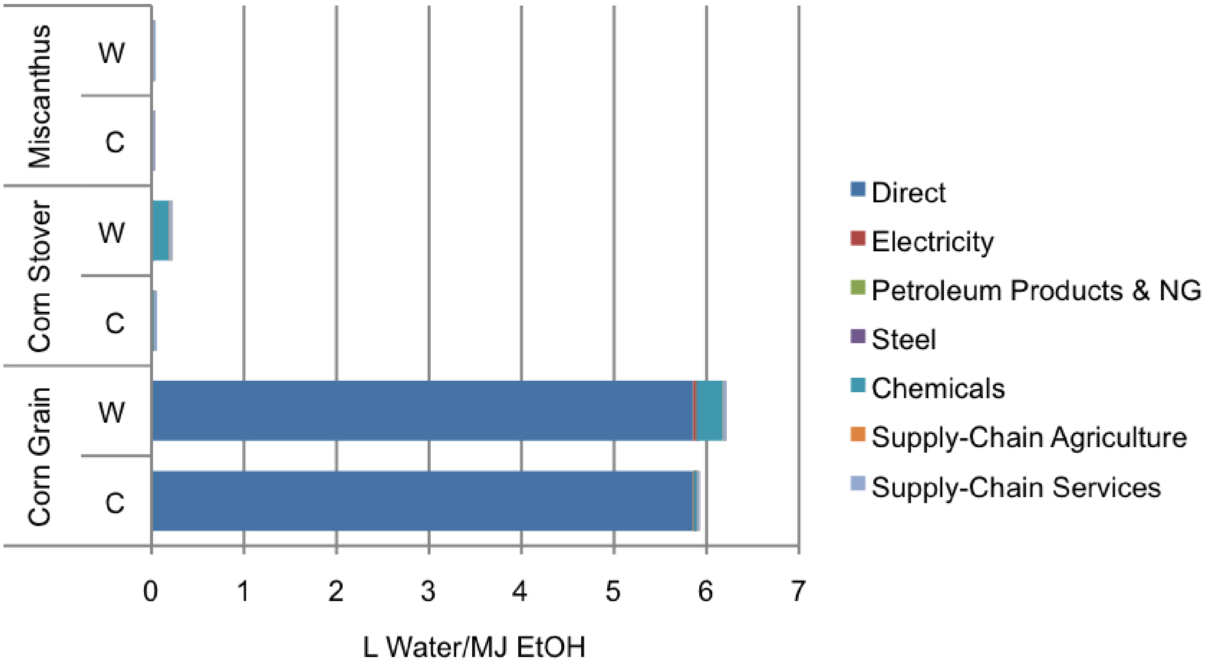

Figure 15: Agriculture Phase Water Footprint by Feedstock

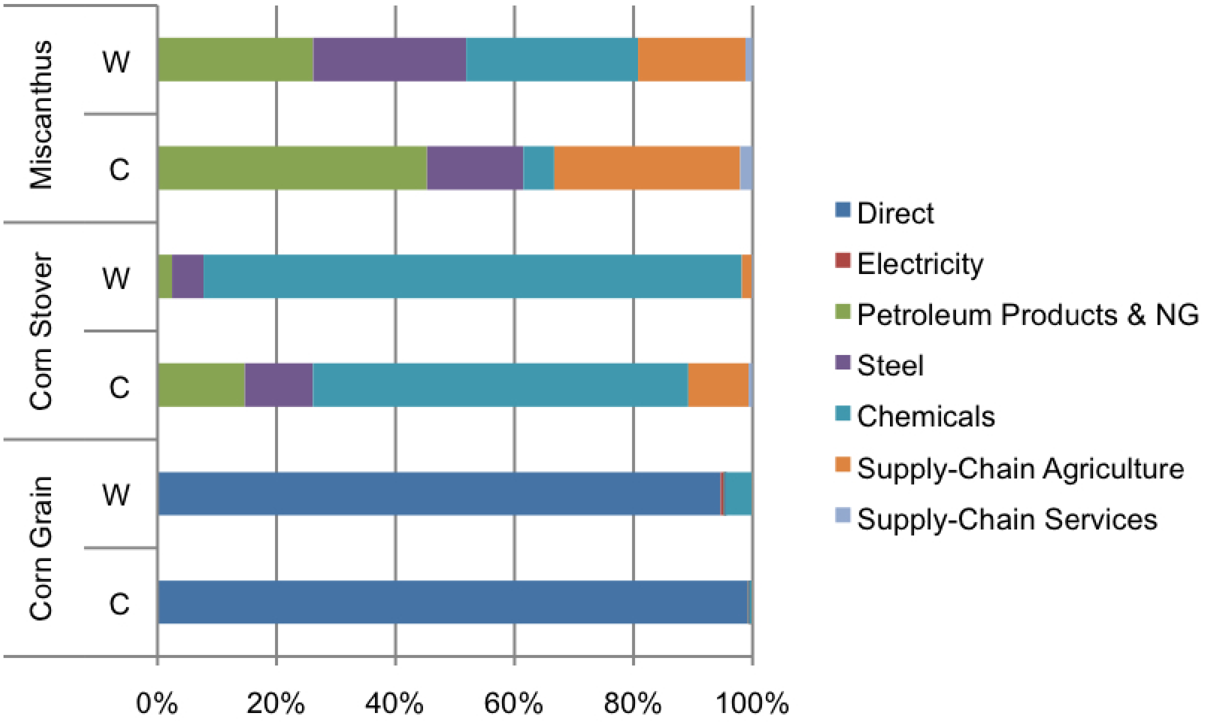

Figure 16: Contributors to Agriculture Phase Water Footprint by Feedstock

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### 3.3.2 Electric Power Generation

Electric power generation is responsible for a large fraction of total freshwater withdrawals in the United States (49% according to reference (*12*)) and a small, yet not insignificant 3% of total consumptive use. Essentially all of this water is used for cooling purposes. Coal, nuclear, and natural gas-fired power plants are the types of power plants most often studied in the context of water use. In this section, all electricity generation, including emerging renewable sources are quantified in terms of withdrawals and consumption. Where possible, individual power plants are quantified in terms of water use based on either empirical data or information about the input fuel and cooling system used. In other cases, average water use factors are developed based on the plant type (input fuel and thermodynamic cycle). These plants are ultimately aggregated into North American Electric Reliability Corporation (NERC) regions, which serve to best approximate the grid mix used at any given location within the United States as well as parts of Canada and Mexico (*131*). NERC regions are defined based on the flow of power through transmission lines such that a minimal amount of electricity travels in and out of each region. Figure 17 shows a map of the NERC regions that make up the contiguous United States. The ASCC and HICC regions are not shown, but are straightforward; the ASCC region covers the entire state of Alaska and HICC covers the state of Hawaii.

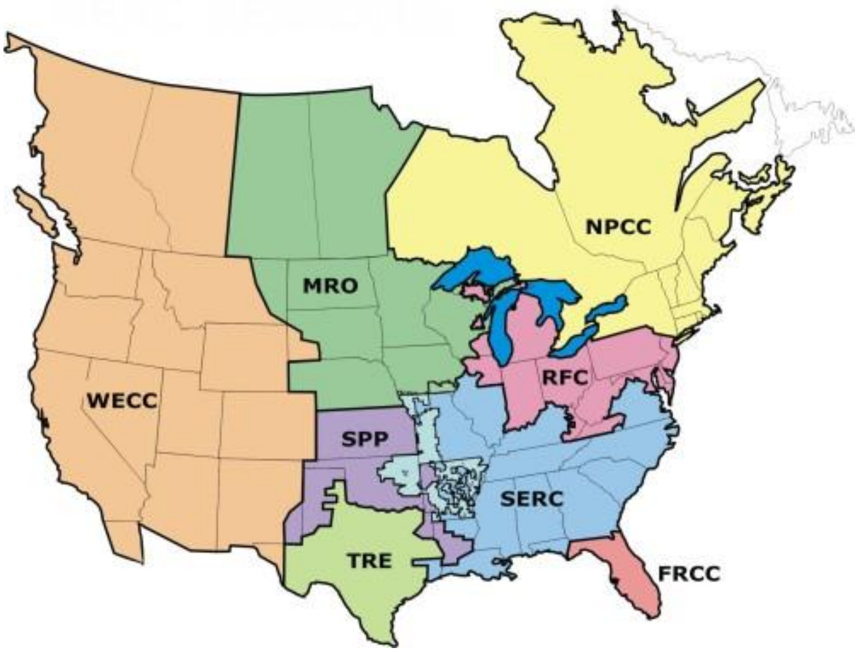

Figure 17: NERC Regions (Source: (*132*))

A variety of factors dictate the electricity mix and resulting water footprint in each NERC region, including resource constraints, fuel prices and availability, and environmental regulations. As shown in Section 3.4, the differences in both total water withdrawals and consumption can be quite pronounced.

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### *3.3.2.1 Fossil Thermoelectric Power Generation*

The vast majority of withdrawals and use are the result of thermoelectric power generation, which includes nuclear, natural gas, and coal power plants. Figure 18 demonstrates that thermoelectric power generation supplies the bulk of U.S. electricity.

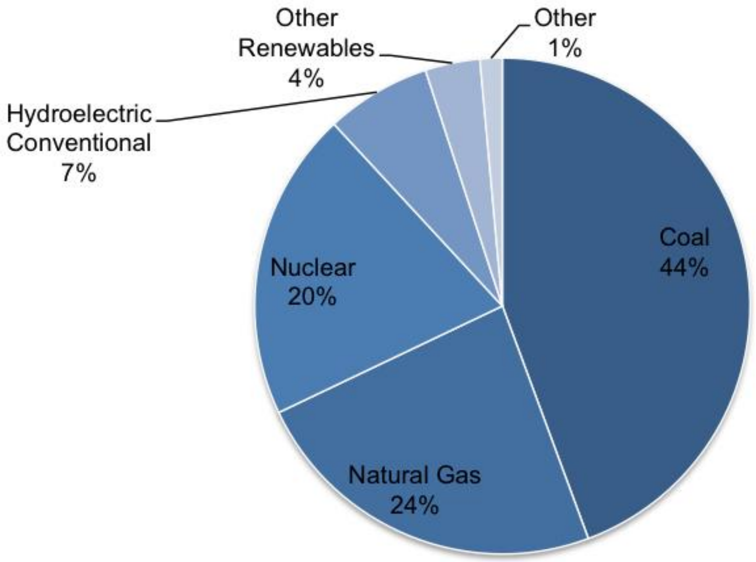

Figure 18: 2009 U.S. Electricity Generation by Energy Source (Data Source: (*133*))

The majority of U.S. electricity generation is thermoelectric: coal (44%), natural gas (24%), and nuclear (20%) (*134*). Thermoelectric power generation requires large volumes of water for cooling. For once-through cooling, water is withdrawn, run through the condenser to absorb the plant's waste heat, and then discharged to its source (typically a river or the ocean for coastal plants) at a higher temperature (see Figure 19). This warm-water discharge results in a heat plume that releases some steam before equilibrating with the ambient river temperature. The amount of water that evaporates from this heat plume is much smaller than the total volume of water that is cycled through the power plant, so withdrawals for once-through cooling systems are much larger (200 times) than consumption (evaporative losses). In contrast, closed-loop cooling systems (see Figure 19) consume less than twice the amount they withdraw. Air, propelled either by a fan or the natural difference in air density at the top and bottom of the tower, enters the bottom of the cooling tower and flows upward while heated water enters near the top and flows down. The air updraft cools the heated water, evaporating some of the water, which exits the top of the tower as steam. Water that reaches the bottom of the tower in liquid form is recirculated, and fresh makeup water is withdrawn from a nearby source to replace the evaporated water, as shown in more detail in Figure 20. To avoid excessive mineral buildup in the recirculated cooling water, this water must be periodically discharged, known as blowdown, when it reaches between 5 and 10 times the natural mineral concentration (known as cycles of concentration) (*31*). Table 12 shows typical cycles of concentration for cooling systems in various industries. It is because of blowdown that withdrawals for closed-loop cooling are slightly higher than consumption.

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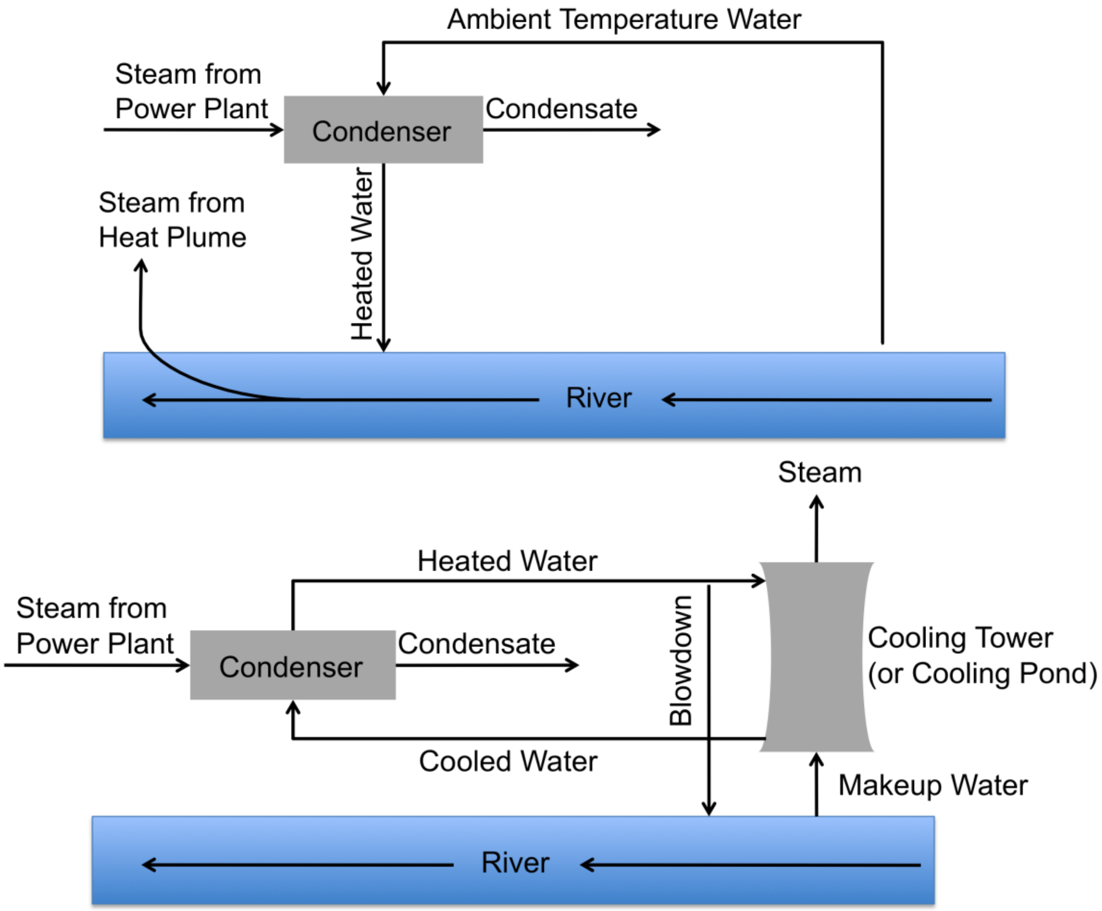

Figure 19: Power Plant Cooling Systems: Once-Through (Top), Closed Loop (Bottom) (Adapted from (*31*))

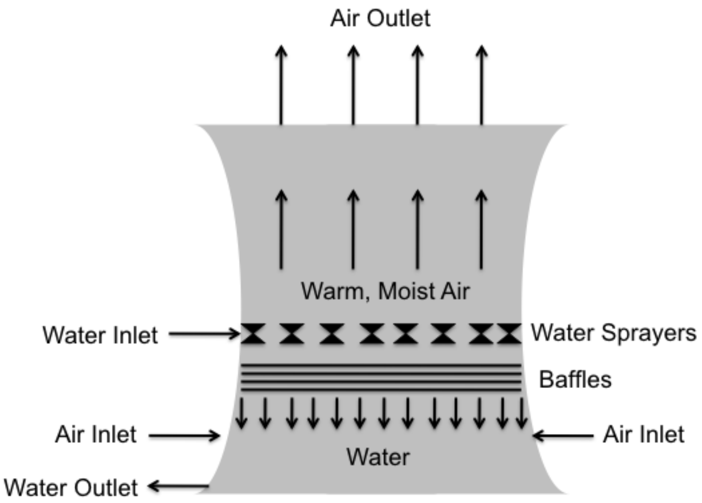

Figure 20: Natural Draft Parabolic Cooling Tower Diagram (Adapted from (*91*))

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| Industry | Typical Cycles of Concentration |
|---|---|
| Fossil Fuel-Fired Power Plants | 5-8 |
| Nuclear Power Plants | 6-10 |
| Petroleum Refineries | 6-8 |
| Chemical Plants | 8-10 |
| Steel Mills | 3-5 |
| Heating, Ventilation & Cooling (HVAC) | 3-5 |
| Paper Mills | 5-8 |

Table 12: Typical Cycles of Concentration for Various Cooling Systems (Data Source: (*135*))

Total withdrawals and consumption per unit of electricity produced varies not only by system type, but also by fuel (nuclear, coal, natural gas, etc.). Data on cooling water use for coal-fired power plants and nuclear plants are taken from reference (*114*), which inventories all coal-fired and nuclear power plants in the United States, identifying each plant's cooling system(s). Because such an inventory does not exist for natural gas, biomass, or oil-fired power plants, each plant listed in the eGRID database (*89*) is assigned the national average water use for coal plants, with 38% of generation utilizing once-through with freshwater, 3% using once-through with saline, and 59% using closed-loop. Finally, water consumption at geothermal plants listed in eGRID is estimated using data from references (*7, 136*).

Line losses between power plants and final users must be accounted for. NERC region-specific loss factors are taken from reference (*131*). Although the electricity is lost, rather than being consumed for some functional use, line losses are treated as electricity consumption for the fuel transportation, distribution, and storage phase. Appendix B shows the electricity mixes for each NERC region as well as region-specific line losses. Table 13 shows water use by thermoelectric plant type. A more detailed list of plant-specific cooling water requirements is shown in Appendix B.

| Fuel | Cooling System | Withdrawals (L/kWh) | Consumption (L/kWh) |
|---|---|---|---|
| Coal | Once-Through | 9.8E+01 | 5.0E-01 |
| Coal | Recirculating | 2.1E+00 | 1.8E+00 |
| Coal | Cooling Pond | 6.5E+01 | 2.3E+00 |
| Natural Gas | Once-Through | 9.8E+01 | 5.0E-01 |
| Natural Gas | Recirculating | 2.1E+00 | 1.8E+00 |
| Biomass | Average | 2.7E+00 | 2.3E+00 |
| Nuclear | Once-Through | 1.2E+02 | 5.2E-01 |
| Nuclear | Recirculating | 4.2E+00 | 2.4E+00 |
| Nuclear | Cooling Pond | 7.9E+01 | 5.4E+00 |

Table 13: Summary of Thermoelectric Power Plant Water Use

In addition to the direct water requirements for cooling, the materials and energy required to construct power plants contribute indirectly to the total water footprint of electricity. Concrete, steel, copper, aluminum, and other materials commonly are used in large quantities to build thermoelectric power plants. Table 15 shows all energy and material inputs for power plant construction used in this study.

### *3.3.2.2 Hydroelectricity*

There is one non-thermoelectric power plant that results in significant water consumption: hydroelectric dams. Although not as obvious as cooling towers venting steam into the air, the production of hydroelectric power also results in water consumption. This is because,

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whenever water flow is altered in such a way that total surface area of the water body increases, total evaporation also increases. This increase in surface area can be estimated as the total reservoir surface area (*27*). To estimate evaporation rates, one must calculate what is known as free water surface evaporation (FWSE), which is based on experimental evaporation data collected by the U.S. National Weather Service and reported by testing station (*137*). FWSE is calculated based on the assumption that the water body in question stores no heat (the temperature remains constant throughout the year). While this is clearly not the case, the storage of heat during the spring, which decreases evaporation should be somewhat counterbalanced by the release of heat in the fall, and hence increased evaporation. If this change in evaporation is attributed exclusively to hydroelectricity production, the results are dramatic; for example, hydroelectricity in Arizona results in 245 L of consumptive water use per kWh of power produced (*27*), as compared to 1.8 L/kWh for a typical closed-loop coal-fired power plant. Table 14 shows state-level water consumption estimates for hydroelectric dams in the United States.

| State | L Water Consumption/kWh Consumed | State | L Water Consumption/kWh Consumed |
|---|---|---|---|
| AL | 140 | MT | 139 |
| AK | N/A | NE | 8.25 |
| AZ | 245 | NV | 278 |
| AR | N/A | NH | N/A |
| CA | 79.0 | NJ | N/A |
| CO | 67.8 | NM | 257 |
| CT | N/A | NY | 21.1 |
| DE | N/A | NC | 39.3 |
| DC | N/A | ND | 219 |
| FL | N/A | OH | N/A |
| GA | 179 | OK | 518 |
| HI | N/A | OR | 16.7 |
| ID | 32.2 | PA | N/A |
| IL | N/A | RI | N/A |
| IN | N/A | SC | N/A |
| IA | N/A | SD | 435 |
| KS | N/A | TN | 164 |
| KY | 584 | TX | N/A |
| LA | N/A | UT | 278 |
| ME | N/A | VT | N/A |
| MD | 25.4 | VA | N/A |
| MA | N/A | WA | 12.1 |
| MI | N/A | WV | N/A |
| MN | N/A | WI | N/A |
| MS | N/A | WY | 518 |
| MO | N/A | U.S. Average | 69.2 |

Table 14: Hydroelectricity-Related FWSE (Data Source: (*27*))

The question of whether all of the evaporative losses should be attributed to hydroelectricity is an important one; dams are also built for irrigation, public water supply, recreation, and flood control. Theoretically, the water consumption resulting from such projects should be attributed in some way to the different services it provides, but even performing a simple market value-based allocation is impossible unless dollar values can somehow be placed on flood control, water storage, and recreation. Because most studies choose not to include hydroelectricity-related water consumption (*7, 31, 114, 138*), this analysis remains conservative and does not include hydro-related water use. However, it will be included in the sensitivity analysis, performed in Chapter 6.

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Lastly, there are material and energy inputs associated with the construction of hydroelectric dams, including large amounts of diesel fuel for excavation and massive quantities of concrete and steel. These are included in the life-cycle inventory and are shown in Table 15.

### *3.3.2.3 Solar Photovoltaics*

Solar panels used for electricity generation have both direct and indirect water impacts. Directly, they require periodic washing to ensure that residue does not collect, blocking sunlight and reducing the panels' efficiency. According to reference (*7*), washing requirements total to approximately 0.1 L of water per kWh of electricity produced. However, this number is likely to vary widely not only because of different washing schedules/techniques, but also because of differences in total electricity production in various locations.

The indirect water footprint of solar power proves to be very significant. Silicon wafers, which make up PV panels are both water-intensive and energy-intensive to manufacture (*139*). To make a kg of silicon, 312 L of water must be used, according to reference (*140*). This is, compared to other literature, a conservative estimate. 2130 kWh of electricity are also required per kg of silicon produced (*120*). The total silicon (and other energy and material inputs) required to produce a typical solar PV array is shown in Table 15.

Combining these solar results with the results for all other forms of electricity generation yields Figure 21, which shows the total withdrawals and consumption for electricity production. Direct water use dominates the total withdrawals, although the electricity lost along transmission and distribution lines (shown as "electricity") is also significant. In Figure 22, the breakdown of both withdrawals and consumption by contributor is shown. While direct water use for cooling and the indirect water use for production of electricity that is lost during transmission and distribution dominate withdrawals, consumption is much more diverse. Supply-chain agriculture makes up a surprisingly high fraction of the total. In terms of consumption, agricultural products are so much more water-intensive than any other sector of the U.S. economy that even when it plays a minor role in a given supply chain, agricultural products are likely to make up a significant fraction of the total water footprint. Appendix B shows the life-cycle water consumption and withdrawals for U.S. electricity production by NERC region.

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| **Plant Type** | **Hydroelectric** | **Solar PV** | **Wind** | **Coal** | **Nuclear** | **Natural Gas** | **Oil** | **Biomass** | **Geothermal** |
|---|---|---|---|---|---|---|---|---|---|
| Lifetime (years) | 100 | 30 | 30 | 40 | 40 | 40 | 40 | 40 | 40 |
| Power Generation (kWh/year) | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 | 5.50E+09 |
| Diesel (MJ) | 5.03E+07 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Electricity (kWh) | N/A | 7.56E+09 | 1.69E+09 | N/A | N/A | N/A | N/A | N/A | N/A |
| Oil (MJ) | N/A | N/A | 2.04E+07 | N/A | N/A | N/A | N/A | N/A | N/A |
| Steel (Mg) | 3.22E+04 | 4.60E+06 | 2.90E+05 | 6.22E+04 | 6.22E+04 | 5.11E+04 | 5.11E+04 | 5.11E+04 | 5.11E+04 |
| Copper (Mg) | 9.00E+01 | 4.80E+05 | 1.57E+03 | N/A | N/A | N/A | N/A | N/A | N/A |
| Concrete (Mg) | 9.91E+06 | 2.22E+06 | 1.27E+06 | 1.78E+05 | 1.78E+05 | 7.13E+04 | 7.13E+04 | 7.13E+04 | 7.13E+04 |
| Aluminum (Mg) | 6.70E+01 | 1.78E+05 | 6.28E+03 | 6.24E+02 | 6.24E+02 | 2.30E+02 | 2.30E+02 | 2.30E+02 | 2.30E+02 |
| Glass (Mg) | 0.00E+00 | 1.07E+06 | 4.93E+03 | N/A | N/A | N/A | N/A | N/A | N/A |
| Silicon (Mg) | 0.00E+00 | 2.47E+04 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Sand (Mg) | N/A | N/A | 9.41E+03 | N/A | N/A | N/A | N/A | N/A | N/A |
| Plastics (Mg) | N/A | N/A | 2.02E+04 | N/A | N/A | N/A | N/A | N/A | N/A |
| Data Sources | (*141*) | (*141*) | (*141*) | (*141*) | Assumed to be similar to coal plant | (*141*) | Assumed to be similar to natural gas plant | Assumed to be similar to natural gas plant | Assumed to be similar to natural gas plant |

Table 15: Energy and Material Inputs for Power Plant Construction

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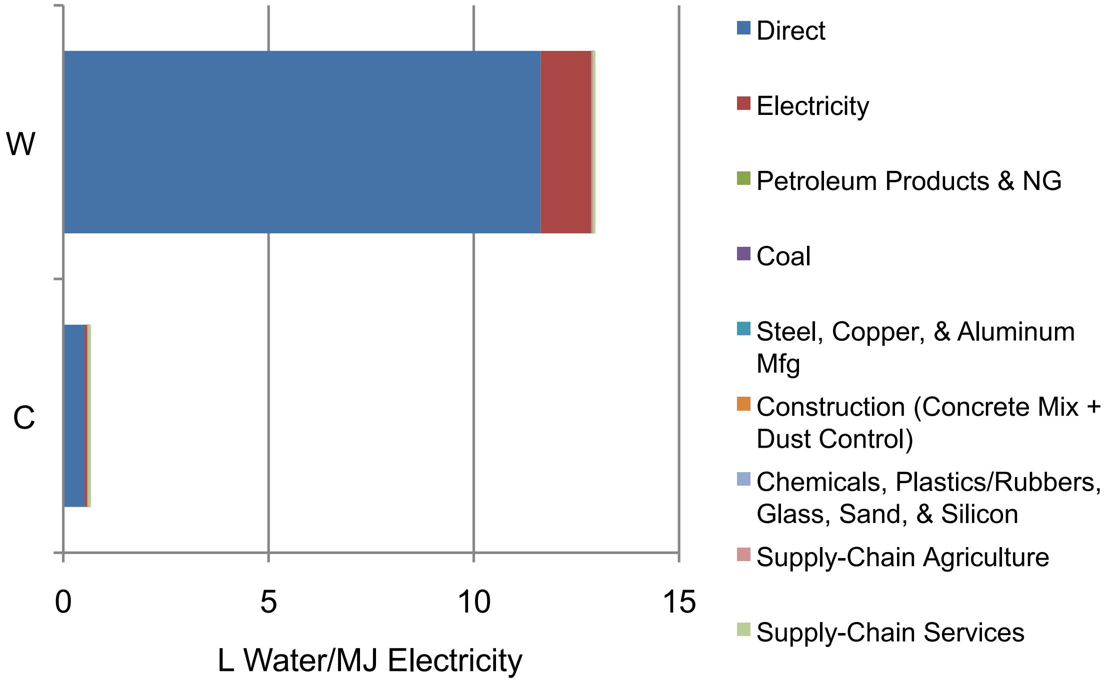

Figure 21: Water Footprint of Average U.S. Electricity Production

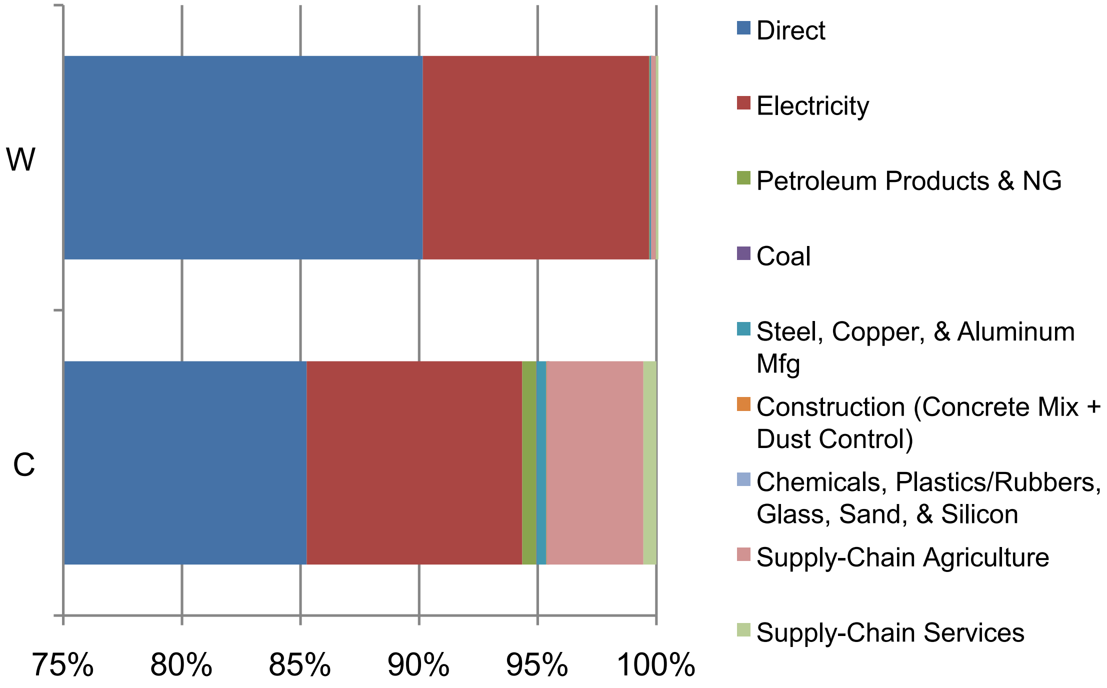

Figure 22: Water Footprint Breakdown by Contributor for U.S. Electricity Production

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### 3.3.3 Crude Oil and Natural Gas Extraction

The water-intensity of gasoline from crude oil is almost exclusively dependent on two life-cycle phases: extraction and refining. Water is used in crude oil extraction for secondary and tertiary recovery, a set of techniques that are used to bring oil to the surface after the natural pressure in the well alone becomes insufficient. The amount of injection water required for these extraction techniques ranges from 1.9 to 13 times the volume of crude oil recovered (*7*). The breakdown of techniques by oil extraction location is shown in Table 16. Although some water is also used in primary recovery, it is relatively small (0.2 times the volume of crude extracted) (*7*).

| **Origin** | **%** | **Primary** | **Secondary Flooding** | **EOR: CO2 Injection** | **EOR: Steam Injection** | **EOR: Forward Combustion** | **EOR: Other** |
|---|---|---|---|---|---|---|---|
| Domestic Onshore | 22.70% | 1.50% | 16.96% | 1.57% | 1.88% | 0.09% | 0.73% |
| Domestic Offshore | 11.20% | 11.20% | N/A | N/A | N/A | N/A | N/A |
| Algeria | 2.50% | 1.25% | 1.25% | N/A | N/A | N/A | N/A |
| Nigeria | 6.10% | 3.05% | 3.05% | N/A | N/A | N/A | N/A |
| Saudi Arabia | 8.10% | 4.05% | 4.05% | N/A | N/A | N/A | N/A |
| Venezuela | 8.00% | 4.00% | 4.00% | N/A | N/A | N/A | N/A |
| Canada: Conventional | 3.32% | 1.66% | 1.66% | N/A | N/A | N/A | N/A |
| Canada: Oil Sands | 7.18% | N/A | N/A | N/A | N/A | N/A | N/A |
| Mexico | 7.30% | 3.65% | 3.65% | N/A | N/A | N/A | N/A |
| Other Countries | 19.80% | 9.90% | 9.90% | N/A | N/A | N/A | N/A |

Table 16: Origin and Extraction Techniques for U.S. Crude Oil Supply (Data Source: (*5*))

Extraction water use data from references (*9, 25-28*), as compiled by reference (*5*) were used to develop estimates for domestic oil production by PADD, as well as imports, where Saudi Arabian extraction is assumed to be representative of U.S. imports. The data are shown in Table 17. When crude is extracted, it carries with it large volumes of water, known as produced water (often more than 10 times the volume of crude), and some of this produced water can be used for reinjection. In this analysis, produced water is not counted as part of freshwater resources because it is highly contaminated with hydrocarbons, so total freshwater required for crude oil extraction is equal to the total technology-weighted requirements, minus any produced water used for reinjection. Offshore oil recovery uses only produced water and seawater for injection, so its freshwater requirements are assumed to be zero. PADD-specific data from references (*142*) and (*143*) are used to account for produced water use in extraction.

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| Source | Non-PW Water for Injection: L/MJ Crude | Consumption: L/MJ Crude | Withdrawals (L/MJ Crude) | Fraction of Domestic Oil Production | PW Used for Re-Injection (L/MJ Crude) | Total Water for Injection (L/MJ Crude) |
|---|---|---|---|---|---|---|
| PADD I | N/A | N/A | N/A | 0.00444 | 0.252 | 0.252 |
| PADD II | 0.0546 | 0.0546 | 0.0546 | 0.0855 | 0.153 | 0.208 |
| PADD III | 0.0598 | 0.0598 | 0.0598 | 0.541 | 0.148 | 0.208 |
| PADD IV | N/A | N/A | N/A | 0.0656 | 0.351 | 0.351 |
| PADD V | 0.140 | 0.140 | 0.140 | 0.303 | 0.0675 | 0.208 |
| Saudi Crude | 0.0779 | 0.0779 | 0.0779 | N/A | 0.130 | 0.208 |

Table 17: Water-Intensity of Crude Oil Extraction by Well Location (Data Source: (*5*))

Crude oil extraction also has indirect impacts as a result of energy and chemical consumption. Primary fuel and electricity are required for water and crude oil pumping, lighting, and services required by rig workers. Chemicals are also used on-site. Biocides prevent microbial contamination of injection water in the form of biofilms and biofouling, which can lead to corrosion (*144*). Surfactants are also commonly used to reduce drag by breaking up the oil, which can increase yields and decrease energy required for extraction (*145*). It is important that these inputs be included because chemical production can be very water intensive (*119*). Energy and chemical requirements for crude oil extraction are shown in Table 18.

| Input Type | Input | Quantity | Source |
|---|---|---|---|
| Energy | Crude Oil | 2.04E-04 MJ/MJ Crude | (*69*) |
| | Residual Oil | 2.04E-04 MJ/MJ Crude | (*69*) |
| | Diesel | 3.06E-03 MJ/MJ Crude | (*69*) |
| | Gasoline | 4.08E-04 MJ/MJ Crude | (*69*) |
| | Natural Gas | 1.26E-02 MJ/MJ Crude | (*69*) |
| | Coal | 0.00E+00 MJ/MJ Crude | (*69*) |
| | Electricity | 3.87E-03 MJ/MJ Crude | (*69*) |
| Chemicals | Biocide | 5.00E-04 kg/L Injection Water | (*144*) |
| | Surfactant | 3.00E-05 kg/L Injection Water | (*145*) |

Table 18: Energy and Chemical Inputs for Crude Oil Extraction

Combining direct and indirect water requirements yields the results in Figure 23. The figure shows that direct water use is dominant for both withdrawals and consumption. As was the case with electricity, however, supply-chain agriculture water use makes up the second largest fraction of the water footprint. This pattern is not uncommon, and implies that investments in water efficiency improvements for agriculture will have a positive ripple effect throughout the economy, lessening the water footprint of almost every product and service in the United States.

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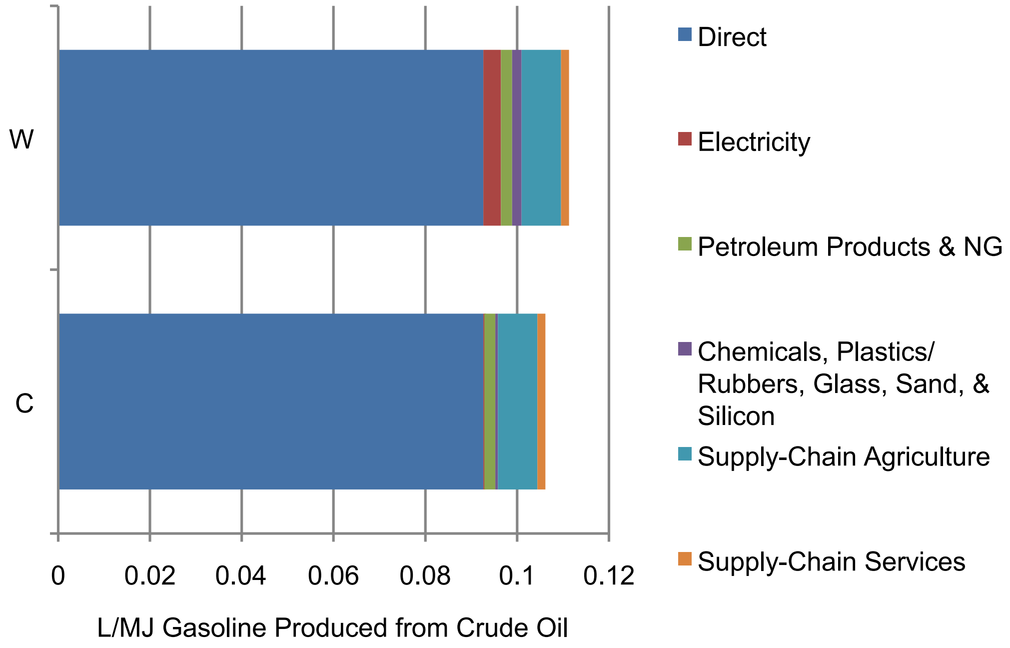

Figure 23: Water Footprint of Crude Oil Extraction

In contrast to crude oil production, natural gas extraction requires only a negligible amount of water as discussed in Chapter 2, which shows that no water impacts associated with combined crude oil and natural gas production should be allocated to natural gas. Additionally, Chapter 2 demonstrates that even "water-intensive" natural gas extraction techniques such as hydraulic fracturing require insignificant amounts of water when normalized by gas output over the lifetime of the well. However, some water is required for natural gas processing, as shown in Table 19.

| Activity | L/MJ Natural Gas |
|---|---|
| Processing | 0.006 |
| Pipeline Operations | 0.003 |
| Other Plant Operations | 0.1 |
| Total = | 0.109 |

Table 19: Water Use for Natural Gas Production (Data Source: (*7*))

Natural gas extraction also requires energy that results in indirect water use, shown in Table 20. Although chemicals such as biocides are used in injection water at natural gas wells (*144*), the amount of injection water used per MJ of natural gas extracted is so negligible that chemical input is not included in this analysis.

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| Energy Input | Recovery (MJ/MJ of NG) | Processing (MJ/MJ of NG) | Transmission & Distribution (MJ/MJ of NG) | Total (MJ/MJ of NG) |
|---|---|---|---|---|
| Diesel | 2.81E-03 | 2.73E-04 | 0.00E+00 | 3.08E-03 |
| Gasoline | 2.55E-04 | 0.00E+00 | 0.00E+00 | 2.55E-04 |
| Electricity | 2.55E-04 | 8.20E-04 | 0.00E+00 | 1.08E-03 |
| NG | 3.30E-03 | 1.48E-03 | 3.67E-03 | 8.45E-03 |

Table 20: Energy Inputs for Natural Gas Production (Data Source: (*69*))

Total indirect water consumption resulting from electricity and primary fuel use is equal to 0.0016 L per MJ of natural gas produced, which falls into rounding error for the total direct consumption of 0.109 L/MJ. Indirect withdrawals are more significant due to the high withdrawals associated with electricity, totaling to 0.015 L/MJ, or 12% of the total life-cycle withdrawals.

## 3.3.4 Oil Sands Extraction and Upgrading

Oil sands, also known as tar sands, are made up of a mixture of hydrocarbons called bitumen, deposited in sand or porous rock. Oil sands are attractive as a substitute for conventional crude oil because they are abundant, with a greater fraction located in North America than is the case for conventional crude (*146*). For example, Canada's oil-sand reserves are estimated at approximately 1.7 trillion barrels of oil equivalent. Once oil sands are converted to synthetic crude oil (SCO), the life cycle is essentially identical to that of conventional crude oil. The extraction and pre-processing phase is largely what sets oil sands apart from conventional crude.

Because oil sands are too viscous to be pumped to the surface at ambient temperature, they must either be mined along with the sand or rock and heated to separate the bitumen (known as retorting), or retorted in-situ. There are three different processes by which oil sands can be retorted in-situ: 1. Steam assisted gravity drainage (SAGD), in which two wells are bored to different depths. Steam is injected in the shallow well to liquefy the bitumen, which drains to the deeper well where it can be pumped to the surface, 2. Cyclic steam stimulation (CSS), which involves alternating steam injection with pumping, and 3. Multi-scheme, which involves various elements of CSS, SAGD, and other recovery techniques (*5*). Of the oil sands extracted in Canada's Athabasca region, where the United States gets the majority of its SCO from oil sands, 56% is extracted using surface mining, 22% through SAGD, 21% through CSS, and 1% using multi-scheme extraction (*5*). In these processes, water is required to produce steam for retorting, and for raw oil sands transport if a slurry pipeline is used. Although the water withdrawals and consumption for SCO production from oil sands is higher than primary extraction of crude oil, it compares favorably to most secondary and tertiary recovery technologies. Direct water use for oil sands extraction by technology is shown in Table 21.

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Consumption and withdrawals are assumed to be equal such that any water is either lost in the form of steam or seepage at the extraction site or it is recycled.

| Extraction Process | Recovery (L/MJ SCO) | Upgrading (L/MJ SCO) | Total (L/MJ SCO) |
|---|---|---|---|
| Surface Mining | 1.04E-01 | N/A | 1.04E-01 |
| In-Situ: SAGD | 7.79E-03 | 2.60E-02 | 3.38E-02 |
| In-Situ: CSS | 3.12E-02 | 2.60E-02 | 5.71E-02 |
| In-Situ: Multi-Scheme | 1.04E-01 | 2.60E-02 | 1.30E-01 |

Table 21: Water Use for Oil Sands Extraction and Upgrading (Data Source: (*5*))

The extraction and upgrading of oil sands also has an indirect water footprint. Fuel and electricity inputs are shown in Table 22. As in the case of crude oil and natural gas extraction, materials such as steel and rubber are assumed to contribute a negligible amount to the total water footprint. Chemicals are also excluded for oil sands extraction and upgrading because reliable data on the types of chemicals and quantities utilized were not available. However, it is likely that biocides and surfactants are used in injection water to some degree, just as they are for crude oil extraction. In future studies, chemical inputs should ideally be included.

| Energy Input | Surface Mining: Bitumen Extraction (MJ/MJ SCO) | Surface Mining: Upgrading (MJ/MJ SCO) | Surface Mining: Total (MJ/MJ SCO) | In-Situ: Bitumen Extraction (MJ/MJ SCO) | In-Situ: Upgrading (MJ/MJ SCO) | In-Situ: Total (MJ/MJ SCO) | Production-Weighted Total (MJ/MJ SCO) |
|---|---|---|---|---|---|---|---|
| Crude Oil | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Residual Oil | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Diesel | 3.29E-04 | N/A | 3.29E-04 | N/A | N/A | N/A | 1.83E-04 |
| Gasoline | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Natural Gas | 4.51E-02 | 1.39E-02 | 5.90E-02 | 1.81E-01 | 1.38E-02 | 1.95E-01 | 1.19E-01 |
| Coal | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Electricity | 9.38E-03 | 3.97E-04 | 9.77E-03 | 5.21E-03 | 3.97E-04 | 5.61E-03 | 7.93E-03 |

Table 22: Energy Inputs for Oil Sands Extraction and Upgrading (Data Source: (*69*))

By combining the direct water use for SCO production and indirect water embodied in extraction/upgrading energy use, the full water footprint is calculated (see Figure 24). One striking difference between these results and the results for crude oil extraction is the contribution of electricity. SCO production relies much more heavily on electricity, which means its withdrawals are significantly higher than those for crude oil extraction.

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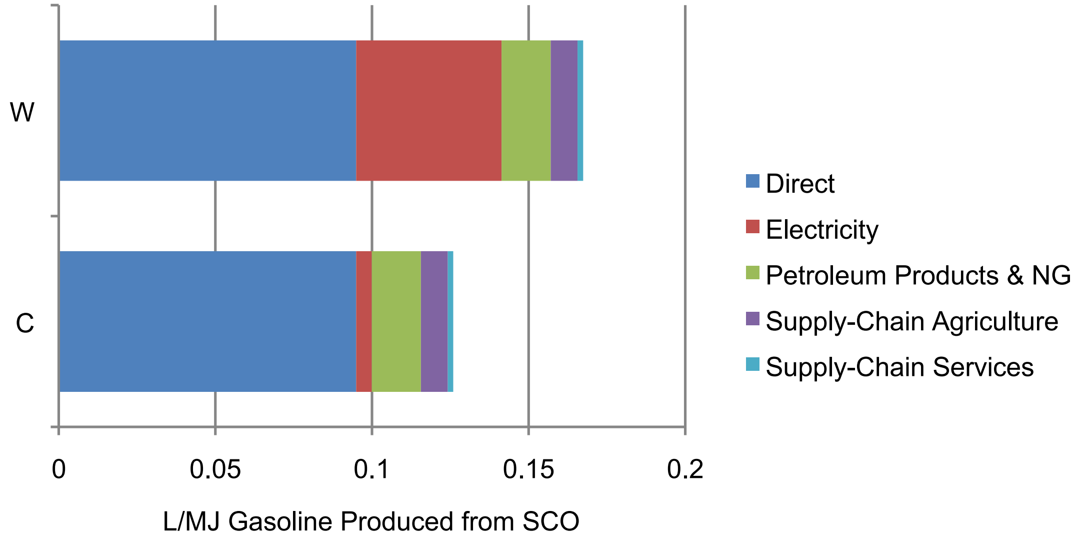

Figure 24: Water Footprint of Extraction and Upgrading of Oil Sands

### 3.3.5 Coal Mining

Water use at coal mines is not as well documented as water for irrigation or power generation, for example. This is likely the case because mining is not a major water user in the United States. According to reference (*119*), the vast majority of water in coal mines is used for dust control, with other minor uses including showers, potable water, sanitary uses, and equipment maintenance. There are two major types of coal mines: underground and surface. After the coal is extracted it must be prepped (also referred to as beneficiation). Other uses of water include revegetation of land after a surface mine is no longer in operation.

Table 23 shows the major assumptions used to calculate total water use for coal mining and Table 24 shows the water use data. The fact that "other plant operations" is approximately an order of magnitude larger than direct use in the mines is counterintuitive given that reference (*119*) characterize miscellaneous water uses to be relatively small. Unfortunately, no other sources provide comparable estimates that could be matched with the number from reference (*7*).

| **Assumption** | **Data Source** |
|---|---|
| % of Surface Mines Requiring Revegetation = 50% | None |
| % of Water Use Withdrawn from Saline Sources = 43% | (*118*) |

Table 23: Assumptions for Coal Mining Water Use Calculations

| **Activity** | **L Water Consumed / MJ Coal Extracted** | **Data Source** |
|---|---|---|
| Surface Mining | 0.002 | (7) |
| Revegetation for Surface Mining | 0.003 | (7) |
| Underground Mining | 0.0115 | (7) |
| Beneficiation | 0.004 | (7) |
| Other Plant Operations | 0.09 | (7) |

Table 24: Source Data for Coal Mining Water Use Calculations

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Withdrawals are assumed to be equal to consumption, which is reasonable because any water used for dust control will evaporate over time and indoor water use is likely diverted to a wastewater treatment plant post-use. Reference (*118*) estimates water use for coal mining to be between 0.0085 and 0.010 L of water per MJ of coal, although it appears that only in-mine usage is included in their analysis (dust control, primarily). When compared with estimates of in-mine water use from reference (*7*), the numbers from reference (*118*) are actually significantly higher. The vast differences between water use estimates for coal mining demonstrate the uncertainty associated with these numbers. It should be noted, however, that water use for coal mining does not prove to be a significant factor in the total life-cycle water footprint of coal-fired power generation, so even order of magnitude changes in these estimates would make little difference in the overall results.

The other contributor to the water footprint of coal production is the indirect water associated with energy used for mining, cleaning, and transportation. The energy requirements are shown in Table 25.

| **Energy Input** | **Mining & Cleaning (MJ/MJ Coal)** | **Fuel Transportation (MJ/MJ Coal)** | **Total (MJ/MJ Coal)** |
|---|---|---|---|
| Residual Fuel | 4.93E-04 | 0.00E+00 | 4.93E-04 |
| Diesel | 3.95E-03 | 5.48E-03 | 9.43E-03 |
| Gasoline | 2.11E-04 | N/A | 2.11E-04 |
| NG | 7.00E-05 | 3.24E-04 | 3.94E-04 |
| Coal | 6.34E-04 | 1.28E-04 | 7.62E-04 |
| Electricity | 1.69E-03 | N/A | 1.69E-03 |

Table 25: Energy Inputs for Coal Production (Data Source: (*69*))

These indirect water requirements are combined with the direct water use for coal mining to develop the total life-cycle water footprint of coal production. The results are shown in Figure 25. The reader should make note that supply-chain services and agriculture are not included here. EIO-LCA data is only used for activities that directly produce the transportation fuels studied in this dissertation: electricity generation, agricultural systems, crude oil extraction, oil sands extraction, petroleum refining, biorefining, and fuel transportation/distribution. This means that the life-cycle water use for coal production is likely to be slightly underestimated, although this will make a negligible difference in the final results.

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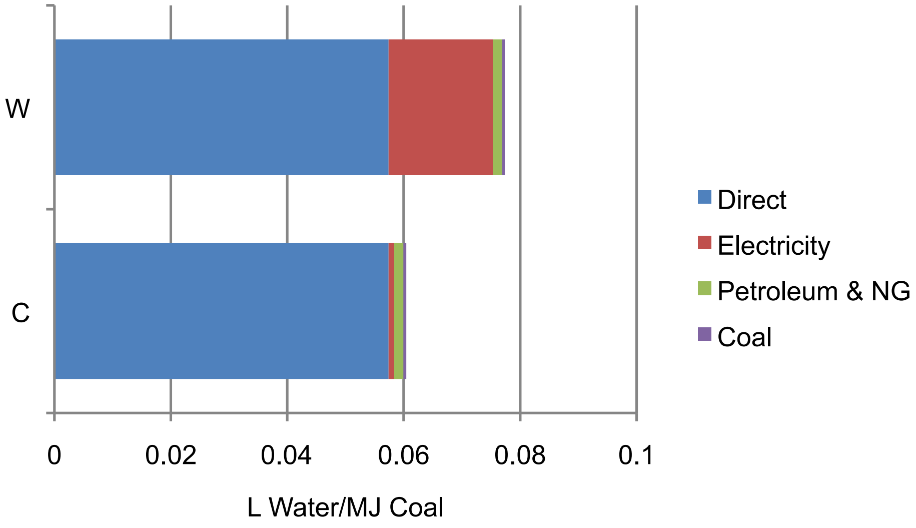

Figure 25: Life-Cycle Water Requirements for Coal Production

### 3.3.6 Nuclear Fuel Mining and Processing

The direct water use for uranium production comes from reference (*7*). The total is calculated based on the assumption that all enrichment in the United States is by gaseous diffusion and all extraction uses underground (in-situ) methods. Table 26 shows the calculated U.S. total water intensity of U-235 and the data used to calculate the total.

| Process | L Consumption/Withdrawals per MJ U-235 | Data Source |
|---|---|---|
| Open Pit Uranium Mining | 0.02 | (7) |
| Underground Uranium Mining | 0.0002 | (7) |
| Uranium Milling | 0.009 | (7) |
| UF6 Conversion | 0.004 | (7) |
| Uranium Enrichment (Gaseous Diffusion) | 0.012 | (7) |
| Uranium Enrichment (Gas Centrifuge) | 0.002 | (7) |
| U.S. Total | 0.0252 | Calculated |

Table 26: Water Use for U-235 Production

The extraction and processing of nuclear fuel also requires energy that contributes to the indirect water footprint. Here, waste storage energy use is also included as part of the fuel cycle. The energy inputs broken out by life-cycle stage are shown in Table 27. The U-235 fuel cycle is far more energy-intensive than that of coal or natural gas extraction, for example, so energy can be expected to contribute a larger fraction of the total life-cycle water use.

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| **Energy Input** | **Uranium Mining (MJ/g U-235)** | **Uranium Enrichment (MJ/g U-235)** | **Uranium Conversion, Fabrication & Waste Storage (MJ/g U-235)** | **Fuel Transportation (MJ/g U-235)** | **Total (MJ/g U-235)** |
|---|---|---|---|---|---|
| Residual Oil | N/A | N/A | N/A | N/A | N/A |
| Diesel Fuel | 4.73E+01 | N/A | N/A | 1.77E-01 | 4.75E+01 |
| Gasoline | 1.43E+01 | N/A | N/A | N/A | 1.43E+01 |
| Natural Gas | 7.05E+01 | N/A | 4.20E+01 | 1.16E-02 | 1.13E+02 |
| Coal | N/A | N/A | N/A | 5.28E-03 | 5.28E-03 |

Table 27: Energy Inputs for the U-235 Fuel Cycle (Data Source: (*69*))

Combining the indirect and direct water requirements yields the results shown in Figure 26. Because energy plays a much larger role in the extraction and processing of nuclear fuel, it also plays a larger role in the total water footprint. Natural gas, gasoline, and diesel fuel combined make up more of the footprint than direct water use itself. This implies that reductions in energy use would also result in improved water impacts. As with coal production, supply-chain services and agricultural production are not included here for the reasons outlined in Section 3.3.5.

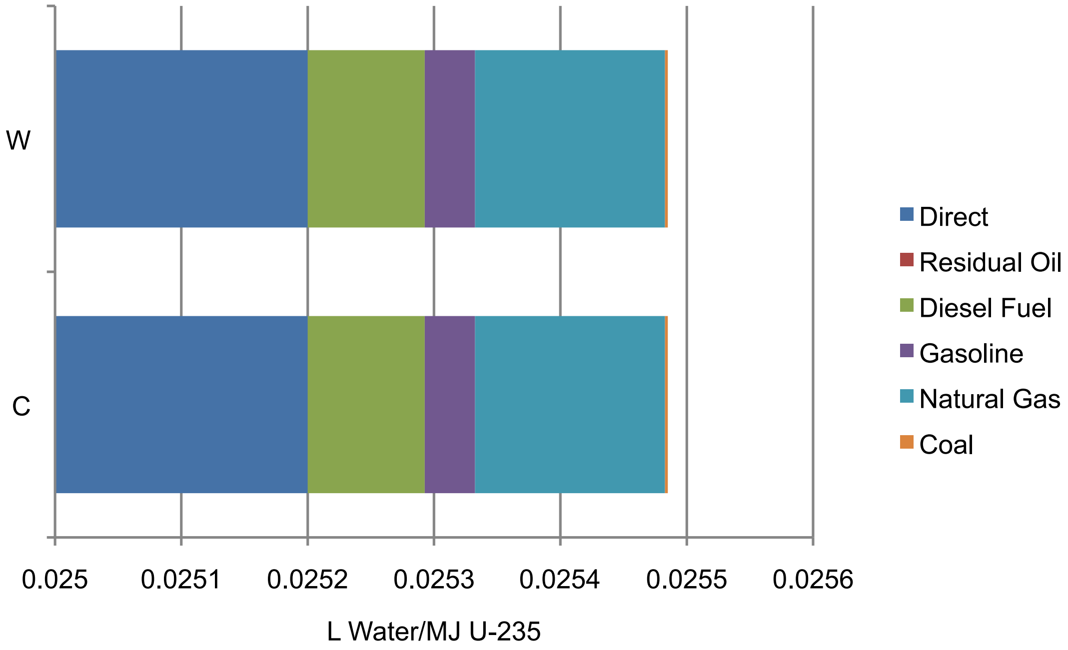

Figure 26: Life-Cycle Water Requirements for the U-235 Fuel Cycle

### 3.3.7 Petroleum Refining

Once oil reaches the refinery, many processes are used to separate and upgrade its components to produce an array of products varying in function and monetary value. Water is primarily used to generate steam for process heat and cooling (*119*), totaling to approximately

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1.5 L of water consumed per L of crude oil input (*5*). More complicated than estimating direct water withdrawals and consumption is the process of allocating this water use to individual refinery products. So far, no study has clearly and defensibly allocated water withdrawals and consumption to refinery products. In the analysis presented here, the allocation scheme is based on market value, which serves as an inherent measure of the economic factors driving production. The factors are taken from reference (*48*), in which allocation is performed on a sub-process level, further capturing the differences between products' impacts based on which processes are involved in their production. Because data on water use for individual processes within the refinery is not available, water use is assumed to correlate with energy consumption. Considering 68% of all withdrawals and 96% of consumption is associated with either cooling or process heat (*119*), this is a reasonable assumption. The result is a larger fraction of impacts allocated to high value products, particularly gasoline, and a much smaller fraction allocated to low value products such as residual oil. For a more in-depth discussion of the allocation method used for petroleum refineries in this dissertation, see Chapter 2. Using the total cooling and process water consumption of 0.040 L/MJ crude input from reference (*5*) and calculated withdrawals of 0.045 L/MJ crude combined with the other plant operations estimate of 0.07 L/MJ crude input from reference (*7*), the total water consumption is calculated as 0.11 L/MJ crude, withdrawals as 0.12 L/MJ crude. With market value allocation, these totals become 0.13 L/MJ of gasoline.

In addition to the direct impacts, petroleum refineries have indirect water impacts associated with energy, chemical, and material use. Table 28 shows the required inputs for petroleum refining by MJ of crude oil input and then allocated specifically to gasoline.

| Input Type | Input | Input/MJ Crude | Input/MJ Gasoline | Data Source |
|---|---|---|---|---|
| Energy | Crude Oil (MJ) | N/A | N/A | (*48*) |
| | Residual Oil (MJ) | 4.21E-03 | 5.16E-03 | (*48*) |
| | Diesel (MJ) | N/A | N/A | (*48*) |
| | Gasoline (MJ) | N/A | N/A | (*48*) |
| | Natural Gas (MJ) | 4.21E-02 | 5.16E-02 | (*48*) |
| | Coal (MJ) | 1.82E-02 | 2.24E-02 | (*48*) |
| | Electricity (MJ) | 5.61E-03 | 6.88E-03 | (*48*) |
| Chemical | NaOH (kg) | 1.21E-07 | 1.49E-07 | (*147*) |
| | Nalko 5196 Neutralizer (kg) | 6.06E-08 | 7.44E-08 | (*147*) |
| | Nalko 5186 Inhibitor (kg) | 6.06E-08 | 7.44E-08 | (*147*) |
| Material | Steel (kg) | 2.23E-06 | 2.74E-06 | Calculated (See Appendix B) |
| | Concrete ($m^3$) | 2.43E-08 | 2.98E-08 | Calculated (See Appendix B) |

Table 28: Energy, Chemical, and Material Inputs for Petroleum Refining

The indirect and direct water footprints of petroleum refining are combined to produce the results shown in Figure 27. Petroleum refining, similar to oil sands extraction and upgrading, is heavily dependent on electricity. For this reason, electricity is a major fraction of total withdrawals. However, for consumption, direct water use makes up the vast majority.

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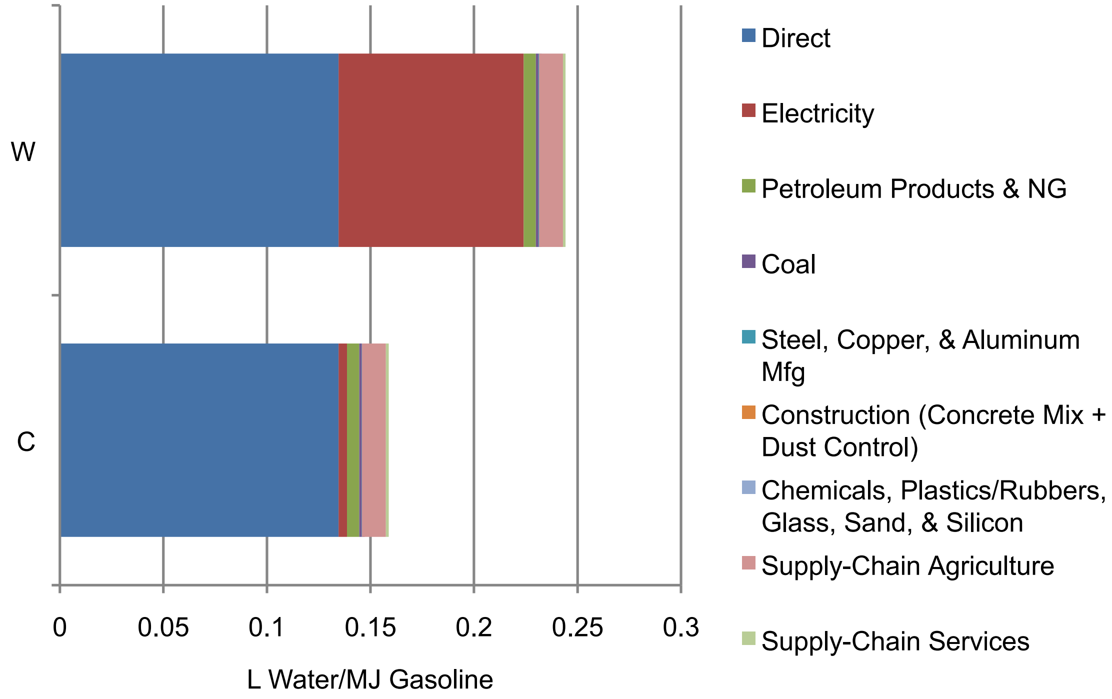

Figure 27: Life-Cycle Water Requirements for Petroleum Refining

## 3.3.8 Biorefining

Throughout this chapter, the bulk of the discussion has centered around mature technologies such as thermoelectric power generation, extraction of fossil fuels, and petroleum refining. Biorefining is, in contrast, a relatively new industry. While commercial scale corn grain-to-ethanol plants exist, cellulosic biorefineries capable of processing corn stover and Miscanthus have only been built on a pilot scale. Hence, corn grain biorefining is based on a great deal of reliable empirical data and the cellulosic biorefinery data is based only on the results of pilot plant studies and chemical engineering process models. This introduces a higher degree of uncertainty, which will be discussed further in Chapter 6.

### *3.3.8.1 Corn Grain to Ethanol*

Corn ethanol biorefineries employ a significantly simpler conversion process than cellulosic biorefineries. The corn is mashed, mixed with water, broken down into sugar using enzymes, and then the resulting sugar is fermented and distilled to yield ethanol. The water usage is taken from reference (*148*), which uses a process model developed by the USDA for a dry milling ethanol plant. According to reference (*5*), which also pulls information from the USDA model, 53% of direct water consumption for ethanol production is used for cooling, 42% is used in the dryer, and the remainder is used in the boiler (3%) and for dried distillers' grains and solubles production (DDGS). Similar to petroleum refineries, allocation issues also arise in corn ethanol plants. However, because the co-products displace existing products whose primary production pathway is not ethanol plants, system expansion can be used (*49*). According to

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GREET 1.8c (*69*), the DDGS co-product displaces 0.71 kg of corn, 0.22 kg of soybean meal, and 0.016 kg of N-Urea per L of ethanol produced. System expansion as an allocation method does not account for elasticity of demand, but it is a simple, reasonable estimate for the purposes of this analysis. Chapter 2 provides more detail about this allocation method for corn biorefineries. Using this method, along with the data shown in Table 29, the life-cycle water use results can be generated (see Figure 28).

### *3.3.8.2 Corn Stover to Ethanol*

The conversion of corn stover to ethanol is a significantly more complex process than what is required to convert corn grain. Although numerous technology options exist, this analysis uses the co-current dilute acid prehydrolysis and enzymatic hydrolysis, referred to as simultaneous saccharification and co-fermentation (SSCF) for corn stover described in detail by reference (*86*). They assume 100% water recycling, so water withdrawals at the biorefinery are equal to consumptive losses. The vast majority of water is lost through evaporation during biomass washing, vents to the atmosphere, and other evaporative losses, while 1% of water losses are contained in solid waste that is landfilled. As was the case with corn ethanol, the biomass-to-ethanol conversion process also results in co-products that must be credited to the biorefinery: gypsum and electricity. In this analysis, gypsum, although technically a co-product, is treated as a waste product (this is consistent with GREET 1.8c). The excess electricity resulting from the burning of lignin that can be exported to the grid is credited through system expansion, as described in Chapter 2. Using this method, along with input data from Table 29, the life-cycle results shown in Figure 28 are generated.

### *3.3.8.3 Miscanthus to Ethanol*

At the biorefinery stage, the Miscanthus pathway is very similar to that of corn stover. The main difference between the two is the amount of electricity that is exported. Corn stover has higher lignin content and because lignin is burned to generate process heat and electricity, the result is higher electricity exports. New results have been generated by building a process model based on reference (*86*), and adjusting the inputs to match the Miscanthus biomass composition. The inputs for Miscanthus biorefining, as well as the electricity co-product, are shown in Table 29. The life-cycle water footprint results are shown in Figure 28.

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| **Feedstock** | **Corn Grain** | **Corn Stover** | **Miscanthus** | **Source** |
|---|---|---|---|---|
| Conversion Process | Dry Milling | SSCF | SSCF | Assumption |
| Plant Size (MJ EtOH/year) | 8.93E+09 | 8.93E+09 | 8.93E+09 | Assumption |
| Plant Lifetime (years) | 25 | 25 | 25 | Assumption |
| Operating Time (days/year) | 300 | 300 | 300 | (*86*) |
| Yield | 236 MJ EtOH/bushel corn | 9.84 MJ EtOH/dry kg stover | 9.84 MJ EtOH/dry kg Miscanthus | (*69, 86-88*) |
| Steel (Mg) | 1.64E+03 | 1.64E+03 | 1.64E+03 | Calculated (See Appendix B) |
| Concrete (m$^3$) | 1.72E+04 | 1.72E+04 | 1.72E+04 | Calculated (See Appendix B) |
| Water for Dust Control (L) | 4.14E+07 | 4.14E+07 | 4.14E+07 | Calculated (See Appendix B) |
| Natural Gas (MJ/MJ EtOH) | 3.05E-01 | N/A | N/A | (*69, 86, 88*) |
| Coal (MJ/MJ EtOH) | 7.63E-02 | N/A | N/A | (*69, 86, 88*) |
| Electricity (MJ/MJ EtOH) | 4.38E-02 | N/A | N/A | (*69, 86, 88*) |
| Propane (MJ/MJ EtOH) | N/A | 2.95E-04 | 2.95E-04 | (*86, 88*) |
| Clarifier Polymer (kg/MJ EtOH) | N/A | 3.20E-05 | 3.20E-05 | (*86, 88*) |
| Sulfuric Acid (kg/MJ EtOH) | N/A | 3.76E-03 | 3.57E-03 | (*86, 88*) |
| Lime (kg/MJ EtOH) | N/A | 2.74E-03 | 2.59E-03 | (*86, 88*) |
| Corn Steep Liquor (kg/MJ EtOH) | N/A | 1.49E-03 | 2.34E-03 | (*86, 88*) |
| Cellulase (kg/MJ EtOH) | N/A | 6.50E-04 | 6.50E-04 | (*86, 88*) |
| Glucoamylase & Alpha-Amylase (kg/MJ EtOH) | 1.78E-04 | N/A | N/A | (*86, 88, 148*) |
| Diammonium Phosphate (kg/MJ EtOH) | N/A | 1.86E-04 | 2.19E-04 | (*86, 88*) |
| BFW Chemicals (kg/MJ EtOH) | 1.14E-06 | 1.14E-06 | 1.14E-06 | (*86, 88*) |
| Cooling Water Chemicals (kg/MJ EtOH) | 2.17E-06 | 2.17E-06 | 2.17E-06 | (*86, 88*) |
| WWT Chemicals (kg/MJ EtOH) | 6.62E-05 | 6.62E-05 | 6.62E-05 | (*86, 88*) |
| WWT Polymer (kg/MJ EtOH) | 2.29E-07 | 2.29E-07 | 2.29E-07 | (*86, 88*) |
| Ammonia (kg/MJ EtOH) | 2.02E-04 | 1.58E-04 | 2.23E-04 | (*86, 88, 148*) |
| Direct Water Consumption (L/MJ EtOH) | 1.28E-01 | 2.59E-01 | 2.59E-01 | (*5, 86, 88*) |
| Direct Water Withdrawals (L/MJ EtOH) | 1.28E-01 | 2.59E-01 | 2.59E-01 | (*5, 86, 88*) |
| Co-Product Credits | 0.0230 kg corn/MJ EtOH, 0.0091 kg SBM/MJ EtOH, 0.00068 kg N-Urea/MJ EtOH | .077 MJ electricity/MJ EtOH | 0.075 MJ electricity/MJ EtOH | (*69, 86, 88*) |

Table 29: Biorefinery Inputs and Co-Products

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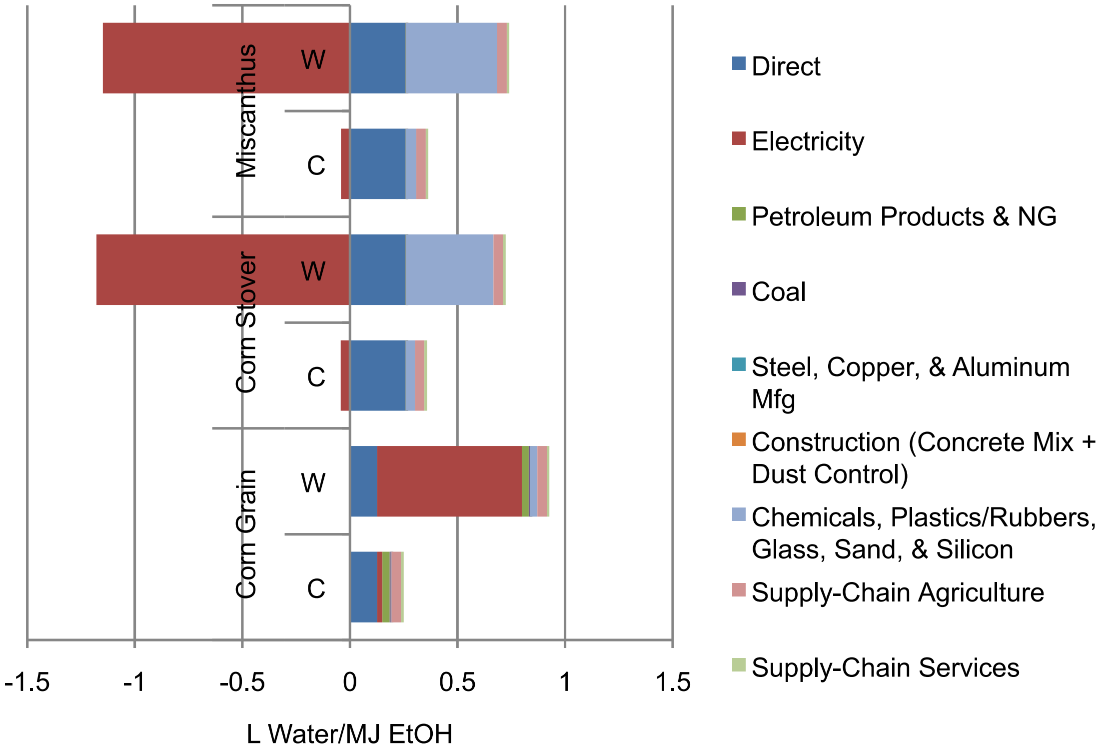

Figure 28: Life-Cycle Water Requirements for Biorefining

### 3.3.9 Pipeline, Marine, Rail, and Truck Transport

After the crude oil is extracted, it is transported to petroleum refineries, primarily by oil tanker, barge, pipeline, and to a lesser extent, railcar. Because the tankers are dedicated to the transport of oil, it can be assumed that any freshwater required for washing is negligible. Pipelines do not require water on a regular basis; water is only used for testing or decommissioning purposes. In the case of decommissioning, the section of pipe being taken out of service is filled with water, drained, and the wastewater is subsequently treated, which means water use is equal to the volume of the pipe section (*149*). Because vast amounts of crude oil and petroleum products pass through pipelines before they must be decommissioned, the water use for pipelines is assumed to be insignificant. The only water use that can be attributed to crude oil transportation is that embodied in the fuels and electricity required.

For the transportation, storage, and distribution of gasoline, energy use is again the only contributor to the water footprint. Pipelines are insignificant for the reasons discussed above. For tankers, barges, railcars, and trucks, these vessels are often dedicated to petroleum product transportation and thus are not cleaned out on a regular basis. Water use is also kept to a minimum because water contamination of petroleum products is problematic from a quality perspective. Gasoline is transported to fueling stations by a combination of pipeline, tanker, barge, railcar, and truck, which results in consumption of diesel fuel, residual oil, natural gas,

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and electricity. The same is true of ethanol feedstock and fuel transportation, distribution, and storage.

### 3.3.10 Chemicals

Reliable water use data for chemical production are notoriously difficult to find. However, chemical use can make up a significant portion of some fuels' water footprint. Reference (*119*) provides both withdrawals and consumption for the top nine chemicals produced in the United States (by volume), as well as the top ten per-lb water users. These lists include specific data for ammonia (used for fertilizer production and biorefining), phosphoric acid (used in fertilizer), and sulfuric acid (used in biorefining). Additionally, water use for lime production (as used in biorefining) is taken from the GaBi LCA software (*150*). For all other chemicals, average withdrawals/consumption for organic, inorganic, and agricultural chemical production is calculated by dividing total water use data from reference (*119*) by total U.S. chemical shipments estimated by reference (*151*), allocated to each category based on monetary output from the 2002 U.S. Economic Census (*58-60*). It is assumed that 28% of total withdrawals are consumed (*152*). The results of these calculations are shown in Table 30.

| **Chemical Type** | **Total U.S. Water Use (million L/day)** | **Total Output (2002 dollars)** | **U.S. annual output: million Mg** | **L water withdrawals /kg output** | **Consumption Rate** | **L water consumption/kg output** |
|---|---|---|---|---|---|---|
| Industrial Organic Chemicals | 1.57E+04 | 5.58E+10 | 2.19E+02 | 2.62E+01 | 28% | 7.34E+00 |
| Industrial Inorganic Chemicals | 9.16E+03 | 5.11E+10 | 2.01E+02 | 1.67E+01 | 28% | 4.67E+00 |
| Plastics and Synthetics | 3.16E+04 | 5.37E+10 | 2.11E+02 | 7.68E+00 | 28% | 2.15E+00 |
| Agricultural Chemicals | 3.16E+03 | 1.61E+10 | 6.32E+01 | 1.83E+01 | 28% | 5.12E+00 |
| Other Chemicals | 2.78E+03 | N/A | N/A | N/A | 28% | N/A |
| Total | 3.52E+04 | 1.77E+11 | 6.93E+02 | 1.86E+01 | 28% | 5.20E+00 |

Table 30: Chemical Manufacturing Water Intensity by Type

Compared to the product-specific estimates from reference (*119*), these averages appear to be conservative. The water footprint of energy used to produce these chemicals is also included, using GREET1.8c (*69*) energy consumption data. See Table 32 for product-specific water intensity estimates of chemicals and other materials.

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| Chemical Type | Total U.S. Water Use (million L/day) | Total Output (2002 dollars) | U.S. annual output: million Mg | L water withdrawals /kg output | Consumption Rate | L water consumption/kg output |
|---|---|---|---|---|---|---|
| Industrial Organic Chemicals | 1.57E+04 | 5.58E+10 | 2.19E+02 | 2.62E+01 | 28% | 7.34E+00 |
| Industrial Inorganic Chemicals | 9.16E+03 | 5.11E+10 | 2.01E+02 | 1.67E+01 | 28% | 4.67E+00 |
| Plastics and Synthetics | 3.16E+04 | 5.37E+10 | 2.11E+02 | 7.68E+00 | 28% | 2.15E+00 |
| Agricultural Chemicals | 3.16E+03 | 1.61E+10 | 6.32E+01 | 1.83E+01 | 28% | 5.12E+00 |
| Other Chemicals | 2.78E+03 | N/A | N/A | N/A | 28% | N/A |
| Total | 3.52E+04 | 1.77E+11 | 6.93E+02 | 1.86E+01 | 28% | 5.20E+00 |

Table 31: Categorical Water Intensities of Chemicals Manufactured in the United States

### 3.3.11 Construction Activities, Materials, and Facility Maintenance

The only direct water use for construction that is quantified in this analysis is dust control. There is a large amount of uncertainty associated with these estimates because they are dependent on how much of the land area is actually undergoing construction at any given time, the total duration of construction, local rainfall and average temperatures, and whether chemical adhesives are also used to enhance dust control, thus resulting in less frequent water application.

The water footprint of materials used in construction of facilities and other equipment required for transportation fuel production has also been calculated. For most pathways, steel and concrete make up the bulk of the construction materials. Concrete mixes require water (approximately 175 L of water per $m^3$ of average, ready-mix concrete) (*153*). This water is consumed by reacting with cement through a process called hydration. In contrast, the steelmaking process does not chemically destroy water molecules, but a great deal of water is withdrawn and evaporated for material conditioning, air pollution control, and heat transfer (*119*). Water consumption and withdrawals are taken from reference (*154*), the breakdown of U.S. electric arc furnaces and blast furnaces, as well as steel imports are taken from (*155, 156*). Finally, energy (both electricity and primary fuels) use at steel plants is taken from the Manufacturing Energy Consumption Survey (*130*). Direct water withdrawals and consumption for construction materials are shown in Table 32.

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| **Material/Activity** | **Direct Withdrawals** | **Direct Consumption** | **Units** | **Source** |
|---|---|---|---|---|
| Misc. Agricultural Chemicals | 1.8E+01 | 5.1E+00 | L/kg output | Calculated |
| Aluminum | 6.4E+01 | 1.6E+01 | L/kg aluminum | (*150*) |
| Ammonia | 1.4E+02 | 1.1E+01 | L/kg ammonia | (*157*) |
| Chlorine | 7.5E+01 | 9.0E+00 | L/kg chlorine | (*157*) |
| Copper | 5.9E+01 | 1.1E-03 | L/kg copper | (*150*) |
| Glass | 3.0E-02 | 5.5E-03 | L/kg glass | (*150*) |
| Hydrogen via Steam Reforming of Natural Gas | 8.5E+00 | 5.6E+00 | L/kg $H_2$ | (*150*) |
| Misc. Industrial Inorganic Chemicals | 1.7E+01 | 4.7E+00 | L/kg output | Calculated |
| Misc. Industrial Organic Chemicals | 2.6E+01 | 7.3E+00 | L/kg output | Calculated |
| Lime | 7.4E-01 | 9.4E-02 | L/kg lime | (*150*) |
| Phosphoric Acid | 2.8E+02 | 3.0E+01 | L/kg $P_2O_5$ | (*157*) |
| Plastics | 1.7E+01 | 2.6E+00 | L/kg PVC | (*150*) |
| Polyethylene | 8.3E+01 | 6.5E+00 | L/kg polyethylene | (*157*) |
| Ready-Mix Concrete | 2.5E-01 | 2.5E-01 | L/kg concrete | (*153*) |
| Silica (Sand) | 2.7E-03 | 6.0E-04 | L/kg silica sand | (*150*) |
| Silicon Wafers | 3.1E+02 | 3.1E+02 | L/kg silicon | (*140*) |
| Steelmaking: Basic Oxygen Furnace | 4.4E+00 | 4.0E+00 | L/kg steel | (*154*) |
| Steelmaking: Electric Arc Furnace | 8.8E+00 | 8.3E+00 | L/kg steel | (*154*) |
| Sulfuric Acid | 6.6E+01 | 5.0E+00 | L/kg sulfuric acid | (*157*) |

Table 32: Water Embodied in Chemicals and Construction Materials

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## 3.3.12 Supply-Chain Agriculture and Services

Water use for both supply-chain services and agriculture are taken from the 2002 EIO-LCA model (*42*). Service sectors encompass domestic-type water use (toilets, sinks, etc.) at facilities involved indirectly in fuel supply chains (such as insurance offices, for example). Indirect purchases of agricultural products, while small, have the potential to be significant in some cases because of the high relative water-intensity of these products. In the water portion of the 2002 EIO-LCA model, only withdrawals are quantified, so it has limited applicability for any analysis in which consumption is also quantified. However, in the case of service sectors (which typically use publically-supplied water) and agriculture, withdrawals are roughly equal to consumption. See Appendix B for model inputs and outputs.

## 3.3.13 Combustion

One life-cycle phase that has yet to be discussed is the combustion phase (fuel use in on-road vehicles). Combustion of fuels does not consume water. $H_2O$ molecules are actually created in the process of oxidizing the fuel, which escape from the vehicle tailpipe in the form of steam. Because evaporation falls under the current definition of water consumption, combustion chemically creates water, which is immediately physically “consumed”. To illustrate the magnitude of this water creation, one can use the oxidation of octane, a major component in gasoline, as an example (see Equation 11).

$$2C_8H_{18} + 25O_2 \Rightarrow 16CO_2 + 18H_2O$$

Equation 11: Complete Combustion of Octane

Assuming carbon has a molecular mass of 12 g/mol, hydrogen of 1 g/mol, and oxygen of 16 g/mol, this balanced equation indicates that 228 g of octane yields 324 g of water, or 1 L of water produced per L of octane combusted. Interestingly, the amount of water created during combustion is significant, equal to approximately two thirds the amount of water consumed during the refining process. A simple hypothesis for why this produced water does not significantly increase freshwater resources can be developed using the Earth’s water cycle. Assuming the water synthesized during fossil fuel combustion is ultimately distributed in a manner similar to existing water resources, at least 98% will become ocean water (98% is calculated using water cycle data from reference (*24*), excluding freshwater contained in underground aquifers not within the zone of active exchange). Reference (*158*) assumed that 100% of this water becomes seawater, contributing an estimated 0.021 mm/year to sea level rise.

# 3.4 Results

In order to fairly compare the life-cycle water footprints of the various fuels, they must be normalized by the ultimate service provided: distance traveled. This is because cars utilizing electricity as their transportation fuel run on electric motors, which have a much higher efficiency than spark-ignited internal combustion engines that burn gasoline and ethanol. The efficiencies of each automobile type are shown in Table 33.

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| **Fuel** | **km Traveled /MJ Fuel** |
|---|---|
| Gasoline | 0.25 |
| Ethanol | 0.25 |
| Electricity | 0.94 |

Table 33: Assumed Efficiencies of Typical Vehicles

Using these assumptions, the life-cycle inventory results for consumption and withdrawals, broken down by life-cycle phase and major contributor are shown in Figure 29, Figure 30, Figure 31, and Figure 32. Figure 29 and Figure 31 compare the liquid fuel pathways to U.S. average electricity and electricity is broken out into the 10 U.S. NERC regions in Figure 30 and Figure 32.

Corn ethanol and electricity stand out as having the largest average footprint. Ninety six percent of total water consumption for corn ethanol is attributable to the agriculture phase, nearly all of which is used for irrigation. The fraction attributable to the agriculture phase drops slightly to 87% for withdrawals because indirect electricity-related water use results in high withdrawals. Indeed, the electricity pathway itself has withdrawals equal to 20 times its total consumption per km traveled. Although corn ethanol clearly has the highest water footprint, it is important to note that these irrigation numbers are based on average U.S. corn and are not necessarily reflective of the marginal unit of corn. To address this potential difference, both non-irrigated corn and the most irrigation-intensive corn are included in the sensitivity analysis. This is true of the other pathways as well, so technology and location have been varied in the sensitivity analysis in order to address the potential disparity between the average and marginal unit (see Chapter 6).

Another interesting result is the net negative withdrawals associated with the marginal unit of cellulosic ethanol production. As is clear from Figure 30, electricity withdraws large volumes of water for power plant cooling. Cellulosic ethanol biorefineries produce electricity by burning lignin and require less cooling water because the waste heat from electricity generation is used as process heat within the facility (*86, 88*). The excess electricity produced at cellulosic biorefineries that is sold to the grid displaces more water withdrawals than it causes. No previous studies on the water impacts of transportation fuels have employed system expansion for the electricity produced at cellulosic biorefineries, so this dissertation is the first body of work to point out the net negative effect.

Finally, perhaps the most striking result shown is the difference between withdrawals and consumption for some fuel production pathways, particularly electricity and cellulosic ethanol production. This begs the question of whether withdrawals or consumption is the better indicator of freshwater resource impacts. This question will be explored further in Chapter 4.

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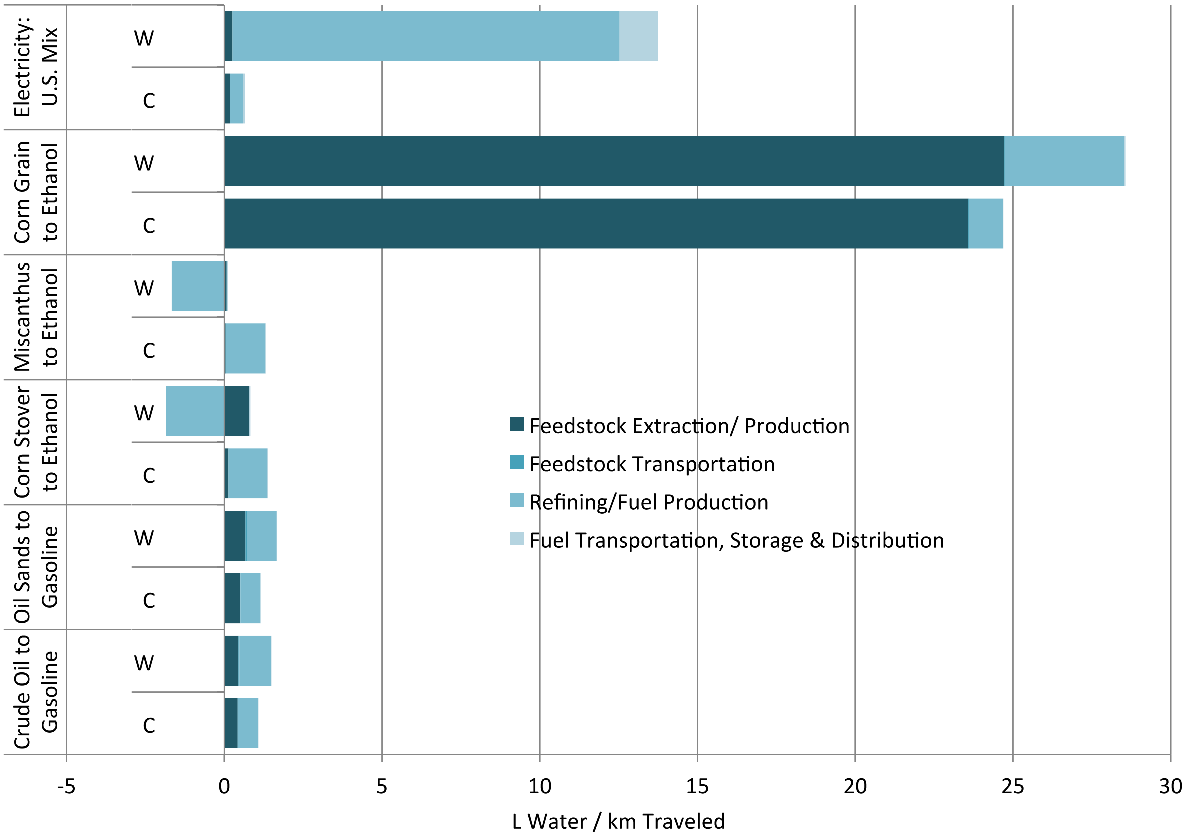

Figure 29: Life-Cycle Water Use for Transportation Fuel Production by Life-Cycle Phase

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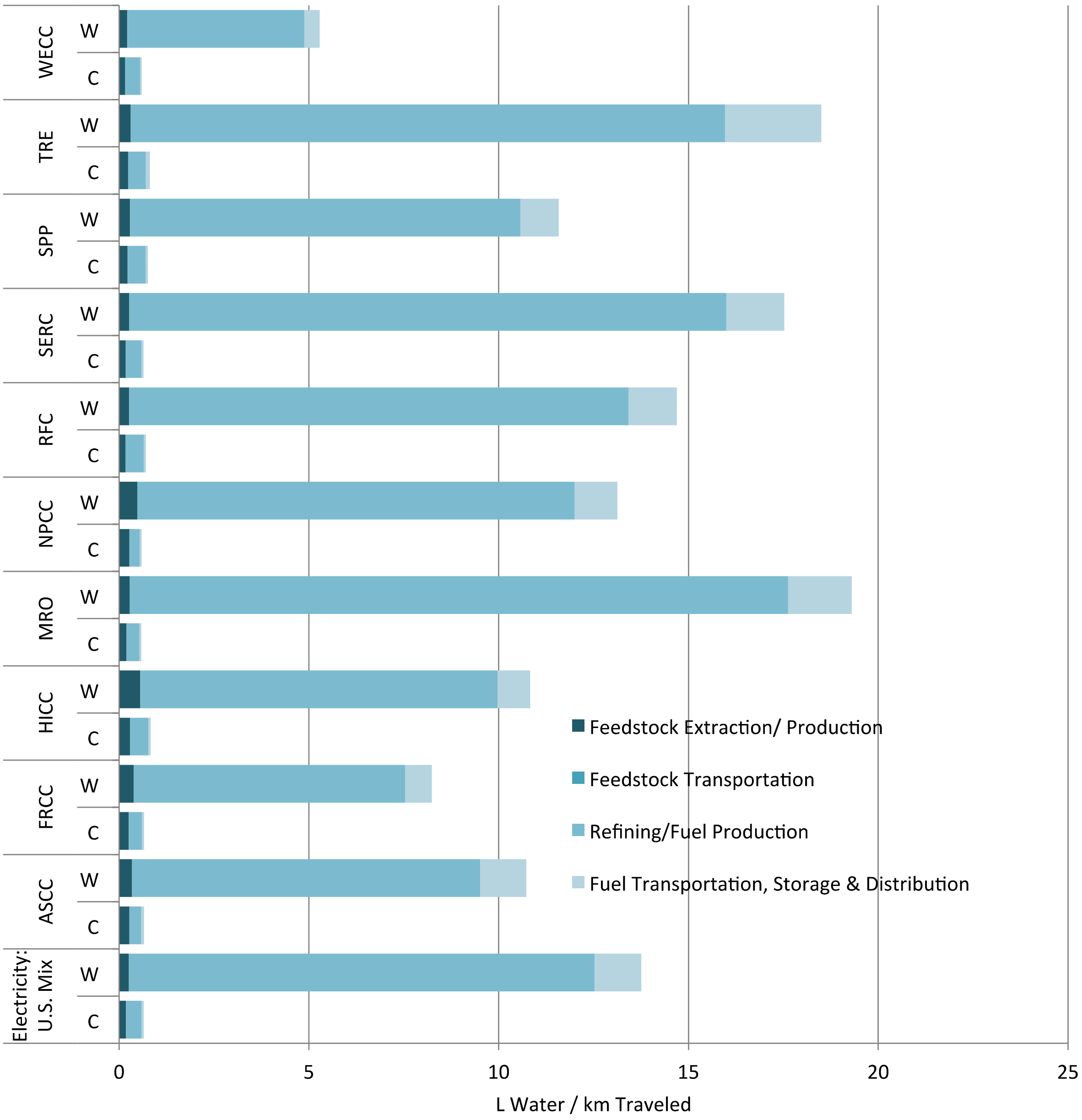

Figure 30: Life-Cycle Water Use for Electricity Production by Life-Cycle Phase

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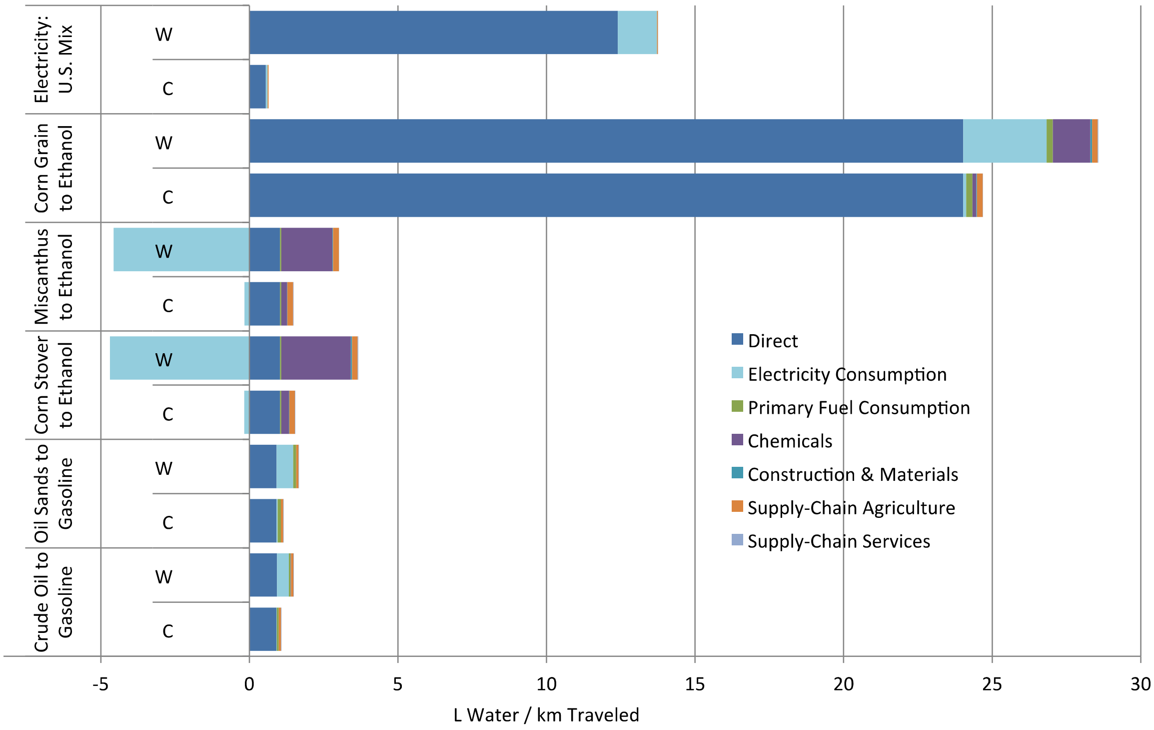

Figure 31: Life-Cycle Water Use for Transportation Fuel Production by Major Contributor

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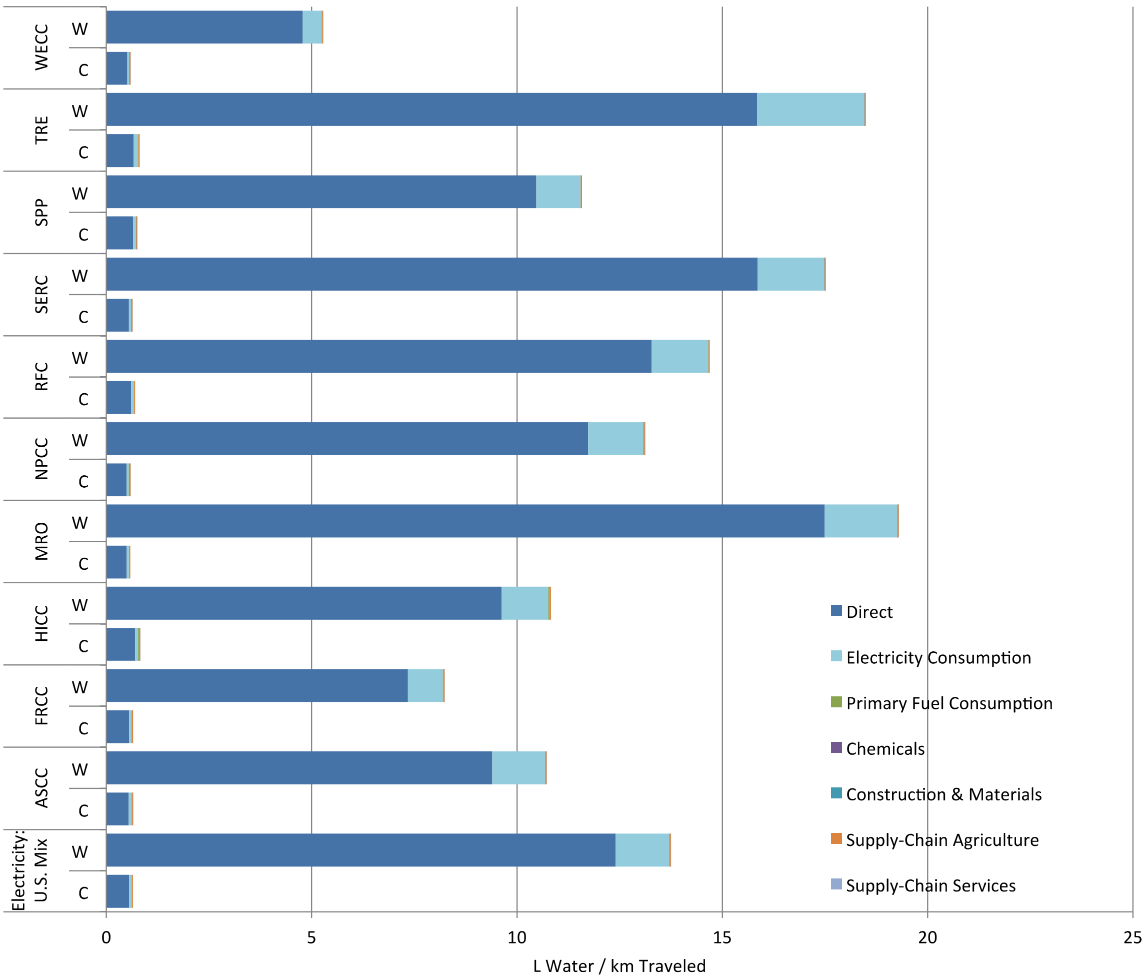

Figure 32: Life-Cycle Water Use for Electricity Production by Major Contributor

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# 4. Impact of Water Use on Ground and Surface Water Availability

Water use impacts are often ignored in LCA because they are difficult to quantify in a manner that is both transparent and comprehensive. Water use is typically reported in terms of consumptive use (essentially evaporative losses) with little or no information about the source (groundwater, surface water, brackish water, seawater) or geographic location where the water use is taking place (*3, 5, 7-9*). The type of water use (consumptive versus total withdrawals), source, and geographic location play major roles in determining the ultimate impact on water resource availability. Even a small amount of freshwater taken from a water-constrained area can cause serious problems. For example, industrial facilities such as Coca-Cola bottling plants that use water are typically ignored because they withdraw small amounts compared to other sectors such as agriculture or thermoelectric power generation. However, shortly after opening a bottling plant in India, Coca-Cola was urged to close the facility because it was depleting groundwater that local residents and farmers depended on for survival (*159*).

As discussed in Chapter 2, the freshwater resources available in any given region can sustainably support a finite amount of human activity and some communities have already exceeded this limit or are poised to do so in the foreseeable future. In Southern California, the population outgrew local water resources and has thus depended on imports from Northern California and the Colorado River (*160*). In other parts of the country, current water use practices have yet to require such drastic measures, but may result in long-term shortages and other impacts. The High Plains Aquifer, which stretches across Wyoming, Nebraska, South Dakota, Colorado, Kansas, New Mexico, Oklahoma, and Texas, continues to be overpumped and as a result the water table has dropped more than 18 m over a period of 20 years in some areas (*14*). These examples demonstrate that, while any water use does place a given region one step close to reaching its sustainable water use limit, some regions are at a much greater risk of reaching that limit in the near future than others.

Attempting to determine what impact water use has on resource availability is a challenging task as it requires information about climate, hydrology, and humans' water consumption patterns. For this reason, a framework for water use impact assessment is only now beginning to take shape in LCA. An important first step is geospatial disaggregation of water use estimates, followed by integration with water availability data in order to determine how at-risk the impacted regions are for water scarcity. Here, existing literature is critically evaluated and, based on this evaluation, a framework for addressing water resource impacts for the purposes of this dissertation is laid out.

## 4.1 Literature Review

Reference (*10*) makes the first and only comprehensive, quantitative attempt to date at assessing the impacts of freshwater consumption in LCA. The authors assess ecosystem quality, human health, and resource availability impacts. Ecosystem quality will not be discussed

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further because it is outside the scope of this dissertation. Human health, although relevant on a global scale, is far less important in the context of the United States and other developed countries because most Americans have access to clean drinking water. Freshwater scarcity in developed countries is more likely to cause an increase in energy-intensive practices such as water importation, desalination, and wastewater recycling. For this reason, human health impacts of water use are also excluded from this discussion.

The water resource impact assessment has two major inputs: demand-side data and resource-side data. Demand-side data includes any water use information that is pertinent to assessing the ultimate impact: total volume, type of use (consumptive or withdrawal), source, time of year, and location. Resource-side data includes data that reflects freshwater availability such as total ground and surface water resources, and temporal variability in resource availability (seasonal and long-term). A summary of the manner in which reference (*10*) treats these two inputs is shown in Table 34.

| **Demand-Side** | | **Resource-Side** | |
|---|---|---|---|
| Total Demand | -Average annual irrigation requirements derived from Virtual Water database, no green water included<br>-Consumptive use only<br>-Resolution: Country | Total Resources | -Derived from WaterGAP2 global model<br>-Resolution: Watershed |
| Source & Quality | -No distinction between ground and surface withdrawals<br>-Saline withdrawals not included | Source & Quality | -No distinction between ground and surface water<br>-Saline resources not included |
| Temporal Variability | -Not addressed | Variability | -Adjusted w/ variation factor based on precipitation<br>-Distinctions made between regulated & non-regulated flows |

Table 34: Summary of Existing Water Use Impact Assessment Literature (*10*)

### 4.1.1 Water Demand Modeling

*Total demand*: Reference (*10*) focuses exclusively on consumptive water use for irrigation, and average annual withdrawals for various crops by country are taken from the Virtual Water database (*22*). However, as reference (*3*) shows, irrigation requirements within a country can vary significantly, so using countrywide averages ignores the possibility of much higher water demands in some areas within a country. Reference (*10*) acknowledges that "for most industrial processes, water use data is scarce and the available data is heterogeneous. To obtain this information in a consistent format will be a major challenge in further studies. In particular, water quality degradation needs to be reported and assessed, as this is a particular concern for industrial production."

*Variability in demand*: Variability in demand as a result of different growing seasons and seasonal variations in precipitation is not accounted for.

*Water source and quality*: Reference (*10*) focused entirely on freshwater, so saline and seawater withdrawals are ignored (saline and seawater withdrawals for irrigation are typically negligible, but can be important when looking at industrial and mining sectors). No obvious differentiation is made between groundwater and surface water withdrawals.

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### 4.1.2 Water Resource Modeling

*Total resources*: Data on freshwater resources by watershed is taken from the WaterGAP2 global model, which bases its estimations on average levels from 1961-1990 (*161*). WaterGAP2 also accounts for socioeconomic factors that limit availability for different populations.

*Variability in resources*: Total freshwater resources available at any given time is dependent on precipitation patterns. Reference (*10*) applies a variation factor that adjusts for rainfall, but accounts for the difference between regulated and unregulated flows.

*Water source and quality*: Ground and surface water are combined to yield a total water availability number for a given country or watershed in reference (*10*). Saline and seawater resources are not included.

### 4.1.3 Limitations of Existing Water Use Impact Assessment

There is an ongoing debate in the LCA community regarding how water use should be treated in impact assessment. The framework presented in reference (*10*), although far from perfect, is a complex and robust method for assessing the global impacts of freshwater consumption. However, some researchers insist that the water footprinting method shown in reference (*17*) is superior because it makes use of tractable, volumetric terms rather than aggregated impact scores like those in reference (*10*) that have no meaning in an absolute sense (*93*). Both parties make important points: presenting results in terms of physical units rather than scores or points allows them to maintain some real-world relevance and meaning outside of the LCA community, but reporting simple volumes does not capture the importance of water scarcity on the total impact that water use has. In this dissertation, a methodology is presented that both maintains water volume as the ultimate unit of measure and incorporates information about water resource availability, using a transparent process that requires only publicly available data.

## 4.2 Water Use Impact Assessment Methodology

Chapter 2 provides a detailed description of the impact assessment methodology used in this dissertation. Water use is geospatially disaggregated by county, split into fresh ground and surface water use, and these data are combined with data on drought vulnerability and groundwater overpumping to produce the following metrics:

- Total Consumption
- Total Withdrawals
- Total Groundwater Consumption
- Total Groundwater Withdrawals
- Total Surface Water Consumption
- Total Surface Water Withdrawals
- Groundwater Consumption in Regions Impacted by Overpumping
- Groundwater Withdrawals in Regions Impacted by Overpumping

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- Surface Water Consumption in Drought-Prone Regions
- Surface Water Withdrawals in Drought-Prone Regions

In order to produce these results using the inventory presented in Chapter 3, water use must first be disaggregated to the county level. Appendix C describes how each process/industry is mapped in the United States. The results of this mapping are shown in Section 4.5. Next, this county-level water use must be split into ground and surface water. The U.S. Geological Survey publishes reports every five years that detail industry-specific county-level groundwater and surface water withdrawals, and those ratios are used to approximate ground- and surface-water use for this impact assessment. Sections 4.3 and 4.4 discuss how drought and groundwater overpumping vulnerability classifications were developed and used to produce the final results.

## 4.3 Surface Water Trends and Availability

Before surface water availability can be integrated into an impact assessment, a decision must be made about exactly what impacts are of interest and on what timescale. For example, if a new natural gas well utilizing hydraulic fracturing is being analyzed, only current and/or short term projections of stream flow and drought incidence are necessary to determine the impact on freshwater availability because all of the water use occurs upfront during establishment of the well.

Conversely, analyzing a process that uses large volumes of water spread out over time requires more long-term surface water projections. This long-term scenario better describes the production of transportation fuels. In the long term, there are two ways in which surface water use can impact availability. Average stream flows may decrease, so areas that already face enduring water shortages due to human development beyond what local resources can support will be forced to import, desalinate, or recycle even larger quantities. The other potential impact is an exacerbation of temporary drought-related shortages. In the former scenario, an increase in desalination, importation, or recycling will increase the energy and GHG-intensity of water supply, which is discussed in Chapter 5. Hence, the focus of this section is the intensification of temporary surface water shortages caused by drought conditions.

There are a number of metrics that can be used to classify drought conditions. The simplest of these is precipitation relative to historic averages. Another method for measuring drought intensity is through soil moisture content; the most common model is provided by the NOAA Climate Prediction Center, which provides data by day, month, and year, along with 25-year averages (*162*). Lastly, there are three Palmer indices: the Palmer Z Index, Palmer Drought Index (PDI) and Palmer Hydrological Drought Index (*163*). There is no index that is clearly superior to the others in terms of accurately measuring drought intensity. To reflect long-term drought conditions, the NOAA has created a weighted average that is made up of 25% Palmer Hydrological Index, 20% 24-month precipitation, 20% 12-month precipitation, 15% 6-month precipitation, 10% 60-month precipitation, and 10% CPC Soil Moisture Model (although the inputs for the western United States are slightly different) (*164*). The NOAA long-term drought measure serves as an indicator of the average stream flow decreases discussed previously. This

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means that, rather than measuring the potential for fluctuations in surface water availability, it shows likely long-term drought conditions such as those present in Southern California and Florida. The U.S. Drought Monitor, however, uses the PDI as its drought measure of choice (*95*). For the sake of simplicity and transparency, this dissertation stays consistent with the U.S. Drought Monitor and uses only the PDI. Table 35 shows the PDI classifications along with descriptions of the impacts associated with each category.

| **Category** | **Description** | **Palmer Index** | **Possible Impacts** |
|---|---|---|---|
| D0 | Abnormally Dry | -1.0 to -1.9 | Going into drought: short term dryness slowing planting, growth of crops, or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered |
| D1 | Moderate Drought | -2.0 to -2.9 | Some damage to crops, pastures; streams, reservoirs, or wells low, some water shortages developing or imminent; voluntary water-use restrictions requested |
| D2 | Severe Drought | -3.0 to -3.9 | Crop and pasture losses likely; water shortages common; water restrictions imposed |
| D3 | Extreme Drought | -4.0 to -4.9 | Major crop/pasture losses; widespread water shortages or restrictions |
| D4 | Exceptional Drought | -5.0 or less | Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies |

Table 35: Palmer Drought Index Descriptions (Adapted from: (*95*))

A county-level map showing the percentage of time spent in severe to extreme drought (D2-D4) is shown in Figure 6. For the sake of comparison, the objective long-term drought indicator blend percentiles are shown in Figure 34. The comparison with Figure 6 reveals some marked differences between the PDI- and the NOAA-weighted average indices. The 100-year PDI map shows the eastern United States as being relatively invulnerable to drought, averaging less than 10 of the last 100 years in severe or worse drought conditions. The western and Midwestern United States, however, are shown to experience drought more frequently. Instead, the NOAA indicator shows the Midwest to have a relatively low long-term drought risk. It also predicts that Florida and California will experience long-term drought conditions. This makes sense given that California and Florida are two of only three states in the United States to have already built sea or brackish water desalination capacity (*165, 166*). The NOAA indicator, however, does not predict that Texas will experience long-term drought conditions, which is counter-intuitive given that the state has already installed desalination capacity and is facing large drops in groundwater levels (*14, 166*). Ultimately, neither the NOAA indicator nor the PDI are perfect measures of drought vulnerability. However, because the focus of this section is on the potential for fluctuations rather than long-term trends (since long-term trends are captured in Chapter 5), the PDI remains the more desirable metric.

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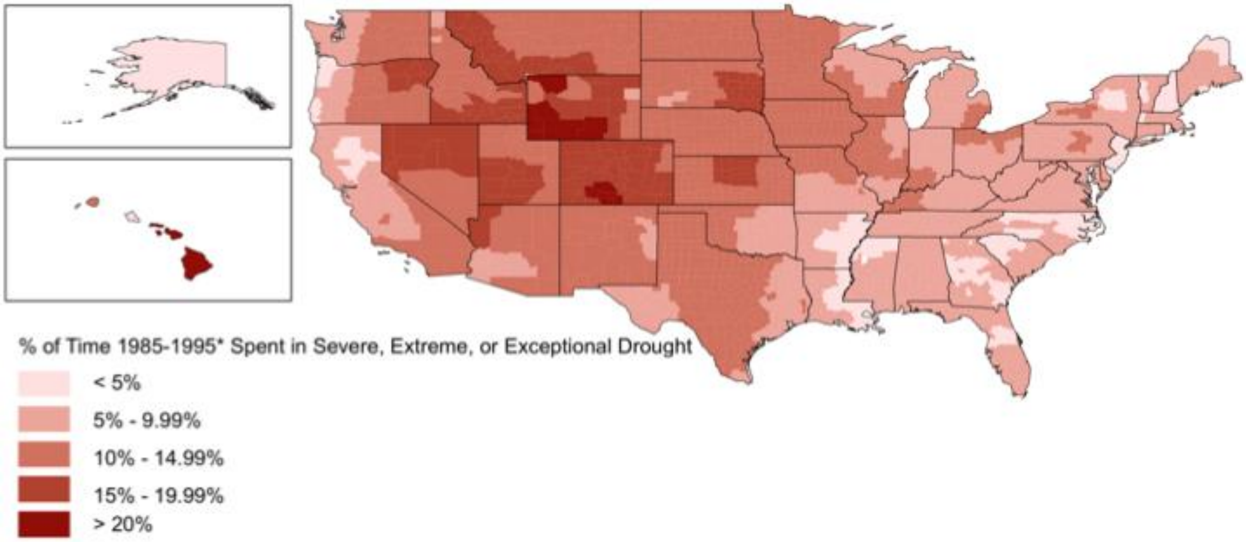

Figure 33: U.S. Drought Incidence Defined by PDSI (Data Source: (*96*))

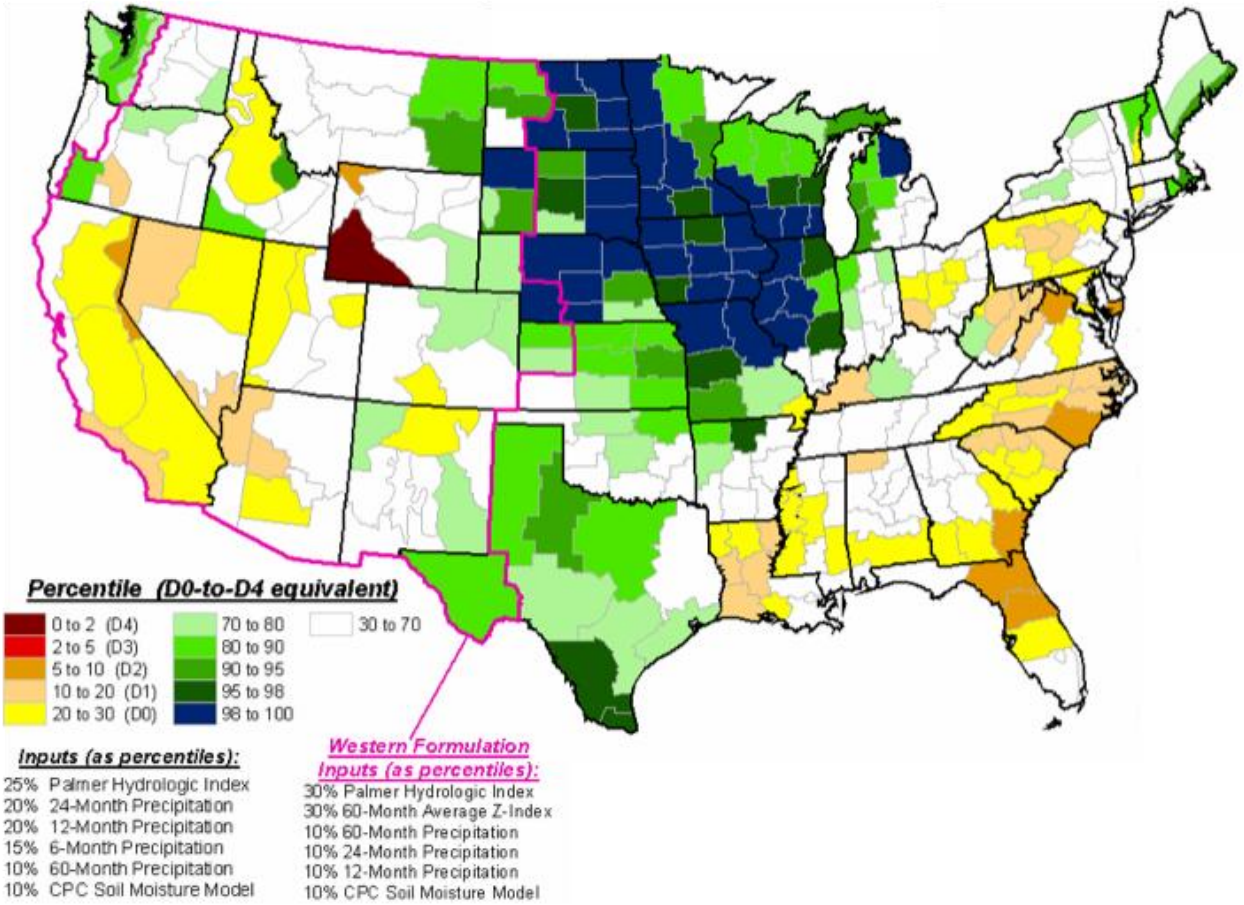

Figure 34: Objective Long-Term Drought Indicator Blend Percentiles (Source: (*164*))

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## 4.4 Groundwater Trends and Availability

Unlike surface water flows and soil moisture content, groundwater levels are not consistently measured throughout the United States. Groundwater is instead monitored by regional, state, and local networks. Regional networks include the High Plains Aquifer Monitoring Network, the Piedmont and Blue Ridge Aquifer Groundwater Network, and state and local networks include Nebraska's Natural Resource Districts, Southern California Basin Network, and the New Jersey Groundwater Network (*167*). Groundwater levels are thus monitored heavily in some areas and barely or not at all in others. Texas, for example, has very few monitoring sites whereas Nebraska monitors the High Plains Aquifer carefully, as shown in Figure 35.

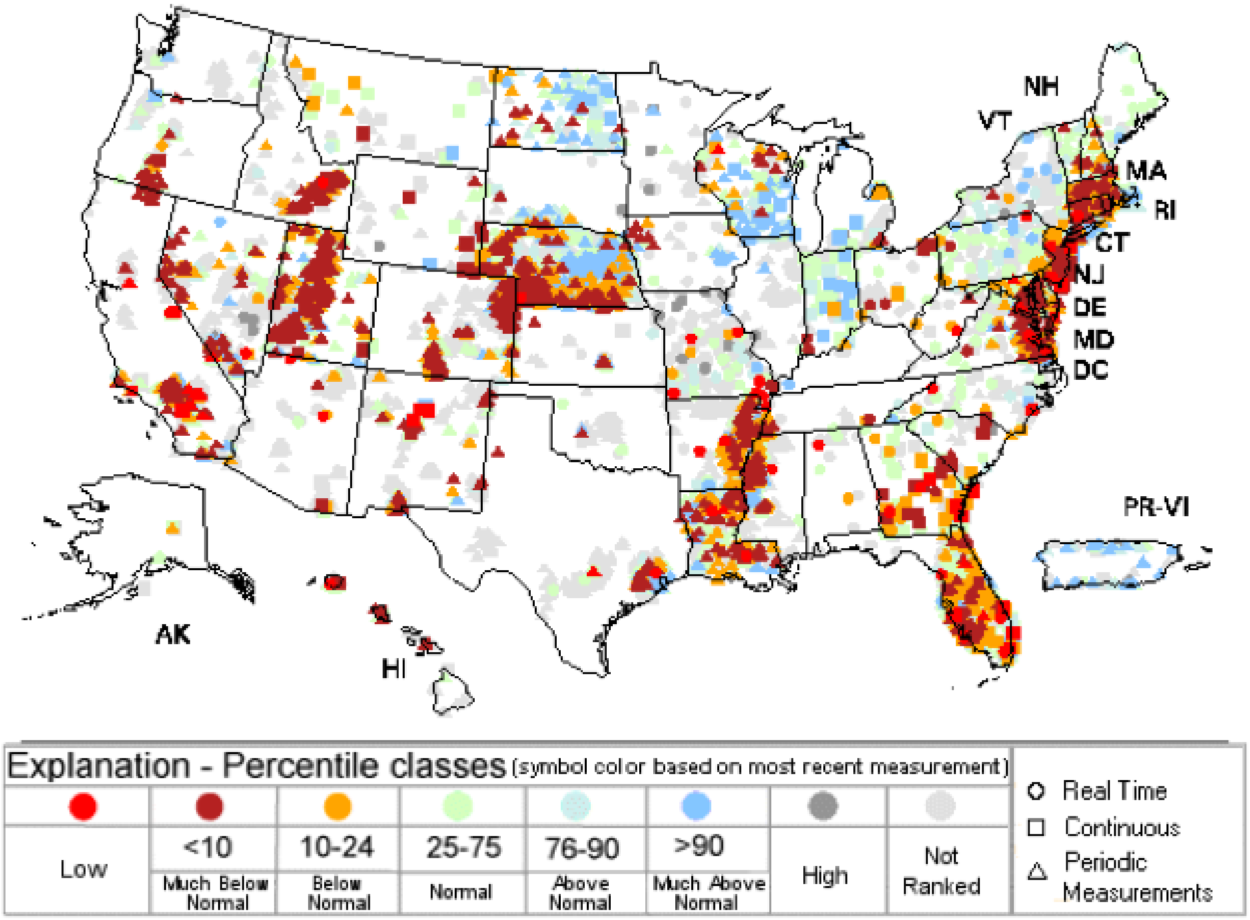

Figure 35: Below-Normal GW Levels as of October 11th, 2010 (Source: (*167*))

Unlike drought vulnerability, the fact that aquifers span multiple states makes categorizing individual counties as at-risk for groundwater depletion difficult if not impossible even if groundwater levels were monitored consistently throughout the country. Furthermore, overpumping in one location can result in no local impacts, but lowering of the water table or subsidence in another location; this issue caused the lawsuit *State of Kansas v. State of Nebraska and State of Colorado* in 2002, where Kansas claimed that Nebraska and Colorado were pumping more than their apportioned share of groundwater (*97*). Given that water rights

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are often negotiated at the state level, groundwater overpumping impacts have been quantified at the state level as well. A lowered water table is the most common impact. Subsidence occurs when the water table drops in such a way that soil and rock on the surface collapse, creating sinkholes and large cracks. In coastal areas, saltwater intrusion is also a problem, caused by a pressure gradient created when underground freshwater aquifers are overpumped, which then draws seawater inland and salinates the aquifers (*26*). Table 36 lists states that experience impacts from groundwater overpumping, along with a brief description of the impacts and Figure 36 shows a map of state-level groundwater overpumping impacts.

| State | Examples of Impacts from Groundwater Overpumping |
|---|---|
| AR | Lowered water table |
| AZ | Lowered water table, subsidence |
| CA | Lowered water table, subsidence |
| CO | Lowered water table, subsidence |
| DE | Lowered water table, subsidence |
| FL | Saltwater intrusion, subsidence |
| GA | Saltwater intrusion, subsidence |
| ID | Lowered water table, subsidence |
| IL | Lowered water table |
| KS | Lowered water table |
| KY | Lowered water table |
| LA | Lowered water table, saltwater intrusion |
| MA | Reduction in surface water flows |
| MS | Lowered water table |
| NE | Overpumping, contributing to lowered water table in KS, lowered water table |
| NJ | Saltwater intrusion, subsidence |
| NM | Lowered water table, subsidence |
| NV | Lowered water table, subsidence |
| NY | Lowered water table, reduction or elimination of stream base flows, decrease in length of perennial streams, inland movement of saline groundwater |
| OR | Lowered water table |
| SC | Saltwater intrusion |
| TN | Lowered water table |
| TX | Lowered water table, subsidence, increased susceptibility to flooding |
| UT | Lowered water table |
| VA | Lowered water table, subsidence |
| WA | Lowered water table |
| WI | Lowered water table |

Table 36: GW Pumping Impacts (Based on References (*26, 96, 97, 167*))

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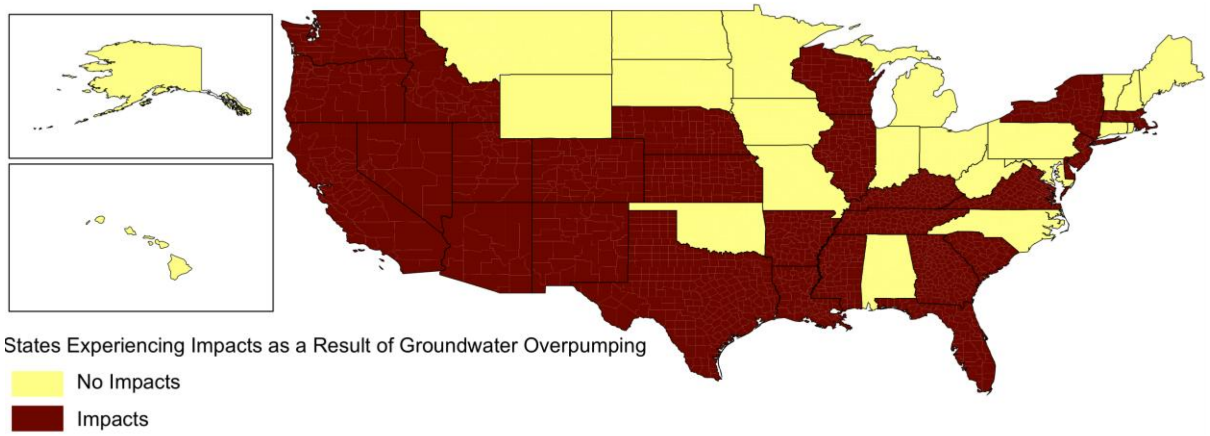

Figure 36: GW Overpumping Incidence in the United States

## 4.5 Geospatially Disaggregated Results

Before the life-cycle water use inventory can be matched up with drought and groundwater overpumping vulnerability data, the inventory must be geospatially disaggregated. Because the drought data are broken up by county and groundwater data are broken up by state, each fuel pathway water-use inventory is disaggregated by county. A discussion of how each industry was mapped to U.S. counties is provided in Appendix C. The results for each pathway are shown in Figure 37 through Figure 48. It should be noted that, while the inventory results presented in Chapter 3 include water used outside of the United States (for crude oil extraction, for example), the maps in this section only include water used within the contiguous United States, Alaska, and Hawaii.

The first set of maps, shown in Figure 37 and Figure 38, display respectively water consumption and withdrawals for the crude oil-to-gasoline fuel pathway. There are three locations that stand out as bearing the largest water burden: Southeastern Texas, Southern California, and Northern Alaska. Figure 33, Figure 35, and Figure 36 all indicate that Alaska is not subject to significant freshwater shortages. However, these figures do show that Southern California has spent more than 10% of the last 100 years in sever or extreme drought and both Southeastern Texas and Southern California suffer from groundwater overpumping, with wells indicating groundwater levels in the 10th percentile of their overall distribution. This indicates that, while crude oil extraction and refining requires less water that some other fuels such as corn ethanol, it does put additional stress on already water-poor areas of California and Texas.

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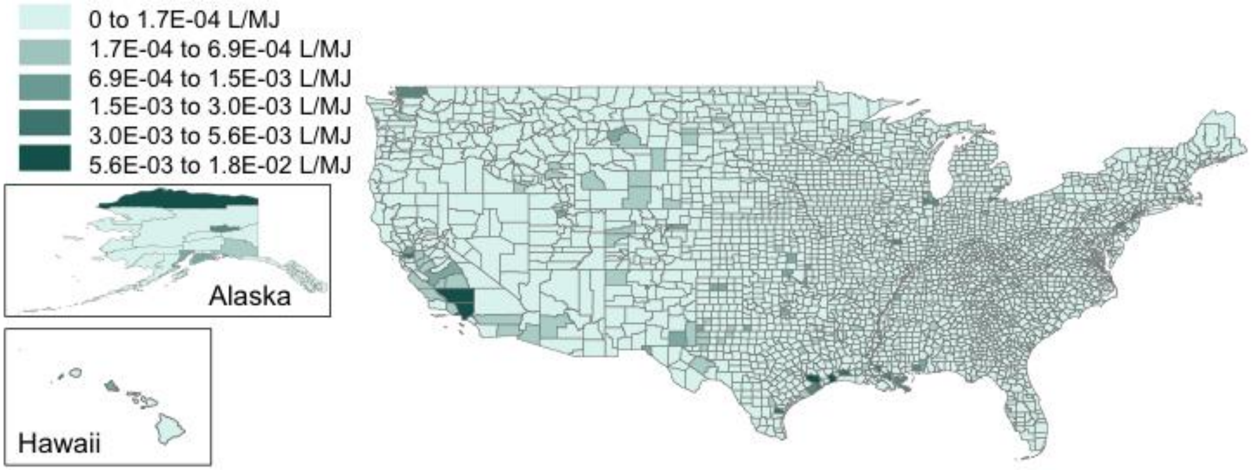

Figure 37: Life-Cycle Water Consumption Map for the Crude Oil-to-Gasoline Pathway

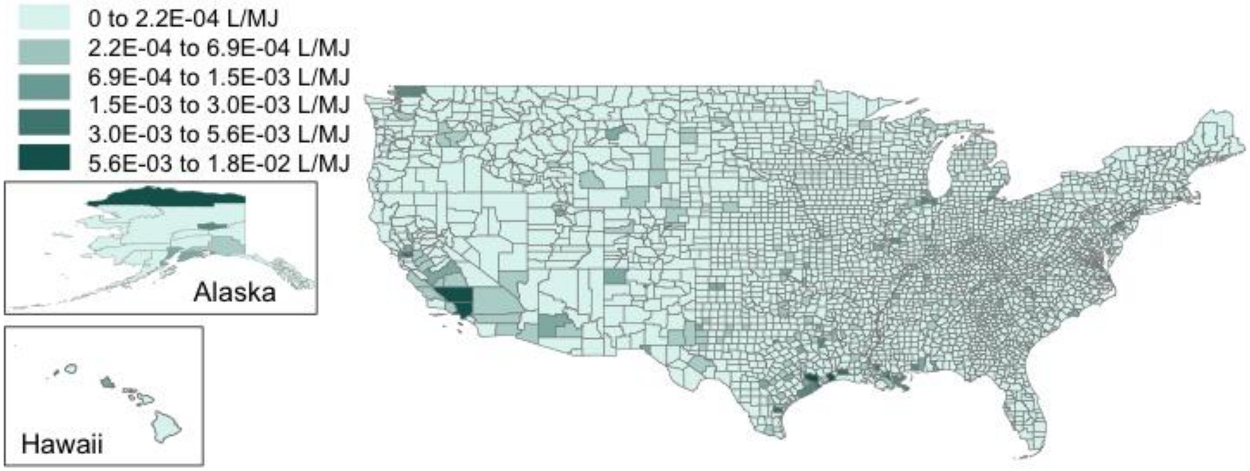

Figure 38: Life-Cycle Water Withdrawals Map for the Crude Oil-to-Gasoline Pathway

The water impacts of the oil sands-to-gasoline fuel pathway are less pronounced on these maps because all of the water for oil sands extraction is used in Canada rather than the United States (*5*). Thus, Figure 39 essentially shows water use for petroleum refineries, plus a small amount of indirect water use. The increase in water use in Figure 40 relative to Figure 39 is primarily due to withdrawals for electricity generation, since petroleum refining is an electricity-intensive process. The Athabasca region of Canada where oil sands are extracted and upgraded is technically within the WECC NERC region, so much of the power comes from U.S. plants as well.

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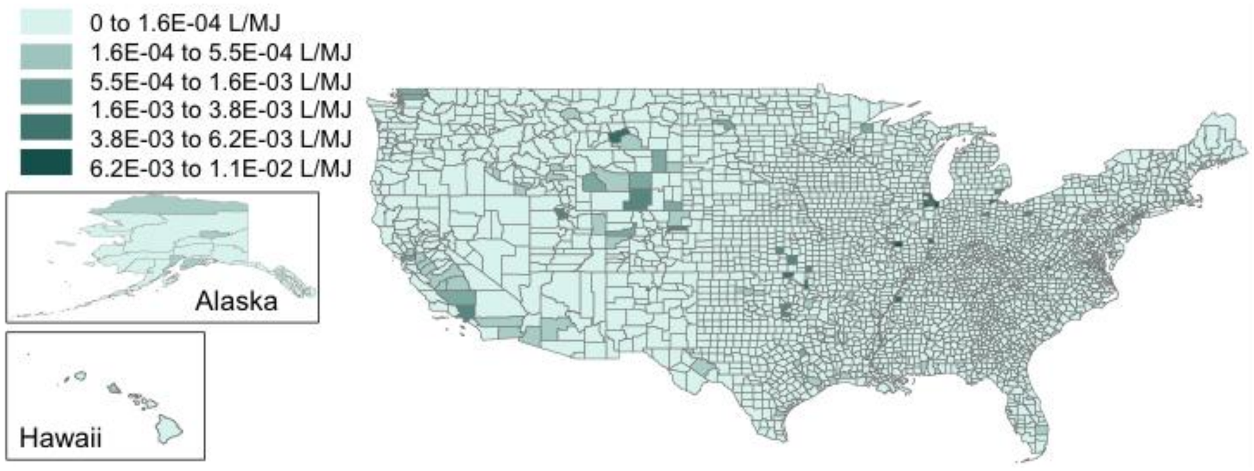

Figure 39: Life-Cycle Water Consumption Map for the Oil Sands-to-Gasoline Pathway

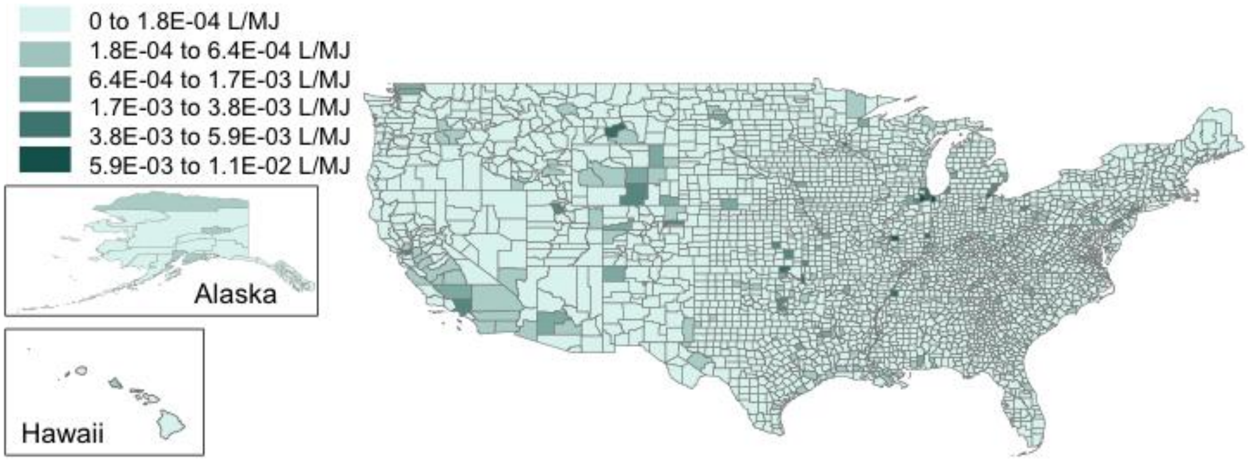

Figure 40: Life-Cycle Water Withdrawals Map for the Oil Sands-to-Gasoline Pathway

Compared to oil sands and crude oil, the corn grain-to-ethanol fuel pathway looks significantly different. The vast majority of irrigation water for corn is used in Nebraska, as shown in Figure 41 and Figure 42, with small amounts of water used in Idaho and Arizona. As shown in Figure 33, Figure 35, and Figure 36, all of these locations are subject to groundwater overpumping impacts and are vulnerable to drought. Nebraska in particular relies heavily on the High Plains Aquifer and will likely be subject to stricter limits on pumping in the future (*97*). The Central Valley of California also shows some water use, but this is primarily due to supply-chain (indirect) agricultural activity as calculated by EIO-LCA (see Section 3.3.12). Because so much irrigated agriculture is concentrated in California, any product or service that requires agricultural products at some point in their supply chain will result in non-negligible water impacts in the Central Valley.

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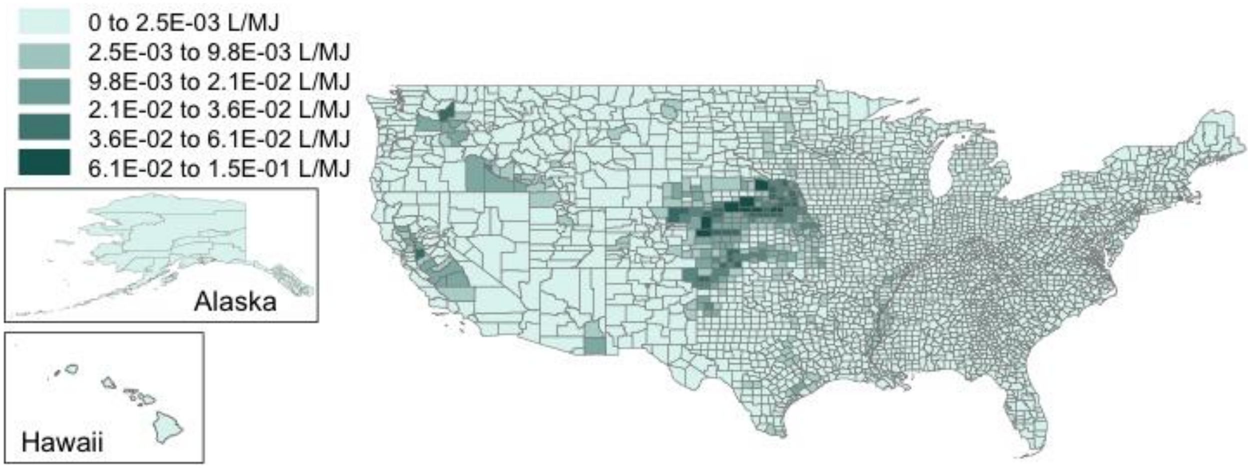

Figure 41: Life-Cycle Water Consumption Map for the Corn Grain-to-Ethanol Pathway

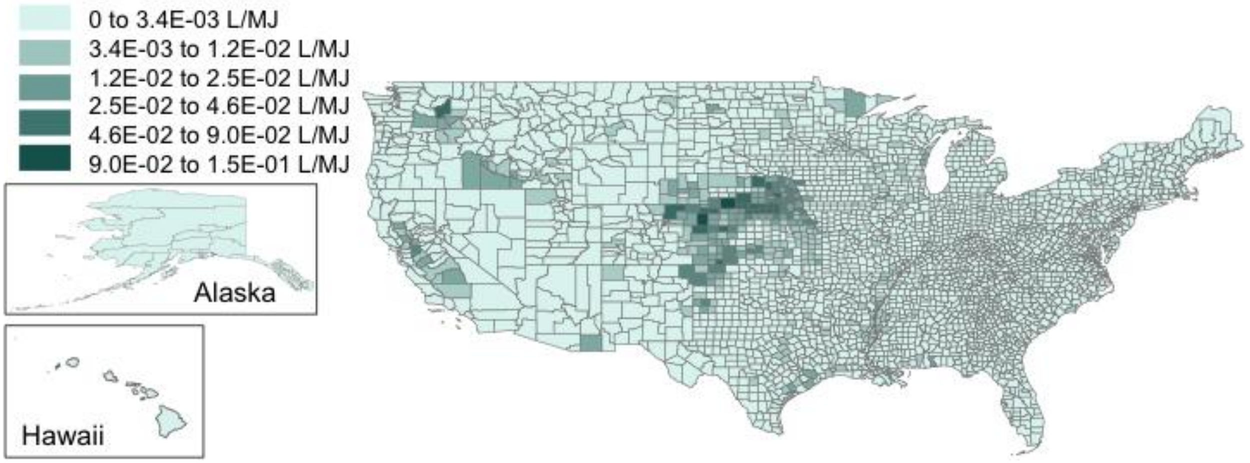

Figure 42: Life-Cycle Water Withdrawals Map for the Corn Grain-to-Ethanol Pathway

The maps for the corn stover-to-ethanol and Miscanthus-to-ethanol pathways look markedly different from the corn grain pathway. First, the reader should note that because some counties actually experience a decrease in water use as a result of cellulosic ethanol production, the lightest colors represent water use reduction and the darkest colors represent an increase in total water use. Counties that experience a reduction in water use contain one or more power plants that are likely to be ramped down as a result of increased electricity production by stover and Miscanthus biorefineries.

Because no irrigation water used for corn grain production is allocated to stover, the water use shown in Figure 43 and Figure 44 represents only that of biorefining and indirect water use for fuel, chemical, material, and other production. The darkened counties in the Midwest indicate the locations of biorefineries. Because stover is simply the biomass by-product of corn crops, it is assumed that existing U.S. corn grain biorefineries will be upgraded with the capacity to process biomass. As seen in Figure 44, counties in Southeastern Texas also face increased water use. This is because much of the chemical manufacturing industry is concentrated on the Gulf Coast (see Appendix C) and cellulosic biorefining is heavily reliant on chemicals, particularly

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for biomass pretreatment (*86*). As shown in Figure 33, Figure 35, and Figure 36, a significant fraction of the water use for the corn stover-to-ethanol pathway occurs in areas that are drought prone and subject to groundwater overpumping.

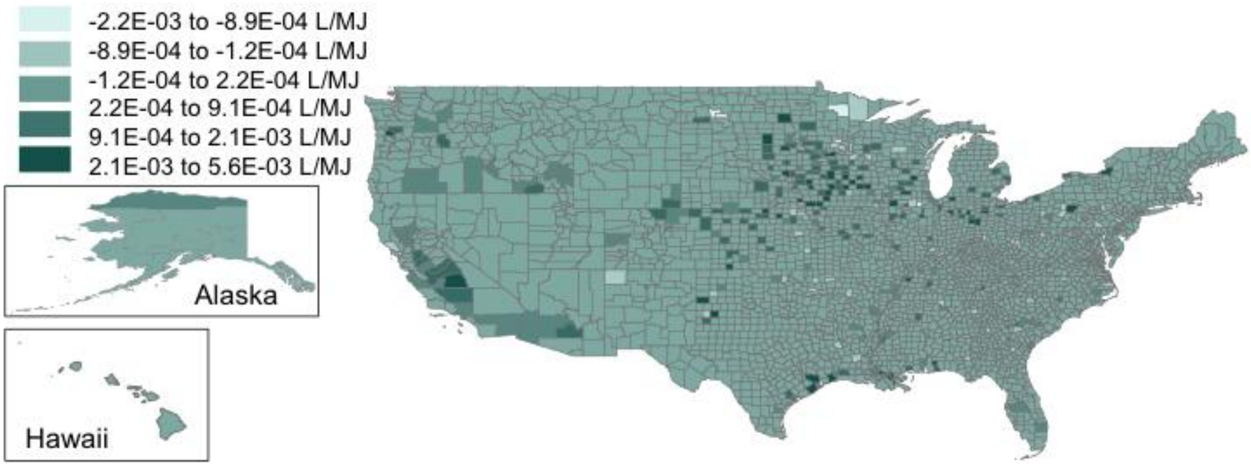

Figure 43: Life-Cycle Water Consumption Map for the Corn Stover-to-Ethanol Pathway

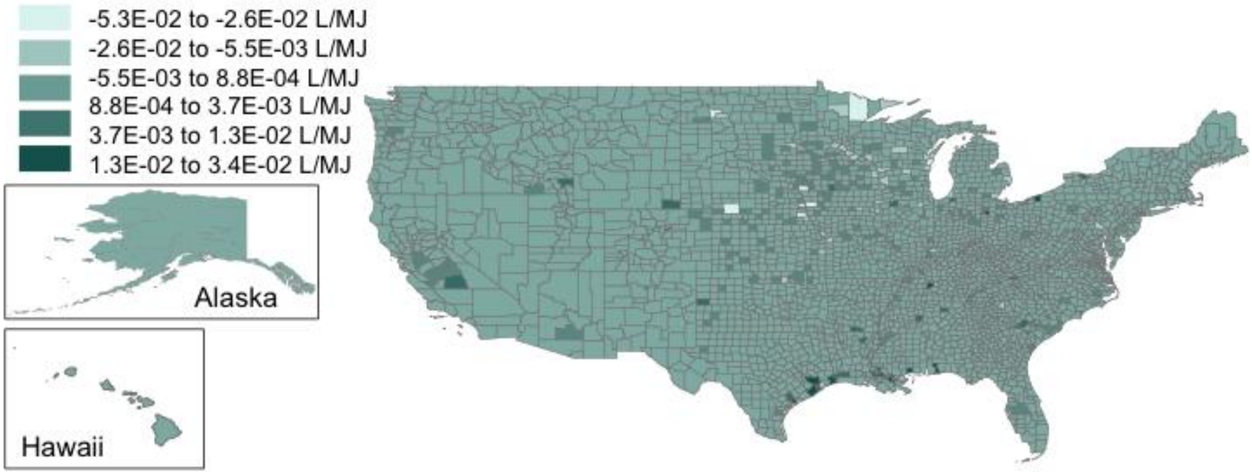

Figure 44: Life-Cycle Water Withdrawals Map for the Corn Stover-to-Ethanol Pathway

The Miscanthus maps (Figure 45 and Figure 46) look nearly identical to those of corn stover. This is because, in the absence of better data on potential Miscanthus crop and biorefinery locations, Miscanthus is also assumed to be processed in upgraded corn grain biorefineries. In recent months, researchers have indicated that while Miscanthus was thought to be best grown in the Midwest, it is recognized to have potential in much of the Mississippi River Watershed, including the Southeastern United States. (*87, 168*).

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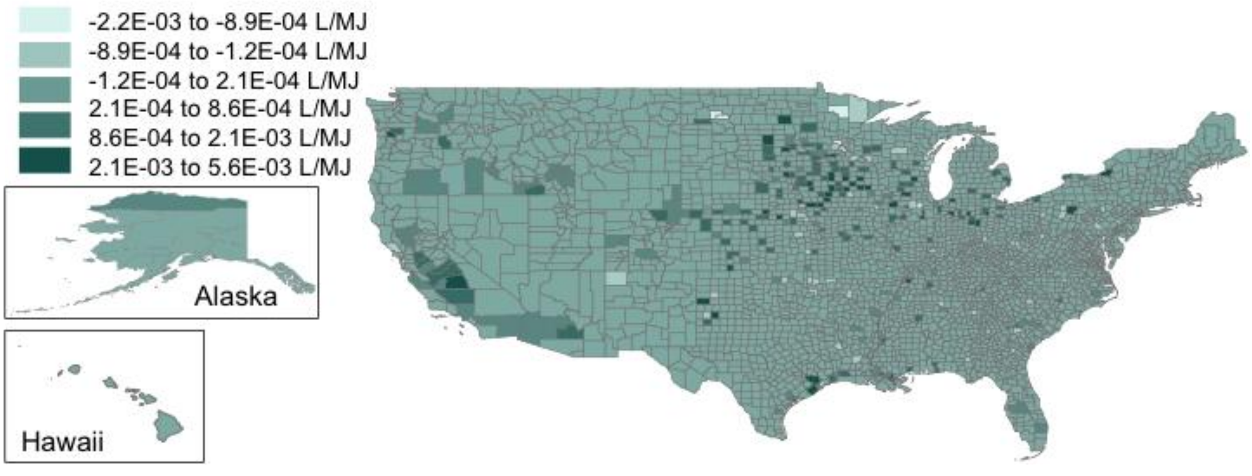

Figure 45: Life-Cycle Water Consumption Map for the Miscanthus-to-Ethanol Pathway

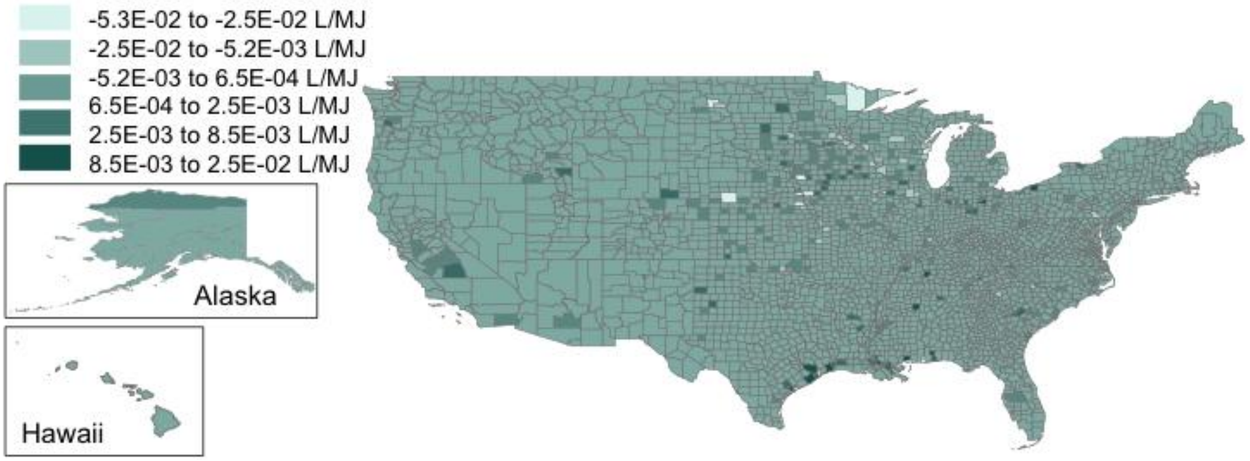

Figure 46: Life-Cycle Water Withdrawals Map for the Miscanthus-to-Ethanol Pathway

The production of U.S. electricity is more distributed than ethanol or gasoline because line losses prevent generation from becoming too centralized (see Figure 47 and Figure 48). Supply must be close to demand, which means that most power is generated near population centers on the coasts and that the rural Midwest has relatively few power plants. The result is a geospatial distribution that is essentially the opposite of ethanol production, which is produced in the sparsely populated Midwest areas and transported to demand centers on the coasts. There is also a more pronounced difference between consumption and withdrawals given that, on average, power plants withdraw far more water than they actually consume (see Chapter 3). Ironically, power plants in the Western United States bear a larger water consumption burden because most power plants in water-stressed areas (as many western states are) are built with closed-loop cooling systems that withdraw far less water than open-loop systems but consume more.

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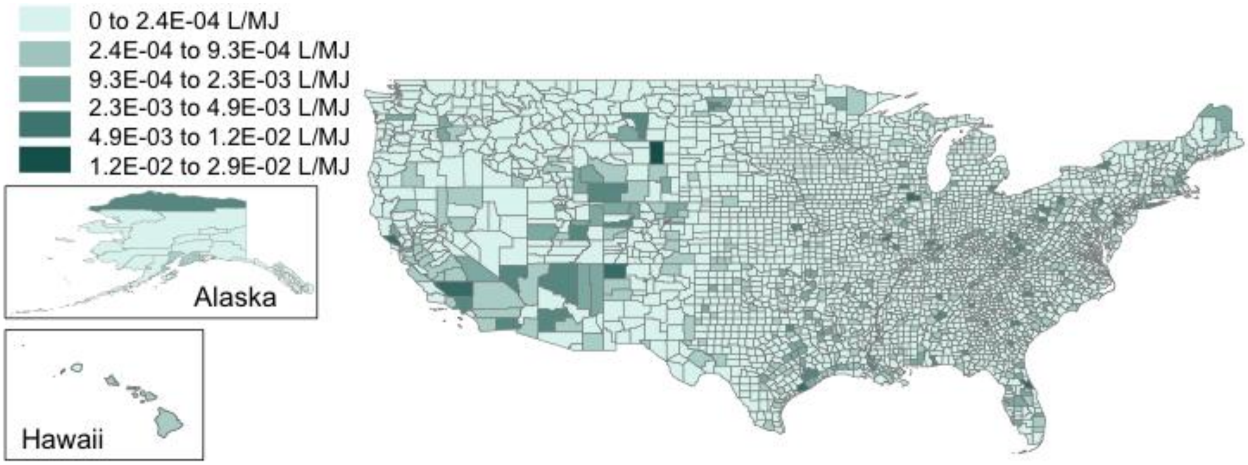

Figure 47: Life-Cycle Water Consumption Map for the Electricity Pathway

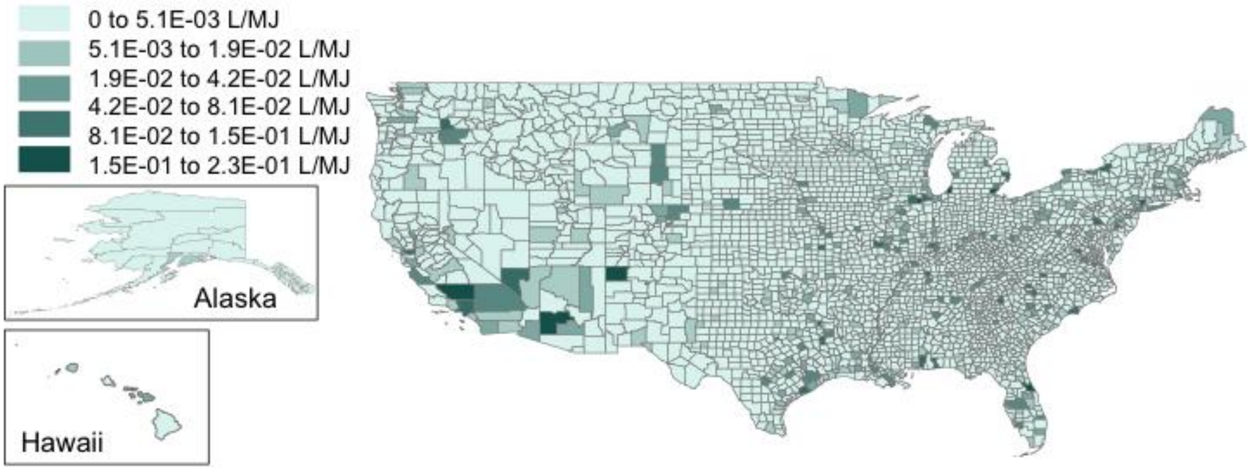

Figure 48: Life-Cycle Water Withdrawals Map for the Electricity Pathway

## 4.6 Weighted Inventory Results

Combining the inventory results presented in Chapter 3, disaggregated as shown in Section 4.5, and the county/state-level groundwater and surface water vulnerability data discussed in Sections 4.3 and 4.4, results in weighted inventories based on how much water use occurs in vulnerable locations. These weighted inventories, split out by ground and surface water as well as consumption and withdrawals, are shown in Figure 49, Figure 50, Figure 51, and Figure 52. Options for obtaining the numerical results are discussed in Appendix C.

Surface water results, particularly withdrawals, are interesting. Surface water consumption is still dominated by corn ethanol, but Miscanthus and corn stover also require a large amount of water, totaling to about 0.7 L/km, 0.5 of which comes from drought-prone regions. Electricity generation water consumption remains relatively constant among NERC regions, although the fraction that occurs in drought-prone regions varies widely. Electricity consumption in the MRO and HICC regions places significant stress in drought-prone areas while FRCC, ASCC, NPCC, and SERC are not expected to contribute appreciably to drought severity. Unlike consumption,

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surface water withdrawals are dominated by electricity. The MRO and HICC regions in particular place pressure almost exclusively on drought-prone areas. Miscanthus and corn stover, because their biorefineries export electricity to the grid in the Midwest, where the MRO region is located, displace approximately 2.5 L/km and nearly 100% of this water use would have occurred in drought-prone areas.

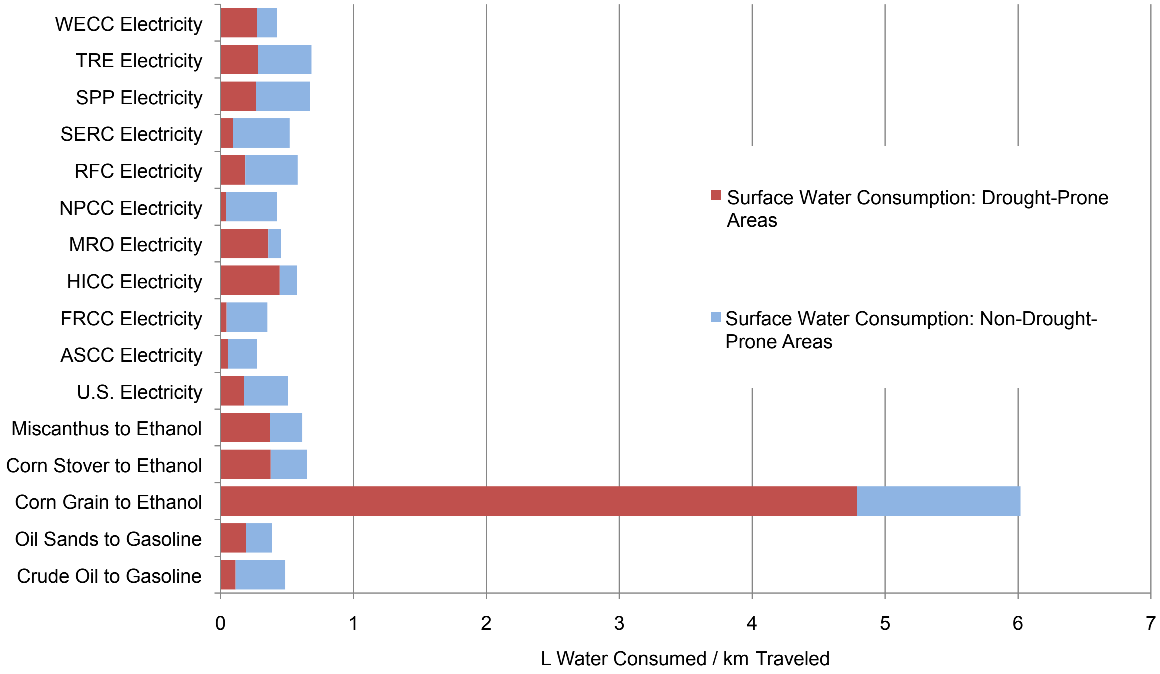

Figure 49: SW Consumption in Drought-Prone and Non-Drought-Prone Areas

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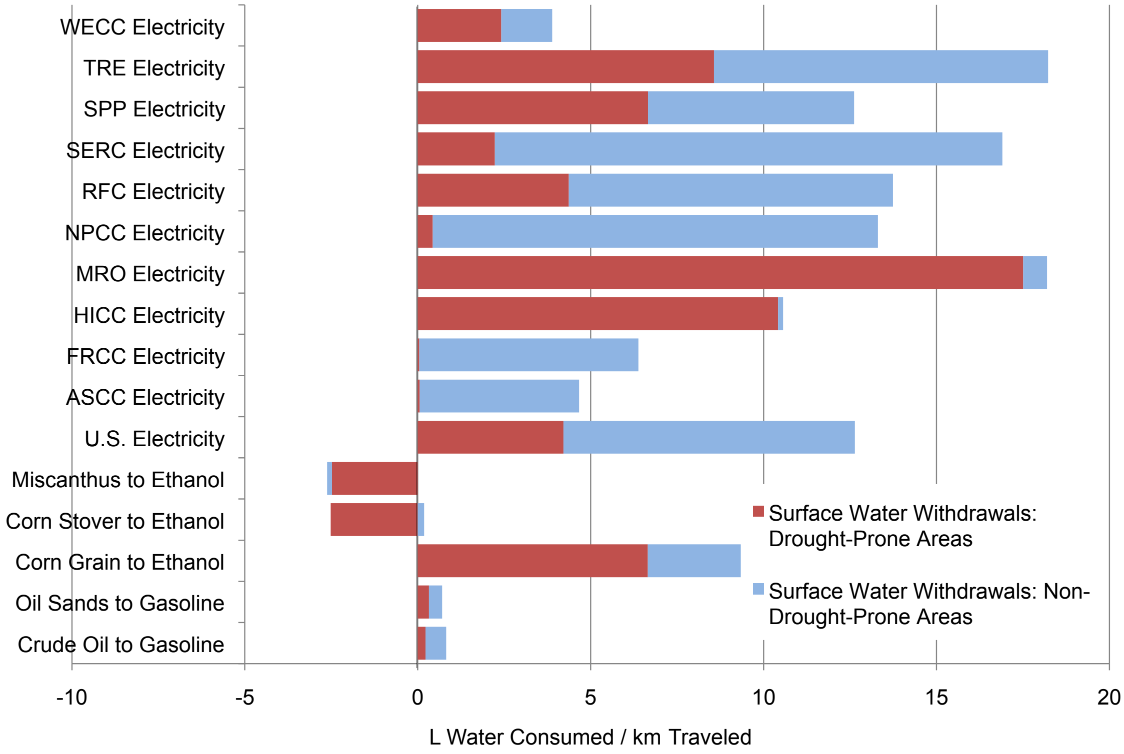

Figure 50: SW Withdrawals in Drought-Prone and Non-Drought-Prone Areas

From a groundwater perspective, corn ethanol is dominant, requiring approximately 18.5 L of water per km traveled, most of which is from states that experience impacts from overpumping (see Figure 51). This is because corn is grown in the Midwest where the High Plains Aquifer provides almost all of the irrigation water, particularly in Nebraska. The High Plains Aquifer is also known to be pumped at an unsustainable rate, causing drops of more than 18 m since 1980 in some locations (*14*). For groundwater withdrawals, electricity and cellulosic ethanol make up a more significant share. While it is possible for facilities to withdraw groundwater and return the water to its original source on a short timescale, it is unlikely that this practice is responsible for the results in Figure 52. Rather, it is due to the fact that the breakdown between ground and surface water use is only provided for withdrawals, but is used for both withdrawals and consumption (*12*). In reality, all groundwater used for cooling is likely to be used for closed-loop systems because the pumping energy required to use groundwater for open-loop cooling would be far too great. The same is true of chemical manufacturing facilities with open-loop cooling systems. While the ground and surface water breakdown used for chemical manufacturing is a generic "industrial" factor from reference (*12*), any facility employing open-loop cooling likely uses surface water exclusively.

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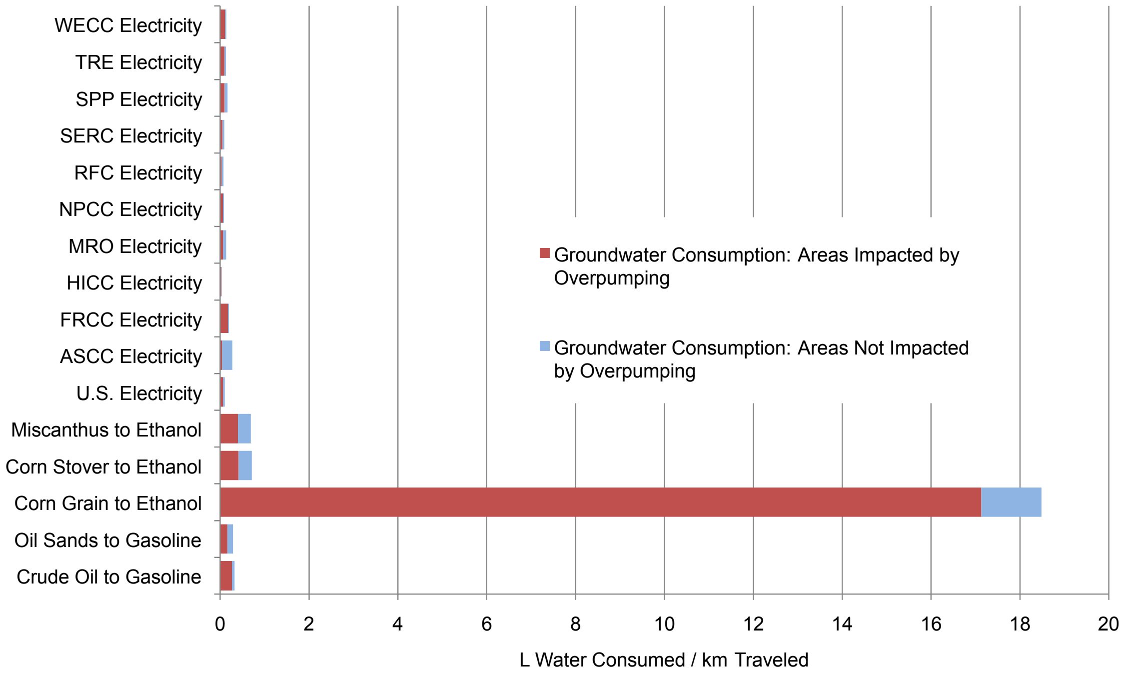

Figure 51: GW Consumption in Areas Impacted and Not Impacted by Overpumping

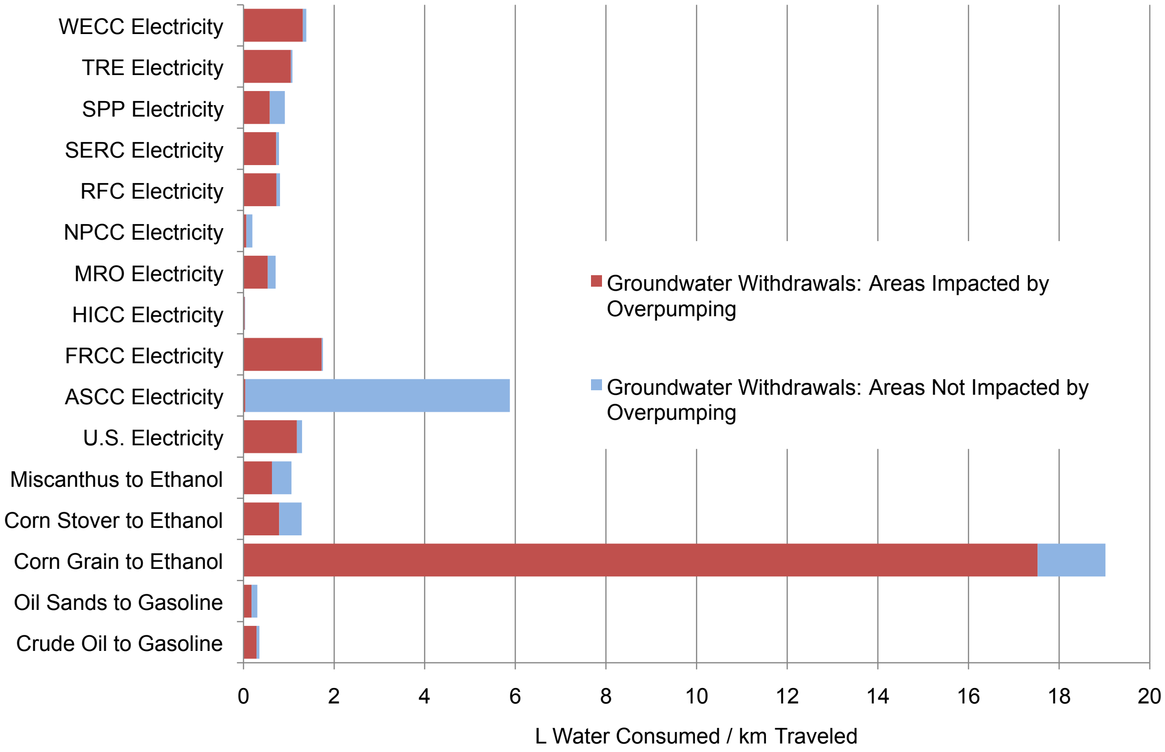

Figure 52: GW in Areas Impacted and Not Impacted by Overpumping

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# 5. Energy and Greenhouse Gas Emissions Embodied in Water Use

As a result of globalization, humans are not limited to depending on the natural resources that are locally available for food, energy, and other commodities. Seasons no longer dictate the availability of fruits and vegetables as agricultural products can be shipped from anywhere in the world; minerals such as uranium, copper, and bauxite travel long distances to their destination; and fossil fuels are often imported from thousands of miles away. Freshwater, however, is one resource that remains largely local. In contrast to crude oil, which is consumed in the United States at an average rate of 6.6 kg/person/day or coal at 11 kg/person/day (*169*), freshwater is withdrawn at an astonishing rate of 5,000 kg/person/day (*12*). If freshwater had to travel the distances that many other natural resources do, the energy required to transport that water would be astronomical.

Freshwater is more ubiquitous than crude oil, coal, or mineral resources, but some communities are growing beyond what local water supplies are able to support (*33*). The pressure on water resources comes not only from public supply and domestic use (12% of total U.S. withdrawals), but also from power generation (49%), agriculture (31%), industry (4%), aquaculture (2%), mining (1%), and livestock (1%) (*12*). As any of these categories grow, so does stress on local resources. When local resources are exhausted, freshwater can be imported from elsewhere via pipeline, produced from local saline or seawater through desalination, or provided by recycling wastewater, all of which have an associated energy premium (*16*). The more reliant humans become on these energy-intensive means of acquiring fresh water, the more inextricably connected energy and water will become, making an energy crisis and water crisis one in the same.

In this chapter, the connection between water supply and energy and its associated GHGs is explored. The ultimate goal of the analysis is to factor in the GHG emissions associated with freshwater supply that are typically left out of transportation fuel LCAs, particularly when the water is supplied by publicly owned infrastructure such as large-scale import systems. Wastewater treatment is not included within the scope because the vast majority of water used throughout the life cycles of transportation fuels is needed for irrigation, mining/extraction, and industrial use (see Chapter 3), which typically is either not treated or undergoes on-site treatment. In the latter case, the GHG footprint of on-site wastewater treatment at a biorefinery, for example, would already be included in most LCAs.

This chapter calculates both the county-level water-related GHG contribution for U.S. transportation fuels as well as that of worst-case scenarios where imported, desalinated, and recycled water are used for industrial processes. The water supply pathways analyzed in this chapter are shown in Figure 53.

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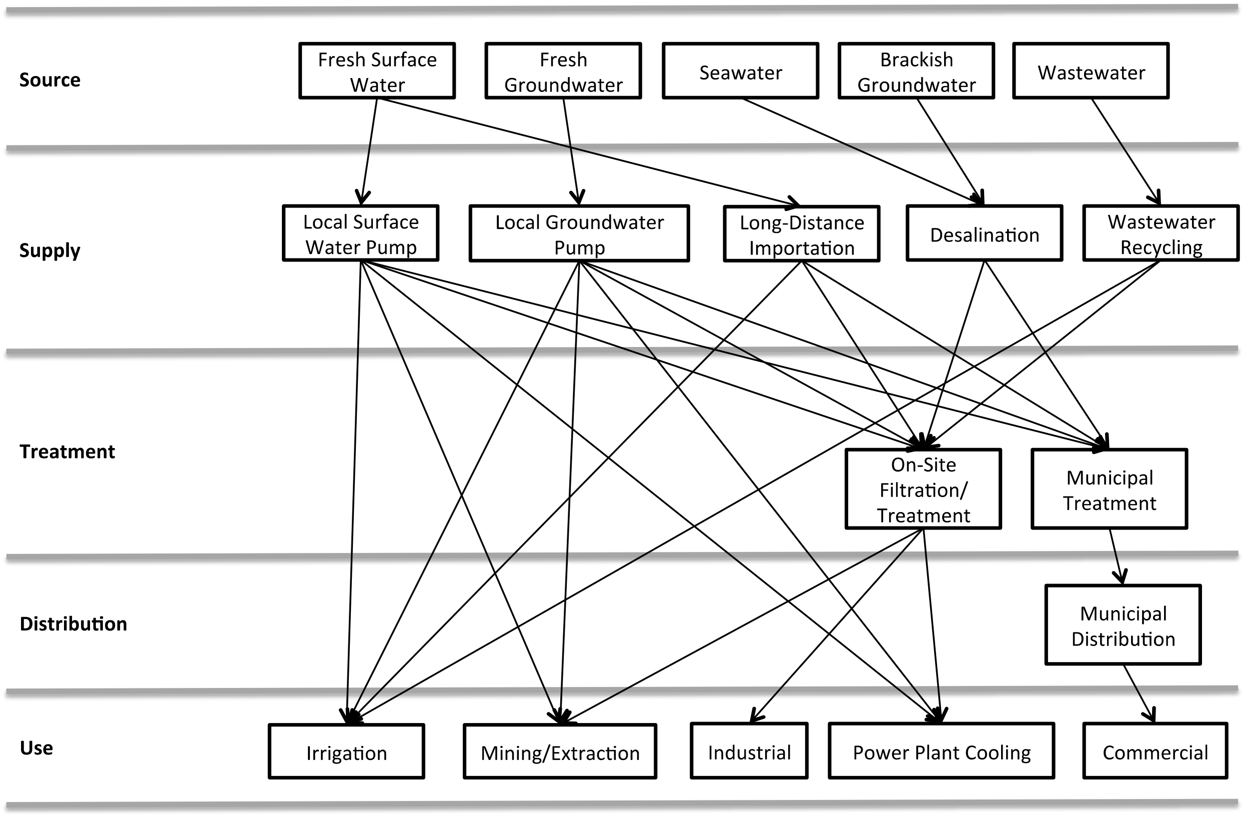

Figure 53: Scope for GHG Footprint of Water Analysis

In the following section, there is a review of existing literature on the GHG-intensity of water supply. In subsequent sections, the GHG-intensity of water supply for various sectors at the U.S. county level is calculated and finally, those results are combined with the county-level water use inventory presented in Chapter 4 to assess how the GHG-intensity of water supply changes the overall GHG footprint of each transportation fuel pathway.

## 5.1 Literature Review

As discussed above, there are no studies that factor energy and emissions embodied in water into an LCA of transportation fuels. However, there are a number of reports and journal papers that deal with energy required for supply, treatment, distribution, and wastewater treatment (categorized here as "direct" impacts). By systematically breaking these studies down into their major components, it is possible to determine where gaps exist by comparing the information needed to what is available from the current literature (Table 37).

Table 37 demonstrates that while there are a number of reports and journal papers that have explored energy and GHGs embodied in water, most are focused on a particular state or city, and except for reference (*170*), they focus exclusively on municipal water. California is a popular case study because its water is very energy intensive compared to other areas within the United States and large amounts of data are available on the pumping energy required by the state's two major import systems: the State Water Project (SWP) and Colorado River

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Aqueduct (CRA). Unfortunately, much of the activities involved in transportation fuel production occur outside of California, so these studies are of limited usefulness. Furthermore, the focus on municipal water means that literature on the energy intensity of water for industrial facilities, mining/extraction, power plant cooling, and irrigation is sparse.

| | Source | (*160*) | (*16*) | (*16*) | (*171*) | (*172*) | (*173*) | (*174*) | (*175*) | (*170*) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Geographic Location | CA | CA | CA | Toronto, Canada | CA | CA | CA | CA | U.S. |
| Supply | Imported | X | X | X | | X | Est. Range | Est. Range | X | |
| | Local Groundwater | X | | | | X | | | X | X |
| | Local Surface Water | X | | X | | X | | | X | |
| | Reuse/Recycling | X | X | X | | X | | | | |
| | Seawater Desalination | X | X | X | | X | | | | |
| | Brackish Water Desalination | | X | X | | | | | X | |
| Treatment | Municipal | X | X | X | X | X | | | | |
| | Industrial | | | | | | | | | |
| Distribution | | X | X | X | | X | X | X | X | |
| Wastewater Treatment | Municipal: Trickling Filter | X | | | | X | Est. Range | Est. Range | | X |
| | Municipal: Activated Sludge | X | | | | X | | | | X |
| | Municipal: Advanced w/out Nitrification | X | | | | X | | | | X |
| | Municipal: Advanced w/ Nitrification | X | | | | X | | | | X |
| | Industrial | | | | | | | | | |

Table 37: Survey of Literature on Embodied Energy/Emissions of Water

Reference (*170*) does provide some information on industrial water use; for example, they estimate how much groundwater and surface water are withdrawn for certain sectors, and the energy used for pumping. Reference (*12*) also provides county-level estimates for how much ground and surface water are withdrawn by industrial facilities. Pumping is important because it may or may not be included in existing life-cycle GHG calculations, depending on whether the pumping energy is reported as part of the facility's total energy consumption. In contrast to water pumping, industrial water treatment remains largely a black box. Because water that enters industrial facilities may have very different quality requirements depending on its ultimate purpose, the energy required for treatment will vary as well. For example, silicon wafer manufacturing requires high purity water, so the facility purchases potable-quality water from a municipal utility and then further purifies it onsite; the onsite purification process alone is responsible for 5% of the facility's total energy use (*120*). Conversely, most industrial facilities do not have such stringent water quality requirements and thus withdraw water straight from surface or groundwater sources, performing whatever treatment is necessary onsite (*12, 170*). As is the case with onsite wastewater treatment, industrial water treatment is typically included in LCAs because it is a part of the facility's total energy and GHG footprint.

One interesting factor that is discussed in the 1981 report by the U.S. Water Resources Council in reference (*108*) is the effect that water use has on hydroelectricity generation, namely the

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reduction in hydroelectric power production as a result of diverting large quantities of water upstream of dams. Their focus is oil shale production in Colorado and they look at two dams: Hoover and Parker-Davis. For the "Low Baseline" production scenario, they predict a total reduction in hydroelectricity generation of approximately 19 MW and for the "High Accelerated" scenario, 27 MW (for comparison, a large coal-fired plant capacity is around 1 GW). Reducing hydroelectricity production will likely result in an increase in the need for fossil fuel-fired power plants, which will in turn increase total GHG emissions. This indirect effect is not accounted for in this dissertation, but may be important for fuel production pathways that require large quantities of water that would otherwise reach hydroelectric dams.

One issue that is not sufficiently addressed in any existing literature is the question of average vs. marginal water supply. If a biorefinery is built, it is important to not only look at the average energy-intensity of water supplied in that area, but the energy-intensity of the marginal unit of water. This can make a large difference in areas where water is scarce; for example, the marginal unit of water for municipal use, and some commercial/industrial uses in Saudi Arabia comes from desalination plants (*5*). It should be noted that, as is often the case in LCA, predicting the marginal source of water is quite difficult because it is dependent on energy prices, rainfall, water rights agreements, the limitations of existing infrastructure, and the ability to build new infrastructure. Rather than attempt to predict the marginal source of water in each U.S. county, this chapter presents the average GHG-intensity of water, along with potential worst-case, GHG-intensive, marginal units. In the following section, the energy and GHG-intensity of baseline freshwater supply (local ground and surface water) and alternative (potentially marginal) sources (desalination, importation, and recycling) are assessed.

## 5.2 Freshwater Supply

Freshwater can come from local surface or groundwater sources, be imported, or produced from saline, seawater, or wastewater. Each of these options has advantages and disadvantages. Local surface water requires relatively little energy for pumping (*170*). However, it generally requires more treatment than groundwater because it has not undergone the natural purification that occurs as water percolates through carbon-rich porous media (*170*). Surface water is also more responsive to climatic fluctuations, so extended dry periods can seriously threaten surface water resource availability (*176*). Conversely, groundwater requires less treatment and is less vulnerable to climatic changes. Groundwater can, however, be depleted through overpumping, resulting in subsidence, deterioration in water quality, and reduced surface flows (*26*). Because groundwater must be pumped to the surface, it requires more pumping energy than surface water and as an aquifer is depleted, the water table lowers, further increasing the energy needed to bring the water to the surface (*26, 170*).

Importation, desalination, and wastewater recycling are significantly more costly and energy-intensive than using local freshwater, and are only used when local supplies can no longer meet the needs of surrounding communities, so these are referred to as "alternative" water supply systems (*177*). Desalination is possible for any communities located near seawater or saline groundwater. Seawater desalination requires more than twice the energy needed for

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wastewater recycling or importation (using Southern California as the importation example) (*16*). To minimize the climate change impacts, some companies have installed solar photovoltaic (PV) panels or solar collectors to meet their plants' energy needs (*166*). Importation can be less energy-intensive than desalination, but water rights can be problematic if resources become scarce in the region from which water is being imported (*16, 25*)

### 5.2.1 Local Surface and Groundwater Pumping

Surface water makes up 77% of total U.S. freshwater withdrawals (*12*). The average amount of energy required to pump surface water from source to destination depends on a number of factors: the distance it must travel, change in elevation, pressure and flow rate, pump efficiency, and the fuel(s) used for pumping. At an electric power plant, the large water requirements for cooling systems mean that, rather than locating plants near fuel sources, power plants are sited as close as possible to water sources (*31*), so pumping requirements will be relatively low. Furthermore, the water is almost exclusively self-supplied (99.9% in the United States, according to (*170*)), which means it can be pumped directly to the power plant rather than being collected in a municipal treatment facility and subsequently pumped through a distribution system. Similar to thermoelectric power generation, irrigation water is entirely self-supplied (*170*), although farmers may not have the luxury of locating their crops as close to water sources as possible since land availability, soil quality, and other factors impact the location. Industrial and commercial water requires a larger fraction from public supply and will, thus, be more energy intensive. A breakdown of water sources by sector is shown in Figure 54.

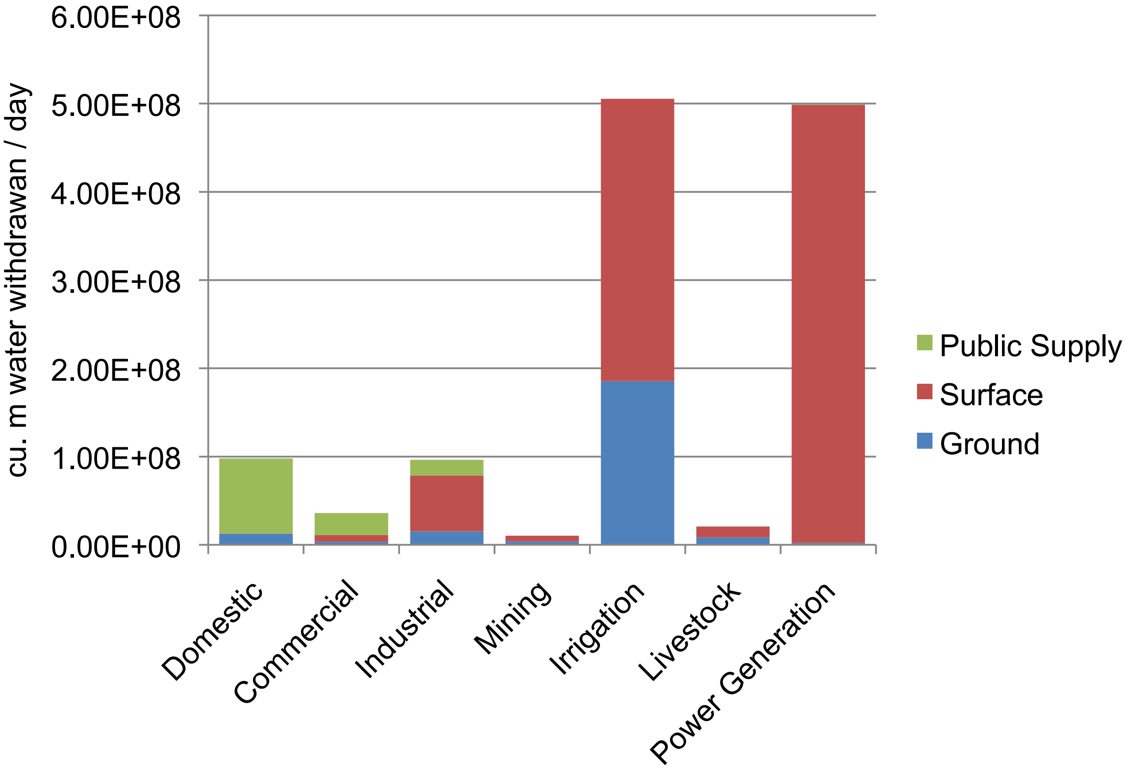

Figure 54: 1995 U.S. Water Withdrawals by Sector (Data Sources: (*116, 170*))

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The amount of energy required to run water pumps depends on a number of factors. Different pump types may be appropriate for different applications: centrifugal, deep well turbine, submersible, or propeller (*178*). The choice will depend on the desired flow rate, type of water source, and total dynamic head (TDH) (*178*). For 19 or more $m^3$ per minute and 152 or more m of TDH, centrifugal and vertical turbine pumps are the most desirable (*178*). Head is a measurement of pressure equal to the water surface elevation at the entrance of a piezometer. The TDH is equal to the sum of total static head (vertical distance that the water must be lifted); the pressure head, which refers to the required minimum pressure when the water reaches its destination (for example, sprinkler and drip irrigation systems require pressure to operate correctly); friction head, which is equal to the loss in pressure due to friction between the water and inside of the pipe; and the velocity head, which is the pressure resulting from the water's movement through the pipe (*178*). Holding the pipe diameter constant, frictional losses increase as the flow rate increases. With a given flow rate, the friction head can be reduced by increasing the pipe diameter or ensuring that the pipe interior remains free of minerals and other buildup.

To estimate the energy required for domestic water pumping, the Arizona Department of Water Resources uses average values for pump efficiency, pressure head, friction head, and velocity head to develop a simple equation that requires only the total static head as an input (see Equation 12 and Equation 13). Separate equations must be used for electric and natural gas-powered pumps since electric motors are significantly more efficient.

$$Electricity(kWh/L) = \frac{1.024 \bullet Depth(ft)}{6.67 \bullet 10^5}$$

Equation 12: Energy Required for Water Pumps Using Electric Motors (Adapted from (*179*))

$$NaturalGas(J/L) = \frac{2793 \bullet Depth(ft)}{0.154}$$

Equation 13: Energy Required for Water Pumps Using Natural Gas (Adapted from (*179*))

If one accepts the assumptions behind these equations as reasonable for domestic water pumping, then determining how much energy is required to pump surface water for a variety of uses still requires information about which fuel(s) are being used to power pumps, the elevation change between source and point of use, and potential increases/decreases in energy requirements depending on the pipe size, pump size, and flow rate.

By using the estimate of 0.185 kWh per 1000 L for domestic groundwater pumping provided by reference (*170*) and back-calculating with Equation 12, the average vertical height that domestic groundwater must be pumped (static head) is estimated to be 37 m, including the total depth of the well plus the height above ground at which the water is stored. According to reference (*180*), however, the National Water-Quality Assessment Program's groundwater monitoring network indicates that the mean depth of drinking water wells is 49 m in the United States. Using 49 m as the total static head, the total electricity requirement for domestic groundwater pumping in the United States is calculated to be $2.5*10^{-4}$ kWh/L of water

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delivered. As is consistent with reference (*170*), it is assumed that domestic water pumps are powered by electricity rather than primary fuels such as natural gas or diesel.

Calculating the pumping energy requirements for municipal surface and groundwater supply requires a different set of assumptions. First, the question of fuel mix must be addressed. Reference (*160*) indicates that, for California, local public water supplies may be pumped using gas or electricity, with their sample case supplying half of the total groundwater needs using natural gas and half using electricity. However, reference (*170*) indicates that the use of natural gas for water pumping is relatively unique to Orange County, CA, and that most utilities in the United States rely on electricity with conventional diesel generators for backup power. Reference (*16*) reinforces this, assuming that all water pumping is powered by electric motors, as do references (*172, 173, 181*).

To estimate the energy required for public groundwater withdrawals, assuming electric pumps, two adjustments must be made: the average depth should, if necessary, be changed, and the overall efficiency must be adjusted based on the assumption that public water utilities operate at a larger scale. Reference (*170*) assumes that the average depth of public groundwater wells is sufficiently similar to that of private wells such that no adjustment in static head must be made. In the absence of data specific to public wells, the same assumption will be made here (total static head for public groundwater wells equal to 160 ft).

In order to account for the difference in scale between domestic groundwater pumping and public groundwater supply, reference (*170*) reduces the total energy use per unit of water delivered by 14%, relative to domestic groundwater supply. Using this scaling factor, electricity use for public groundwater supply is calculated to be $2.2\text{x}10^{-4}$ kWh/L.

Unlike private (domestic) water supply, public utilities also draw from surface water sources because they have the ability to carry out the more extensive treatment required to ensure that it meets drinking water standards. Unfortunately, Equation 12 and Equation 13 were designed only to assess groundwater extraction. Assessing the energy requirements for surface water supply can be more complex because the horizontal distance it must travel can be highly variable, and even if the net change in elevation between source and destination is equal to zero, elevation changes along the water's path will contribute to the total pumping needs. This is why, although surface water is likely to require less pumping energy than groundwater in most cases, the estimate put forth in reference (*160*) of essentially zero energy use for surface water supply is improbable. In contrast, reference (*170*) assumes a municipal surface water pumping energy intensity of 0.073 kWh per $m^3$ of water. Although it is approximately three times lower than local supply energy use estimates in reference (*16*), this appears to be the most realistic estimate for U.S. average municipal surface water pumping.

Pumping energy use for commercial, industrial, power generation, and mining/extraction water supply is even harder to obtain than for private and municipal uses. This is because, rather than being reported separately as is the case for irrigation water and public/private drinking water, the energy used for pumping commercial, industrial, power generation, and mining/extraction water is typically included in total facility or site-wide energy usage numbers.

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The scale at which water must be delivered also varies widely depending on the size and type of process. Additionally, a number of factors go into determining what fuel will power the water pumps. At power plants, electricity is available onsite, and will almost certainly be used to power cooling water pumps. At oil wells, it is more likely that associated natural gas or some other petroleum product will be used to run the pumps providing injection water. At industrial and commercial facilities, electricity will likely be used unless the facility is a petroleum refinery or natural gas processing plant and has excess product, in which case primary fuel may be used. The assumptions made in this analysis are shown in Table 115 of Appendix D. The electric and natural gas motor efficiencies shown were taken from reference (*182*) and the energy use per L of water delivered are taken from reference (*170*), with the natural gas motor energy use adjusted to reflect the lower efficiency of natural gas motors.

For facilities known to use a different fuel than the default assumptions shown in Table 115 of Appendix D, the energy usages shown can be converted using the new motor's efficiency. Gasoline motors typically used for water pumps are calculated to have an efficiency of 25%, based on the new gasoline motor efficiency from reference (*182*), adjusted down slightly to reflect the average efficiency over the lifetime of the motor. Using the same methodology, diesel motors are estimated at 30% efficiency.

Surface and groundwater pumping for irrigation is much more thoroughly documented than for any other sector. The U.S. Department of Agriculture (USDA) conducts a Farm and Ranch Irrigation Survey (*126*) that covers state-level energy use for water pumping in terms of fuel purchases. Purchases in dollars were converted to fuel quantities using state average electricity prices from reference (*169*), U.S. average natural gas price from reference (*78*), U.S. average No. 2 diesel price from reference (*183*), U.S. average propane price from reference (*183*) to approximate propane, butane, and LPG purchases, and U.S. average gasoline price from reference (*183*) to approximate gasoline and gasohol purchases. By dividing the total energy used for irrigation pumping by the total water applied for each state, state-level average fuel use per L of irrigation water can be calculated, as shown in Table 116 of Appendix D. To determine the GHG footprint of the primary fuel consumption, the emission factors shown in Table 117 of Appendix D are used. Because the factors only include pumps operated by the farmers themselves, energy required for large-scale importation, water recycling, and other water supply projects are not included. These alternatives to local freshwater supply are discussed in the upcoming sections.

Having calculated the energy and GHG footprint of water pumping, the question that remains is how these numbers should be incorporated into existing energy and GHG footprints of water-intensive production systems. While it is very important that water pumping not be ignored, it is equally important that it not be double counted. For most sites that pump their own water such as farms, industrial facilities, mines, etc., pumping energy would likely be included in the reported total energy usage. However, even if this is the case, it is important to understand the connection between water and energy because reduced water usage can be translated into a reduction in GHG footprint.

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In cases when the energy use occurs offsite, such as commercial facilities, homes that use primarily publicly supplied water, or sites that use water provided by large importation, desalination, or water recycling projects, the full energy and GHG footprint of this water is rarely included, and can be very significant.

### 5.2.2 Water Imports

For the vast majority of the country, enough freshwater is locally available to support human needs. However, some states such as Florida, New York, Arizona, Texas, and California are facing long-term shortages that require additional infrastructure to ensure a steady supply of freshwater to their residents. This infrastructure may come in the way of desalination plants, wastewater recycling facilities, or importation infrastructure. Both New York and California utilize long-distance water importation as a method of supply. New York is fortunate in that it can operate an entirely gravity-powered aqueduct to bring water down from the Catskill Mountains, known as the Catskill Aqueduct (*184*). Because the Catskill Aqueduct is driven by gravity, it requires no more energy than a typical local water source. Unlike New York, water conveyance in California cannot rely solely on gravity.

California provides for the water-stressed Central Valley and southern part of the state using three long-distance water conveyance projects: the Colorado River Aqueduct (CRA), State Water Project (SWP), and Central Valley Project (CVP). The CRA delivers water from the Colorado River to Southern California, the SWP (shown in Figure 55) brings water to Southern California from the Northern part of the state, and the CVP brings water from the North to California's Central Valley. The CVP and SWP overlap, and the CVP relies almost exclusively on SWP pumping facilities, with the exception of the Tracy Pumping Plant (*185*). Unlike the SWP and CRA, the CVP is a net power producer because the hydroelectricity it produces outpaces its power usage (*186*). For this reason, only the SWP and CRA will be explored in this section because they are net power consumers. Once SWP and CRA water reaches the Southern part of the state, the Metropolitan Water District of Southern California (MWD) serves as the regional water wholesaler that resells this water to agencies in Southern California (*160*). Water is also allocated directly to irrigation districts, such as the Palo Verde Irrigation District, Imperial Irrigation District, and other independent organizations such as the Yuma Project Reservation Division (*187*). Initially, the focus of this section will be on water managed by the MWD, followed by a discussion specifically pertaining to irrigation water.

The total volume of water delivered by the SWP varies from year to year, with the largest delivery to date occurring in 1989, totaling to 3.5 billion $m^3$ (*160*). In 2008, SWP deliveries to MWD member agencies totaled to 1.3 billion $m^3$ (*188*). The SWP also serves as a generator of hydroelectricity and consumer of grid electricity. By allowing the water to run turbines whenever it flows downhill, it produces an average of 6.5 billion kWh of electricity and has the ability to produce 8.6 billion kWh. The SWP is a major consumer of electric power in CA as well, much of which is needed to pump water almost 600 m up over the Tehachapi Mountains. This adds up to an annual average of 11.6 billion kWh of total electricity consumption or 5.1 billion kWh net use after factoring in its hydroelectric power generation (*189*), which makes up 2-3%

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of total electricity consumption in CA (*172*). The net electricity consumption at each SWP pumping plant is shown in Table 38.

Figure 55: California State Water Project (Source: (*160*))

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| Facility Name | Total Power Consumption | Net Power Generation in 2005 |
|---|---|---|
| Banks Pumping Plant | 2.40E-01 kWh/m$^3$ | N/A |
| South Bay Pumping Plant | 6.46E-01 kWh/m$^3$ | N/A |
| Del Valle Pumping Plant | 5.84E-02 kWh/m$^3$ | N/A |
| Gianelli Pumping-Generating Plant | 8.51E-02 kWh/m$^3$ – 2.33E-01 kWh/m$^3$ | -3.90E+08 kWh |
| Dos Amigos Pumping Plant | 1.12E-01 kWh/m$^3$ | N/A |
| Las Perillas Pumping Plant | 6.24E-02 kWh/m$^3$ | N/A |
| Badger Hill Pumping Plant | 1.62E-01 kWh/m$^3$ | N/A |
| Devil's Den Pumping Plant | 5.72E-01 kWh/m$^3$ | N/A |
| Bluestone Pumping Plant | 5.72E-01 kWh/m$^3$ | N/A |
| Polonio Pass Pumping Plant | 5.72E-01 kWh/m$^3$ | N/A |
| Buena Vista Pumping Plant | 1.96E-01 kWh/m$^3$ | N/A |
| Teerink Pumping Plant | 2.39E-01 kWh/m$^3$ | N/A |
| Chrisman Pumping Plant | 5.18E-01 kWh/m$^3$ | N/A |
| Edmonston Pumping Plant | 1.81E+00 kWh/m$^3$ | N/A |
| Oso Pumping Plant | 2.27E-01 kWh/m$^3$ | N/A |
| Warne Power Plant | -4.65E-01 kWh/m$^3$ | 2.89E+08 kWh |
| Castaic Power Plant | -7.89E-01 kWh/m$^3$ | 2.96E+08 kWh |
| Alamo Power Plant | -8.51E-02 kWh/m$^3$ | 1.05E+08 kWh |
| Pearblossom Pumping Plant | 5.70E-01 kWh/m$^3$ | N/A |
| Mojave Siphon Power Plant | -7.70E-02 kWh/m$^3$ | 7.40E+07 kWh |
| Devil Canyon Power Plant | -9.02E-01 kWh/m$^3$ | 1.15E+09 kWh |

Table 38: Electricity Consumption/Generation at SWP Facilities (Data Sources: (*89, 160*))

The way in which the SWP generates and consumes electricity poses a methodological problem. If the SWP is treated as a production system, its primary purpose is to deliver freshwater to Southern California. Secondarily, it produces enough electricity to make up for a fraction of what it consumes. If the electricity was used instantaneously, thereby never actually exporting any power on to the grid, then one could simply define the electricity use (and its resulting environmental impacts) as the total required for pumping minus the amount generated. However, this is not how the SWP operates. By looking at Figure 55, one may observe that, before major hydroelectricity power plants, there is typically a storage facility (lake or reservoir); Quail Lake precedes the Warne Power Plant, Pyramid Lake precedes the Castaic Power Plant, and Sherwood Lake comes before the Devil Canyon Power Plant. This allows for water to be pumped uphill during off-peak times, and then stored until it is released to generate power during peak times. Not only does this provide economic benefits because power during peak times can be sold at a higher price, it also helps to prevent blackouts by allowing for the pumps to be operated during off-peak times when the grid is unlikely to be overloaded. Because the grid mix varies depending on the time of day, the electricity consumed during off-peak times is also likely to have a different greenhouse gas footprint than the electricity that is displaced during peak times when the hydroelectric power plants are allowed to run at or near capacity. Unfortunately, developing a clear picture of exactly which fuels are being consumed and displaced by this practice involves significant modeling efforts. For perspective, however, the eGRID annual average $CO_2$ emission rate for the CAMX subregion (part of the WECC NERC region), which covers the majority of California, is 328 kg/MWh while the non-baseload emission rate is 491 kg/MWh. Non-baseload electricity is not always more carbon-intensive; in two of the three other WECC subregions, the annual average emission rates are higher than the non-baseload rates (*89*). It should also be noted that, while eGRID provides GHG emission factors for average and non-baseload mixes, it does not provide emission factors for baseload-only mixes. The SWP pumping plants operating during off-peak

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times do not consume the average grid mix, but rather a mix that is likely to be much heavier in coal, nuclear, and hydroelectricity from other parts of the WECC region.

The second issue is whether or not, by including the hydroelectric power generation within the SWP in net electricity consumption, this power is being double counted. In electric power databases, the SWP power plants may or may not be included as hydroelectricity in the general grid mix. If this is the case, including them in net electricity consumption calculations for the SWP would serve as double counting. Unfortunately, the commonly used eGRID database does include these power plants as part of its total hydroelectric power generation (*89*). However, the SWP power plants make up only approximately 1% of the approximately 1.72 x $10^8$ MWh/year of hydroelectricity generation that occurs within the WECC region NERC region (*89*). Hence, removing the SWP power generation from the WECC total would make a negligible difference in its GHG emission factors.

By proving that the “double counting” issue is essentially negligible from a GHG perspective, one is left only with the question of whether or not the SWP pumping plants and power plants should be treated as part of the same system, or as separate entities. For the purposes of this research, the SWP is assumed to be a single production system, with delivered freshwater as the primary product and hydroelectricity as a co-product. This is because the two are dependent on one another; the power plants cannot operate unless the pumping plants deliver water to the reservoirs that feed them, and the water cannot reach its destination without passing through the SWP hydroelectric power plants (although operators can choose to shut generators down if the power is not needed). Furthermore, if the amount of water conveyed increases, the amount of power generated will also increase. System expansion can then be used to allocate GHG emissions to the power produced by the SWP, leaving the remaining emissions to be allocated to the delivered freshwater. Because grid modeling is not performed to determine separate GHG emission factors for the off-peak power consumed by the pumping plants and the peak power displaced by the SWP power plants, the GHG footprint per unit of power consumed is equal to the GHG footprint per unit of power generated. Hence, using system expansion is equivalent to simply taking the net electricity consumption, and calculating its GHG footprint.

It is also important to note that the SWP does not have one destination for all of its water, but rather makes deliveries along the way via “branches”. Water that is delivered via the Coastal Branch and West Branch is assigned the impacts of pumping water down to those specific branches, and is kept separate from any pumping or power generation that occurs beyond the points of delivery.

The CRA is similar to the SWP in that it delivers water as its primary function. The MWD entitlement of Colorado River water is 678 million $m^3$/year, although it receives an average of 1.5 billion $m^3$/year through special arrangements and use of “surplus” water (*160*). In 2008, 1.1 billion $m^3$ were received (*188*). This is approximately half of the average amount delivered by the SWP. The aqueduct starts at Lake Havasu on the Colorado River and ends 389 km away at its terminal reservoir, Lake Matthews in the Los Angeles basin (*160*). The five pumping plants, shown in Figure 56 and Table 39, provide the power required to move the water from source to

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destination.  Transmission lines connect each of these plants to the Hoover Dam, which lies upstream of the CRA, as well as the Parker Power Plant.

Unlike the SWP, the hydroelectric power plants that provide energy to the CRA pumping plants generate power in excess of pumping needs, and are able to export the additional power to the grid.  This poses a different methodological question: should the CRA pumping plants be treated as using only hydroelectric power, and hence given a GHG footprint of essentially zero, or should be they assigned the average grid mix?  One could argue that, physically, the electrons do come from power generated at hydroelectric plants.  However, unlike the SWP, the power generated by the Hoover and Parker Dams is not directly related to the amount of water pumped along the CRA.  Additionally, if the dams operate at or near capacity, an increase in pumping will require power that would otherwise have been exported to the grid, thus resulting in a need for increased electricity generation from the grid as a whole.  For these reasons, CRA pumps are treated as separate from the hydroelectric plants that power them, and are assigned the average grid mix.

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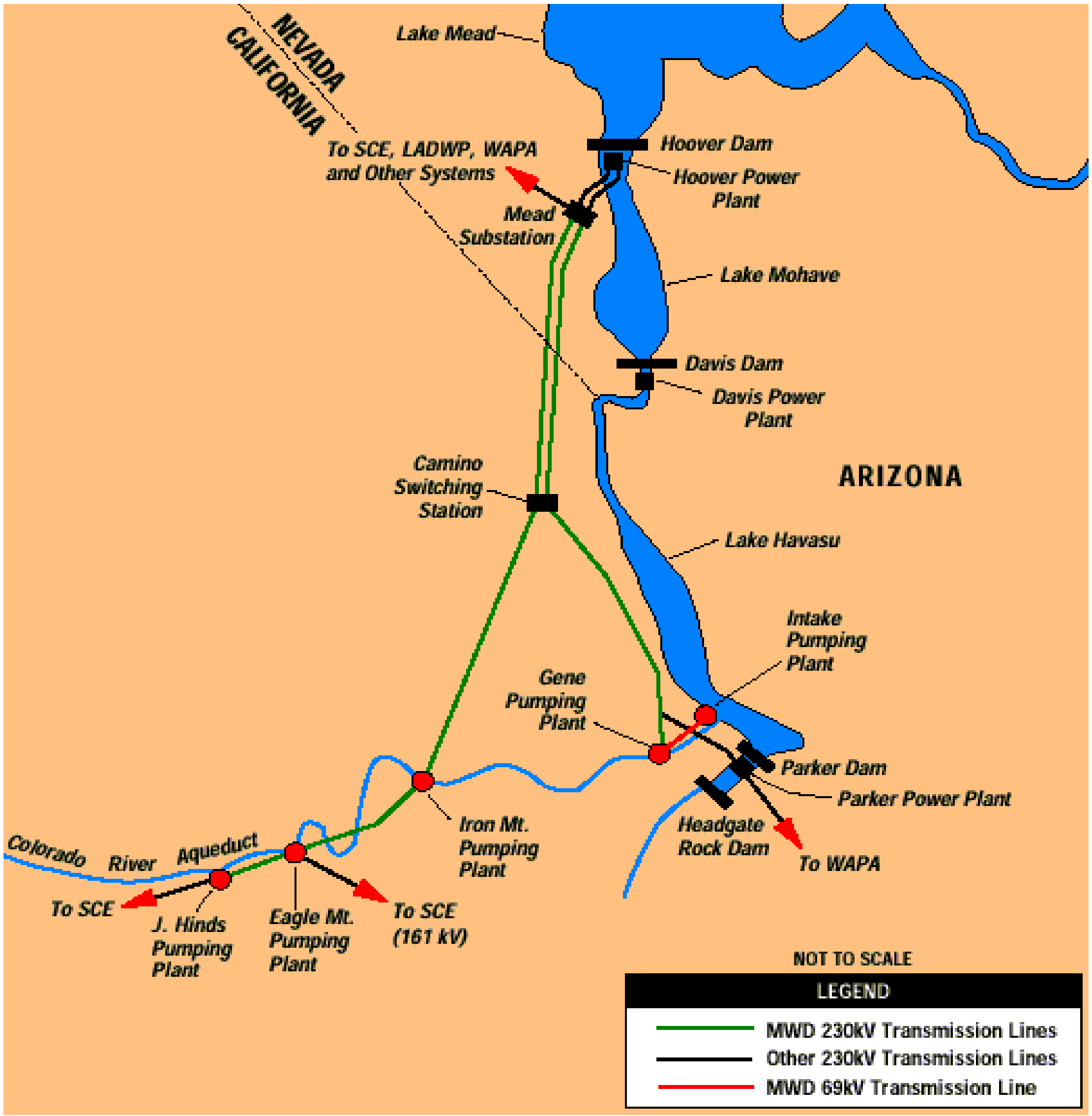

Figure 56: Colorado River Aqueduct and Nearby Infrastructure (Source: (*160*))

| Facility Name | Δ Elevation | Estimated Energy Use |
|---|---|---|
| Whitsett Pumping Plant | 88.7 m | 2.9E-01 kWh/$m^3$ |
| Gene Pumping Plant | 92.4 m | 3.0E-01 kWh/$m^3$ |
| Iron Mountain Pumping Plant | 43.9 m | 1.4E-01 kWh/$m^3$ |
| Eagle Mountain Pumping Plant | 134 m | 4.4E-01kWh/$m^3$ |
| Hinds Pumping Plant | 134 m | 4.4E-01 kWh/$m^3$ |

Table 39: Estimated Electricity Use of CRA Pumping Stations (Calculated from (*160*))

The ultimate goal of carefully analyzing the CRA and SWP is to develop accurate energy and GHG intensities for the imported freshwater used throughout California. The MWD, which manages water from the CRA and SWP, serves the six counties shown in Table 118 of Appendix D. However, it should be noted that the MWD does not supply each of these counties in their entirety. Table 119 of Appendix D shows the amount of total water use in each member agency that is supplied by MWD, and Table 120 of Appendix D shows the total for each county, assuming that each county receives water only from MWD member agencies. Finally, Table

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121 of Appendix D shows the calculated energy intensity for imported water within each of the six counties served by the MWD. The differences in SWP energy intensity are due to the fact that Los Angeles and Ventura counties are located on the West Branch, whereas the others are located farther south. Because the member agencies do not purchase water directly from the SWP or CRA, but rather from MWD (the organization that manages water from both projects), attempting to assign county-specific fractions of SWP and CRA water is a useless exercise. Hence, each county has been assigned the fractions that made up the total MWD supply in 2008: 47% from the CRA and 53% from the SWP, as shown in Table 122 of Appendix D.

As touched upon previously, irrigation water is managed by a variety of agencies, unlike municipal water from the CRA and SWP, which is managed exclusively by the MWD. This makes tracking the energy required to supply irrigation water to each county a more complicated task. Fortunately, reference (*175*) tracks energy requirements for delivery and application of irrigation water throughout California by collecting survey data. The analysis is performed based on modified evapotranspiration zones, referred to here as irrigation regions. The original evapotranspiration zones can be found in reference (*190*) and the modified regions are shown in Figure 69 of Appendix D. Because these boundaries are based on climate and soil characteristics, they have no connection to political boundaries. This research depends on county-level analyses, so the irrigation regions had to be mapped to counties. Table 122 of Appendix D lists the irrigation regions and the breakdown of freshwater sources for each one. Table 124 of Appendix D shows each county, along with each irrigation region that intersects it. For those counties that fall into multiple regions, a simple average is taken of the regions' energy-intensities.

Perhaps surprisingly, the most energy-intensive agricultural water is not that used in the southernmost part of the state, but rather the water used in the San Joaquin Valley. This is because the SWP, which requires pumps to move its water, supplies agricultural water in the San Joaquin Valley. In particular, pumps along the Delta Mendota Canal and California Aqueduct deliver much of California's agricultural water (*175*). Irrigation districts such as the Coachella Valley Water District, Imperial Irrigation District, Palo Verde Irrigation District, and Yuma project receive Colorado River water via a branch separate from the Colorado River Aqueduct, including the All American Canal and Coachella Canal (see Figure 57). This branch does not require significant net pumping energy. The most recent allocations of Colorado River water to these agricultural water agencies and the MWD are shown in Table 40. Smaller priority numbers refer to a higher priority. As shown in Figure 57, water allocated to the MWD will be diverted along the CRA, while water allocated to the listed irrigation districts will continue southward.

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Figure 57: Colorado River Water Supply (Source: (*191*))

| Priority Number | Agency | Allocation ($m^3$/year) |
|---|---|---|
| 1-3 | Palo Verde Irrigation District<br>Yuma Project<br>Imperial Irrigation District<br>Coachella Valley Water District | 4.75E+09 |
| 4 | MWD (including San Diego County/City) | 6.78E+08 |
| 5 | MWD (including San Diego County/City) | 8.17E+08 |
| Surplus Water Diversions | MWD (including San Diego County/City) | 2.22E+08 |

Table 40: Colorado River Water Allocation (Data Source: (*192*))

This background information should provide context for the energy intensities shown in Table 124 of Appendix D. It is clear that surface water, whether it is pumped locally by the irrigation district or imported, comes at a relatively small energy cost, while on-farm groundwater pumping is roughly an order of magnitude larger, making it the most energy-intensive water supply method. This is because, on average, groundwater must be pumped approximately 50 m to the surface (*175*), and on-farm pumps are typically smaller and less efficient than large groundwater pumps operated by the irrigation districts themselves.

## 5.2.3 Desalination

Regions that do not have access to sufficient freshwater resources do often have access to sea or saline water, as is the case in states such as California, Florida, and Texas. This makes desalination an attractive option because it eliminates the need to fight for limited freshwater

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resources and ensures a steady supply, regardless of climatic variations. Desalination is already utilized on a large scale in the Persian Gulf. At 18% of global capacity, Saudi Arabia is the world's leading producer of desalinated water, with its first plant having been built in 1938 (*166, 193*). The practice of desalination in the United States is growing and now makes up 17% of global capacity (*166*).

The five most common systems are reverse osmosis (RO) (46% of global capacity), multi-stage flash (MSF) (36% of global capacity), electrodialysis (ED) (5%), vapor compression (VC) (5%), and multi-effect distillation (MED) (3%) (*166*). RO uses a semi-permeable membrane through which water can travel, but dissolved salts cannot. By applying significant pressure to force freshwater through the membrane, 30-85% of the input water's volume can be recovered (*166*). Much like RO, ED uses a membrane to separate salts from freshwater. In this case, electrical currents move salt ions through the membrane. The remaining three processes rely on heat to separate water from salts through evaporation. MSF involves pumping the input water through a plant that is made up of a series of compartments, each kept at a different pressure and separated by heat exchangers. The water heats up as it is passed along the heat exchangers until it reaches a heater at the end. It is then sent back through the compartments, cooling down as it makes its way back. Each compartment is kept at the pressure corresponding to the boiling point of the water's temperature as it passes through, so freshwater is evaporated and captured in each compartment. MED is similar to, but simpler than MSF. The MED process passes input water through multiple compartments, using heat to evaporate water and then utilizing the steam that has been generated in each compartment as a supplementary heat source for subsequent compartments. Lastly, VC, also a thermal process, utilizes heat produced by compressed vapor for distillation, along with the latent heat of vapor that is released during condensation. For all of these desalination processes, energy makes up the largest single cost, averaging to 44% of total costs in a typical RO plant and 59% for thermal plants (*166*).

Because of the energy-intensity and high cost of desalination, the practice is only now becoming attractive in some of the most water-stressed areas of the United States. It is not uncommon for new plants to be halted in the planning phase, or be built only to remain idle or operate at a small fraction of total capacity. For this reason, it can be difficult to track actual desalination outputs at any given time and even more difficult to predict which of the many planned facilities will ultimately become successfully operating plants. The analysis here uses only plants that are fully constructed and confirmed to be operating, although projections for future desalination will be discussed in the following section.

There are two plants in the United States that are assumed to be fully operational at the current time: a brackish groundwater desalination plant in El Paso that produces 38 million $m^3$/year of water for both El Paso and Ft. Bliss, TX (*194*) (both located in El Paso County), and a seawater desalination plant in Tampa Bay, FL (Hillsborough County) that produces 35 million $m^3$ of water per year (*165*). Both plants use RO. Based on total public freshwater supply data from reference (*12*), it is estimated that the El Paso plant supplies 21% of the county's public water and the Tampa Bay plant provides 15% of its county's needs. In 2002, Proposition 50 provided

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funding for research, feasibility studies, and construction of desalination plants in CA. Despite this support, only one desalination plant is currently producing potable water; the Sand City brackish groundwater desalination facility began operating in May 2010 using RO. However, the Sand City plant produces only 370,000 $m^3$/year, which is an order of magnitude lower than the plants in FL and TX. A larger plant located in Carlsbad has received final approval from every required regulatory and permitting agency in the state, but won't be operating until 2012 (*195*). Meanwhile, some plants that used to be operable have shut down. The Marina Coast Water District plant produced water in the late 1990's, but has since been shut down due to high costs and lack of demand. Recent trends indicate that desalination has an uncertain future in the short term, but as communities grow beyond their local water resources' ability to support them, it will almost certainly play a significant role in the long term.

Reference (*16*) contains a thorough life-cycle inventory for RO desalination of seawater and brackish water based on case study data. Because RO is the only technology currently used in the United States, it is the only process analyzed in this research. Reference (*16*) presents case study data for both seawater desalination via RO using conventional pretreatment and membrane pretreatment. Here, only conventional pretreatment is shown rather than both because the distinction makes a minor difference (3% change in life-cycle GHG emissions). Conventional pretreatment involves flocculation and filtration, whereas membrane pretreatment passes feedwater through a membrane before filtration. Both pretreatment techniques are followed by RO and finally disinfection. The life-cycle inputs for desalination are shown in Table 41.

| **Input** | **Seawater w/ Conventional Pretreatment** | **Brackish Groundwater** | **GHG Intensity** |
|---|---|---|---|
| Water Supply: Electricity | 0.38 kWh/$m^3$ | 0.26 kWh/$m^3$ | Depends on NERC Region |
| Desalination: Acid (Assumed to be $H_2SO_4$) | 81 g/$m^3$ | 65 g/$m^3$ | 0.45 $gCO_2e$/g chemical |
| Desalination: Aqueous Ammonia | 8 g/$m^3$ | 13 g/$m^3$ | 2.9 $gCO_2e$/g chemical |
| Desalination: Calcium Carbonate | 26 g/$m^3$ | N/A | 0.011 $gCO_2e$/g chemical |
| Desalination: Caustic Soda | N/A | 17 g/$m^3$ | 4.3 $gCO_2e$/g chemical |
| Desalination: Carbon Dioxide | 26 g/$m^3$ | N/A | 0.92 $gCO_2e$/g chemical |
| Desalination: Ferric Chloride | 18 g/$m^3$ | N/A | 0.20 $gCO_2e$/g chemical |
| Desalination: Sodium Hypochlorite | 6 g/$m^3$ | 11 g/$m^3$ | 0.030 $gCO_2e$/g chemical |
| Desalination: Other Chemicals | 8.2 g/$m^3$ | 3 g/$m^3$ | 0.87 $gCO_2e$/g chemical* |
| Desalination: Electricity | 4.1 kWh/$m^3$ | 2.4 kWh/$m^3$ | Depends on NERC Region |
| Distribution: Electricity | 0.72 kWh/$m^3$ | 0.22 kWh/$m^3$ | Depends on NERC Region |

Table 41: Life-Cycle Inputs for Desalination (Data Sources: (*16, 150, 196*))

*Calculated as an average of the carbon intensity of all other input chemicals

One variable yet to be discussed is the co-location of desalination plants with power plants. There are two reasons for desalination plants to be placed in close proximity to power plants; the first is for RO plants that can benefit by sharing the power plant's cooling water intake and discharge systems (*197*), and the second is for thermal desalination plants that can benefit from power plants' waste heat (*198*). The former has been done in the United States because of its ability to reduce costs. Typically, RO plants are co-located with coastal power plants using seawater in once-through cooling systems. The desalination plant captures a fraction of the power plant's discharged cooling water, which is desalinated to produce potable water. The resulting waste brine is then disposed of through the power plant's cooling water discharge

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canal, thus diluting it prior to reaching the ocean. This process not only makes facility permitting easier, it also reduces construction costs because separate intake and discharge structures are not needed (*197*). However, this type of power plant co-location should not make a major difference in energy consumption or GHG emissions; the only possible difference could be a slight improvement in pumping efficiency due to the use of larger pumps. The use of power plant waste steam to run turbines that in turn power the high pressure feed pumps for RO plants has been considered by the San Diego County Water Authority in the past, but due to technical and cost issues, was never implemented (*199*).

In contrast, co-locating thermal desalination plants with power plants has a significant impact on the overall efficiency and carbon-intensity (*198*). MSF, MED, and VC all require heat sources to operate, and can benefit from being placed near power generating facilities by utilizing the waste heat. This is common practice in Saudi Arabia and other Gulf nations, and makes thermal processes, which are otherwise less efficient than RO, less energy- and carbon-intensive than RO (*200*). Reference (*200*) explores the institutional and policy barriers that have prevented this practice from occurring in the United States and acknowledges that it has potential in the future. Because thermal processes are not utilized for public freshwater production in the United States, the impact of power plant co-location is not explored further in this dissertation, but should be accounted for in any future studies of thermal desalination plants.

There is one final complication involved in the assessment of desalination plants. It is well known that any desalination process is significantly more energy-intensive than local water, or even existing long-distance conveyance projects. To offset this energy use, there is a push to install on-site renewable energy sources such as solar panels or wind turbines (*166*). While cost prevents this from being a common practice in the United States for the present time, potential future carbon cap-and-trade systems or other regulations could incentivize utilities to install on-site renewable generation. The relationship between these renewables and desalination plants is similar to that of SWP water deliveries and the hydroelectric power that it generates. Because the wind or solar generators would not exist without the desalination plant, they should not be treated as separate facilities. However, because wind and solar are intermittent and unpredictable, the desalination plant will inevitably rely on grid power as well, even if its net consumption is zero or it is a net electricity producer. To determine the actual GHG emissions resulting from a joint desalination and wind/solar power facility, it is necessary to compare the electricity mix that is displaced by the wind/solar generator(s) during times when power is exported to the grid mix that is consumed during times when consumption exceeds generation.

### 5.2.4 Wastewater Recycling

Recycled wastewater, also known as reclaimed water, refers to wastewater that is treated for reuse in non-potable applications such as irrigation, commercial, and industrial activities. Recycled water can also be used for environmental restoration. Treated wastewater in Orange County, CA is injected into the underground aquifer there to prevent saltwater intrusion; this qualifies as indirect potable reuse because the underground aquifer also serves as a source for

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potable water. In total, 6.4 m$^3$ of wastewater are recycled per day in the United States, with Florida recycling the most, followed by California, Texas, and Arizona; water reuse programs are also growing in Nevada, Colorado, Georgia, North Carolina, Virginia, and Washington (*135*).

Municipal wastewater is not recycled for direct potable use in the United States because current treatment technologies are not guaranteed to remove pathogens, hormones, and other trace chemicals that can be present. According to reference (*16*), the most striking differences between wastewater recycling and typical surface water treatment to potable standards are in the volume of chemicals required and the electricity required for distribution. The inputs for recycled wastewater are shown in Table 42.

| Input | Recycled Wastewater | GHG Intensity |
|---|---|---|
| Wastewater Supply: Electricity | 0.45 kWh/m$^3$ | Depends on NERC Region |
| Recycling: Alum | 53 g/m$^3$ | 0.31 gCO$_2$e/g chemical |
| Recycling: Chlorine | 19 g/m$^3$ | 1.4 gCO$_2$e/g chemical |
| Recycling: Other Chemicals | 4 g/m$^3$ | 0.87 gCO$_2$e/g chemical* |
| Recycling: Electricity | 0.19 kWh/m$^3$ | Depends on NERC Region |
| Distribution: Electricity | 1.5 kWh/m$^3$ | Depends on NERC Region |

*Calculated as an average of the carbon intensity of all other input chemicals

Table 42: Life-Cycle Inputs for Wastewater Recycling (Data Source: (*16*))

### 5.2.5 Consequential vs. Attributional: Origin of the Marginal Unit of Water

It has been emphasized that this research takes a consequential approach in its analysis. In some cases, the distinction is unnecessary, but it would be irresponsible not to acknowledge that the marginal unit of water is almost certainly not equal to the average unit of water used. The factors that govern how additional water needs will be met include operating costs, political decisions (such as MWD's preferential water allocations), and resource availability due to climatic changes. These factors are often difficult to predict, and hence accurately determining the source of marginal water units in each county is a challenge. Additionally, the sources change depending on whether the water is being used for industrial, municipal, or agricultural purposes, as well as the time of year during which the water is needed.

Difficulties aside, it is possible to gain some understanding of the origin of a marginal unit of water by using available data. Table 125 in Appendix D and Figure 58 show the fraction of each MWD member agency's preferential supply that was used in fiscal year 1998-1999. While clearly it is possible to consume more than what is promised, provided that other agencies do not use their maximum allowable water, agencies that use almost all or more than their allowances will likely not be able to increase their imported supply significantly. This is an instance where the distinction between marginal and incremental becomes important as well. Adding one biorefinery to a county such as San Bernadino that uses close to its full allotment may result in an increase in imports from MWD, but adding ten biorefineries may require that other water sources be explored, such as desalinated seawater or recycled wastewater. In counties where importation and local supplies cannot support additional demand, the marginal unit of water is likely to come from desalinated brackish groundwater, desalinated seawater, or recycled wastewater (for non-potable uses). Additionally, counties may seek to become more

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independent, and will thus opt for more expensive water supplies in an effort to reduce imports; San Diego county is aiming to significantly reduce water imports by 2020 in favor of increased conservation measures and desalination (*201*). By identifying counties that have considered, or are successfully pursuing desalination or water reclamation projects, these locations can be flagged as potentially having energy-intensive marginal units of freshwater supply. Regardless of whether the projects are successful in the short term, their consideration indicates that local resources (and existing importation, if any) cannot meet the community's needs. According to reference (*166*), twenty one desalination projects have been considered in California alone, although only one of those is actually operating now.

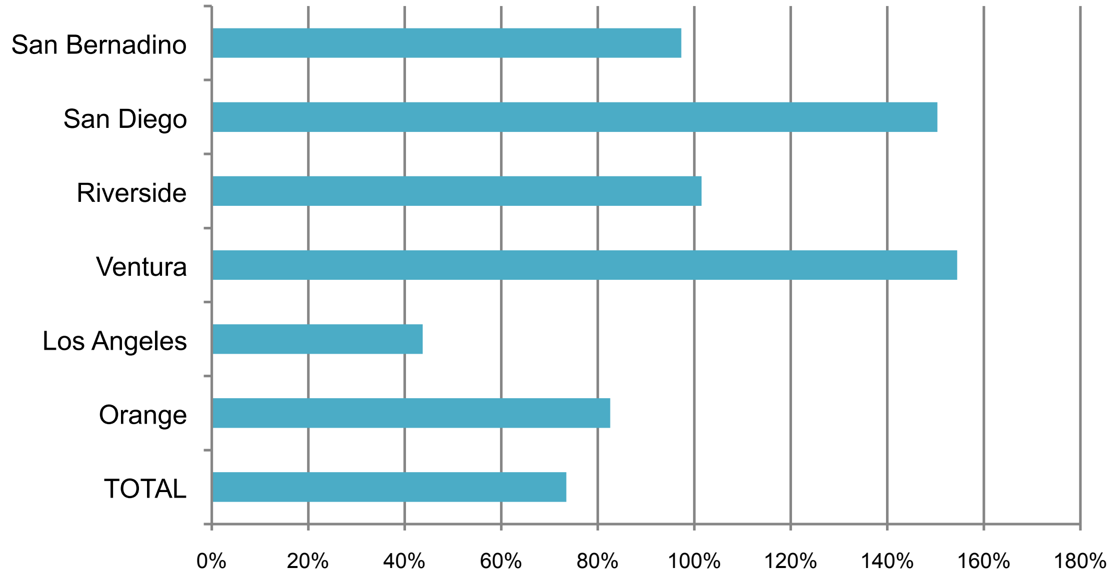

Figure 58: Utilization of MWD Preferential Supply (Data Source: (*202*))

One important factor that has yet to be discussed is the possibility that total water use in some counties may decrease over time. Water use in the United States peaked in 1980 at 600 km$^3$ per year and has decreased, despite predictions that total water use would as much as triple between 1980 and 2000 (*201*). In counties where, even after taking on a new power plant, biorefinery, or other water-consuming facility, the total water use decreases, calculating the marginal source freshwater can be more challenging. As a general rule, it is reasonable to assume that the most expensive water sources will always lie at the margin. If a new biorefinery is built and the county's water use is simultaneously reduced, the marginal unit of water used by the biorefinery should be attributed to whatever source would have otherwise been reduced, and that decision is likely dependent on cost.

In the absence of better information, cost of water supply options can serve as an indicator of which sources are likely to be at the margin, it is useful to compare the average costs of each technology (local surface water, local groundwater, imported water, desalinated brackish groundwater or seawater, and recycled wastewater). Table 43 implies that even the most energy-intensive imported water is still preferable to desalination and wastewater recycling

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from a cost perspective. Thus, water imports will likely be used as much as possible before turning to wastewater recycling or brackish groundwater desalination, and finally seawater desalination. However, importation raises water rights issues that are not problematic for seawater, brackish water, or recycled water, so the amount that can be feasibly imported may change over time depending on the associated legal activities.

| Process | Facility Location | Total Cost | Data Source |
|---|---|---|---|
| Brackish Groundwater: RO | El Paso, TX | 0.43 $\$/m^3$ | (*201*) |
| Seawater: RO | Tampa Bay, FL | 0.67 $\$/m^3$ | (*166*) |
| Seawater: RO | Carlsbad, CA | 0.77 $\$/m^3$ | (*166*) |
| Seawater: RO | Moss Landing, CA | 0.96 $\$/m^3$ | (*166*) |
| Importation: State Water Project | CA | 0.24 $\$/m^3$ | (*188, 189, 203*) |
| Wastewater Recycling | N/A | 0.49 $\$/m^3$ | (*204*) |

Table 43: Alternative Water Supply Cost Data

## 5.3 Treatment

After freshwater is delivered to the community or facility that will use it, the water often requires treatment before it is useable. Water is used for many different purposes, including cooling systems, boilers, domestic activities such as toilet flushing and drinking, irrigation, and a host of others. Accordingly, there are many different ways in which water can be treated in order to achieve the quality necessary for such a wide variety of activities.

### 5.3.1 Municipal Water Treatment

With the exception of recycled wastewater that is suitable for irrigation and other non-potable uses, all water supplied by public utilities is treated to potable standards. This is often cited as wasteful, considering the majority of domestic water is not used for purposes that require it to be drinkable (*172*). There are multiple options for treating fresh water to potable standards. The main distinction is between surface and groundwater treatment plants. Groundwater undergoes some natural purification as it makes its way through soil; the soil serves as a filter as well as a carbon source that can adsorb contaminants. Assuming the underground aquifer has not become contaminated in some way (by underground storage tank leaks, for example), it requires minimal treatment. Most groundwater requires only filtration and disinfection (*170*). Conversely, surface water is typically less clean than groundwater and must therefore undergo more extensive treatment. Figure 59 shows the process flow diagram for a typical municipal surface water treatment plant. More solids are present in surface water, so coagulants must be used to form larger particles that will settle in sedimentation tanks before the water can be filtered and disinfected (typically with chlorine, although ultraviolet radiation is also effective).

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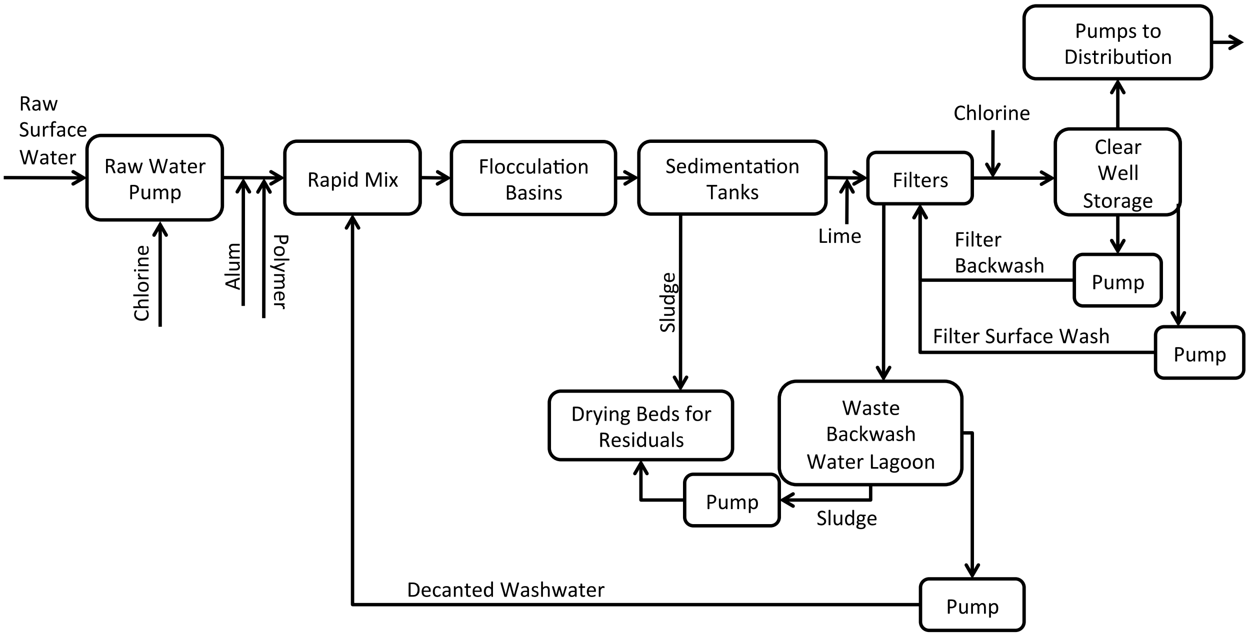

Figure 59: Typical Municipal Surface Water Treatment Plant (Adapted from (*170*))

Of the energy required directly by the treatment plant, 97% goes to powering pumps, of which 85% powers the high-service pumps that feed into the distribution network (*170*). As shown in Figure 59, there are also chemical inputs that have a GHG footprint. Table 44 summarizes the chemical and energy inputs for municipal supply of groundwater, surface water, desalinated brackish or seawater, as well as recycled wastewater. The table also shows the GHG-intensity of each input. The GHG-intensity of electricity is dependent on which NERC region the supply and treatment infrastructure is located in.

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| **Inputs** | **Surface Water (g/m$^3$)** | **Groundwater (g/m$^3$)** | **Brackish Groundwater (g/m$^3$)** | **Seawater (g/m$^3$)** | **Recycled Wastewater (g/m$^3$)** | **GWP (g/g chemical)** |
|---|---|---|---|---|---|---|
| Alum | 3.5E-01 | N/A | N/A | N/A | 5.3E+01 | 3.1E-01 |
| Aqueous Ammonia | 8.4E-01 | N/A | 1.3E+01 | 8.0E+00 | N/A | 2.9E+00 |
| Calcium Carbonate | N/A | N/A | N/A | 2.6E+01 | N/A | 1.1E-02 |
| Caustic Soda | 3.3E+00 | N/A | 1.7E+01 | N/A | N/A | 4.3E+00 |
| Chlorine | 5.3E+00 | 5.3E+00 | N/A | N/A | 1.9E+01 | 1.4E+00 |
| $CO_2$ | N/A | N/A | N/A | 2.6E+01 | N/A | 9.2E-01 |
| Ferric Chloride | 4.0E+00 | N/A | N/A | 1.8E+01 | N/A | 2.0E-01 |
| Sodium Hypochlorite | 1.9E+00 | N/A | 1.1E+01 | 6.0E+00 | N/A | 3.0E-02 |
| Sulfuric Acid | N/A | N/A | 6.5E+01 | 8.1E+01 | 0.0E+00 | 4.5E-01 |
| Other | 2.8E+00 | N/A | 3.0E+00 | 8.2E+00 | 4.0E+00 | 1.5E+00 |
| Electricity (kWh/m$^3$) | 7.1E-01 | 1.5E+00 | 2.9E+00 | 5.2E+00 | 2.1E+00 | Depends on Location |
| Data Source: | (*16, 170*) | (*170*) | (*16*) | (*16*) | (*16*) | (*150*) |

Table 44: Municipal Water Supply Energy and Chemical Inputs

### 5.3.2 Industrial Process Water

Industrial process water is a broad category that includes essentially any industrial water that is not used as cooling water or boiler feed water (BFW). As shown in Figure 54, the majority of industrial water is self-supplied rather than purchased from a municipal utility. By self-supplying water, facilities can cut costs by only performing the treatment necessary to meet their specific needs. The quality requirements for industrial process water vary widely depending on how the water is used. For example, water used in semiconductor manufacturing goes through a rigorous purification process including vacuum distillation to ensure that it does not contaminate the otherwise highly pure silicon (*120*). This water is far purer than typical municipal drinking water, which contains minerals, chlorine, and often fluoride. Other industrial process water can be far below potable standards; some industries are capable of using reclaimed municipal wastewater (*205*).

The energy and resulting GHG footprint of industrial water treatment is rarely explored for two reasons: first, the required treatment is difficult to generalize because it is so process-specific and second, the energy and emissions associated with industrial water treatment are typically included in the facility’s overall energy use and emissions reporting, so it is already included in most LCAs. Ultimately, there is value in understanding the full GHG footprint of water use, including industrial water treatment, because it helps decision makers understand the climate change implications of increasing or decreasing water used for a particular process. However,

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because the goal of this dissertation is to quantify the water-related GHG emissions not already included in the overall transportation fuel GHG footprints, industrial process water is not included except in cases where the treatment occurs offsite.

### 5.3.3 Boiler Feed Water and Cooling Water

Boiler feed water (BFW) and cooling water are more consistent in their quality requirements than industrial process water, and are not as stringent as most industrial process water or municipal water. In fact, recycled wastewater can be used for cooling purposes, as is proposed for a new MSW/woody biomass biorefinery in Pontotoc, MS (*206*). The main concern for BFW and cooling water is mineral content because these substances can precipitate on surfaces, ruining their heat transfer properties (*31*). To prevent this from happening in boilers, a small amount of BFW chemicals are added (*86*). For cooling water, the relevance of mineral content depends on the type of cooling system. It makes no difference in open-loop systems, and in fact, seawater or brackish water can be used in open-loop cooling systems because the salt and mineral concentrations never become high enough to be problematic (*31*). For closed-loop systems, this is not the case because, as freshwater evaporates to carry away waste heat, the concentration of contaminants increases. As discussed in Chapter 3, operators mitigate this problem by periodically purging the concentrated water, presumably because it is a more cost-effective method than treating the cooling water before it enters the system.

## 5.4 Results

Table 45 compiles data presented in the previous sections, separated by water source (local surface, local ground, brackish ground, seawater, and recycled wastewater) and ultimate function (public supply, industrial, oil extraction, and power generation). For power generation and oil extraction, the treatment requirements for seawater and brackish water are listed as zero. This is because on offshore platforms, where seawater is used exclusively for oil extraction, no desalination is required; the seawater is injected directly into the well. For power generation, a distinction must be made between open and closed-loop cooling systems. Currently, sea and brackish water are only used for open-loop cooling systems and require no treatment aside from basic filtration of the intake water, as discussed in Section 5.3.3. However, if these sources were to be used for closed-loop cooling, treatment would be necessary.

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| Function | Source | MJ Electricity/L | MJ Natural Gas/L | g $CO_2$ Embodied in Chemicals/L | g $CH_4$ Embodied in Chemicals/L | g $N_2O$ Embodied in Chemicals/L |
|---|---|---|---|---|---|---|
| Public Supply | Local Surface Water | 2.5E-03 | N/A | 1.8E-02 | 5.0E-04 | N/A |
| | Local Groundwater | 2.5E-03 | N/A | 4.4E-03 | 1.3E-04 | N/A |
| | Brackish Groundwater | 1.0E-02 | N/A | 8.9E-02 | 2.5E-03 | N/A |
| | Seawater | 1.9E-02 | N/A | 5.7E-02 | 1.6E-03 | N/A |
| | Recycled Wastewater | 7.7E-03 | N/A | 2.8E-02 | 8.0E-04 | N/A |
| Industrial | Local Surface Water | 2.2E-05 | N/A | N/A | N/A | N/A |
| | Local Groundwater | 5.1E-05 | N/A | N/A | N/A | N/A |
| | Brackish Groundwater | 9.6E-03 | N/A | 8.9E-02 | 2.5E-03 | N/A |
| | Seawater | 1.6E-02 | 0.0E+00 | 5.7E-02 | 1.6E-03 | N/A |
| | Recycled Wastewater | 2.3E-03 | N/A | 2.8E-02 | 8.0E-04 | N/A |
| Oil Extraction | Local Surface Water | N/A | 7.6E-05 | N/A | N/A | N/A |
| | Local Groundwater | N/A | 1.8E-04 | N/A | N/A | N/A |
| | Brackish Groundwater | N/A | 1.8E-04 | N/A | N/A | N/A |
| | Seawater | N/A | 7.6E-05 | N/A | N/A | N/A |
| | Recycled Wastewater | 2.3E-03 | N/A | 2.8E-02 | 8.0E-04 | N/A |
| Power Generation | Local Surface Water | 2.2E-05 | N/A | N/A | N/A | N/A |
| | Local Groundwater | 5.9E-05 | N/A | N/A | N/A | N/A |
| | Brackish Groundwater | 5.9E-05 | N/A | N/A | N/A | N/A |
| | Seawater | 2.2E-05 | N/A | N/A | N/A | N/A |
| | Recycled Wastewater | 2.3E-03 | N/A | 2.8E-02 | 8.0E-04 | N/A |

Table 45: Energy and GHG-Intensity of Water by Sector and Source

Combining the data in Table 45 with county-level data on water sources for different sectors (shown in Appendix D) yields the national average GHG-intensity numbers for water used over the life cycle of transportation fuels shown in Table 47. For comparison, the overall GHG footprints of transportation fuels, not including water-related emissions, are shown in Table 47 as well. The baseline GHG footprints for corn stover and Miscanthus (assumed to be sufficiently similar to switchgrass) were adjusted to use system expansion allocation for the electricity co-product, as shown in Table 47. The average GHG contribution from water use is

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very small compared to the overall footprint. This is because most water in the United States comes from local freshwater sources. The total GHG emissions resulting from supply of freshwater for each fuel pathway are shown in Figure 60. However, as Table 47 shows, if the industrial, mining/extraction, and closed-loop cooling water were to come from desalinated seawater, brackish groundwater, recycled wastewater, or imported sources, as would be the case in some parts of the country, the contribution becomes more substantial. For the time being, it is assumed that irrigation water for corn would not come from alternative sources, although doing so would result in a very large water-related GHG contribution. Figure 61 shows the overall GHG footprint for each fuel and the range in contribution from water-related emissions, with desalinated seawater being the extreme case. For cellulosic ethanol, because a large portion of the water required is industrial, the contribution is substantial, resulting in a 23% increase in the GHG footprint of corn stover and a 47% increase for Miscanthus. This should be taken into account when considering construction of biorefineries in water-stressed areas that already rely on desalinated water such as Texas, Florida, and California.

| **GHG-Intensity** | **Switchgrass** | **Corn Stover** |
|---|---|---|
| Reported Results: g CO2 / L EtOH | 229 | 185 |
| Reported Results: g N2O / L EtOH | 0.828 | 0.443 |
| Reported Results: g CH4 / L EtOH | 0.652 | 0.565 |
| Pre-System Expansion: g CO2e/MJ EtOH | 20.7 | 14.0 |
| Electricity Co-Product (MJ/MJ EtOH) | 0.124 | 0.124 |
| Final Results (g CO2e/MJ Fuel) | -4.64 | -11.4 |

Table 46: Adjustment of Reference (*207*) Results Using System Expansion

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| **Fuel Pathway** | **Baseline GHG Emissions (g $CO_2e$/km Traveled)** | **Nat'l Avg Water-Related Contribution (g $CO_2e$/km Traveled)** | **Desalinated Seawater (g $CO_2e$/km Traveled)** | **Desalinated Brackish Groundwater (g $CO_2e$/km Traveled)** | **Recycled Wastewater (g $CO_2e$/km Traveled)** | **CA Imported Surface Water (g $CO_2e$/km Traveled)** |
|---|---|---|---|---|---|---|
| Gasoline from Crude Oil | 383 | 0.014 | 1.69 | 1.06 | 0.270 | 0.705 |
| Gasoline from Oil Sands | 389 | 0.015 | 1.82 | 1.14 | 0.290 | 0.724 |
| Corn Grain Ethanol | 379 | 0.381 | 6.29 | 4.06 | 1.28 | 2.68 |
| Corn Stover Ethanol | -45.7 | 0.011 | 10.5 | 6.54 | 1.60 | 4.06 |
| Miscanthus Ethanol | -18.5 | 0.008 | 8.63 | 5.37 | 1.32 | 3.30 |
| NG-Fired Power Plant w/ Closed-Loop Cooling | 143 | 0.002 | 2.03 | 1.28 | 0.318 | 0.905 |
| Coal-Fired Power Plant w/ Closed-Loop Cooling | 228 | 0.003 | 2.35 | 1.46 | 0.363 | 0.926 |

Table 47: Contribution of Water-Related GHG Emissions to Overall Footprint (Baseline Emissions from (*207-210*))

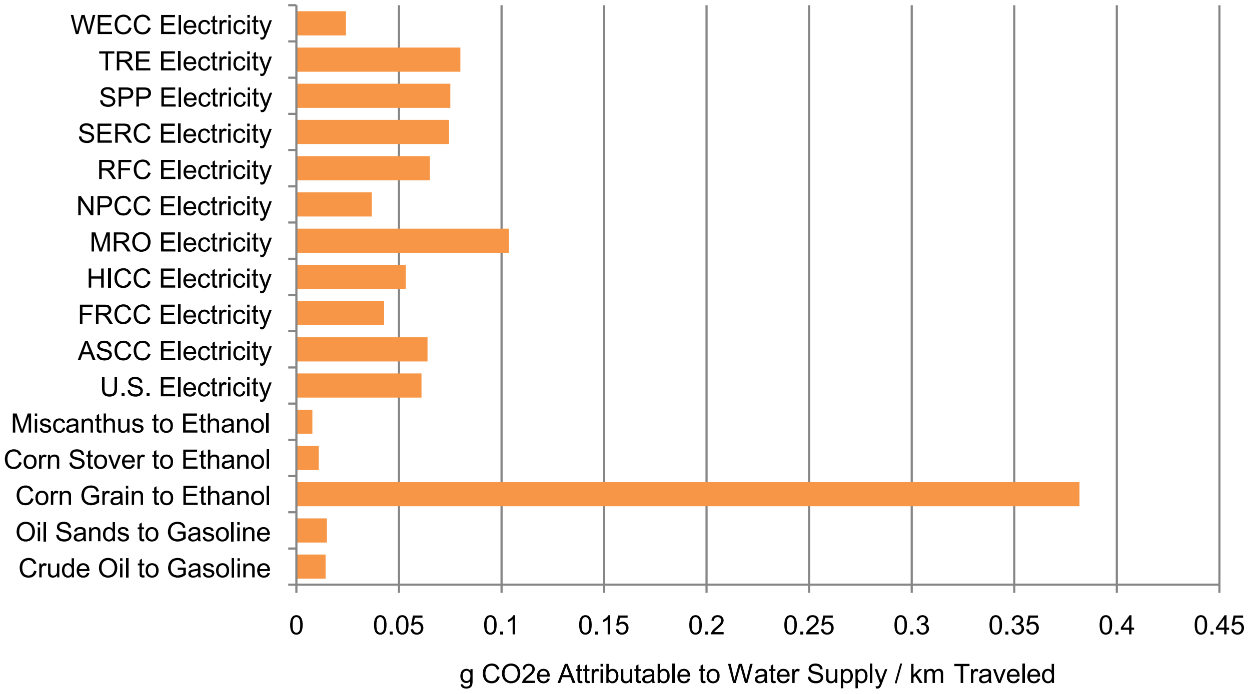

Figure 60: GHG Emissions Resulting from Freshwater Supply

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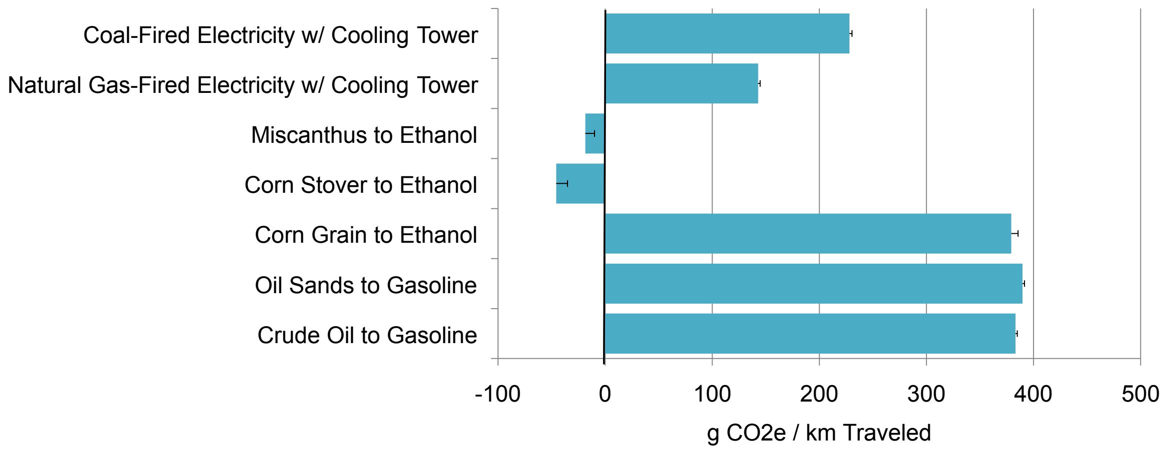

Figure 61: Water-Related GHG Contribution to Transportation Fuel GHG Footprints

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# 6. Discussion of Results

## 6.1 Inventory, Impact Assessment, and Greenhouse Gas Results

By performing a life-cycle inventory of water withdrawals and consumption, the results produced in this dissertation are more complete than those that only include direct water use (often only reporting consumption or withdrawals) for each life-cycle phase. Including indirect effects provides a clearer picture of how increasing (or decreasing) production of a particular transportation fuel will impact total U.S. water use. However, modeling indirect water use in addition to the direct impacts is time and labor-intensive, so the ultimate question is: does the inclusion of indirect water use significantly change the results?

Table 48 shows how the results change when indirect impacts are included. Both consumption and withdrawals are shown, where withdrawals are equal to the amount of water that is temporarily or permanently removed from its source and consumption is the fraction of withdrawn water that is lost through evaporation or otherwise not immediately returned to its source. For liquid fuels, the indirect impacts cause major changes in the total withdrawals, some resulting in a net decrease and others causing a net increase. Conversely, indirect water use has more of an impact on total consumption for electricity generation than for withdrawals.

| Fuel Pathway | Consumption | Withdrawals |
|---|---|---|
| Crude Oil to Gasoline | +19% | +60% |
| Oil Sands to Gasoline | +26% | +82% |
| Corn Stover to Ethanol | +33% | -199% |
| Miscanthus to Ethanol | +28% | -250% |
| Corn Grain to Ethanol | +3% | +19% |
| Electricity: U.S. Average Mix | +17% | +11% |
| Electricity: ASCC NERC Region | +21% | +14% |
| Electricity: FRCC NERC Region | +18% | +12% |
| Electricity: HICC NERC Region | +19% | +12% |
| Electricity: MRO NERC Region | +18% | +10% |
| Electricity: NPCC NERC Region | +21% | +12% |
| Electricity: RFC NERC Region | +16% | +11% |
| Electricity: SERC NERC Region | +17% | +10% |
| Electricity: SPP NERC Region | +16% | +11% |
| Electricity: TRE NERC Region | +22% | +17% |
| Electricity: WECC NERC Region | +16% | +11% |

Table 48: Percent Change in Results Due to Inclusion of Indirect Water Use

The results from Table 48 are best explained by breaking down each water footprint into direct and major indirect contributors, as shown in Figure 62. It is clear from the results in Figure 62 that the changes in total withdrawals are largely due to the inclusion of electricity (indicated by the red bars); the consumption of electricity results in a significant increase and the displacement of electricity through exports to the grid (as is the case for cellulosic ethanol production) results in a significant decrease in withdrawals. In fact, the Miscanthus to ethanol

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and corn stover to ethanol pathways displace so much electricity that their net withdrawals are negative. So far, no other comparable study has pointed out this displacement effect.

Chemical manufacturing also contributes significantly to total withdrawals for biofuel production, another effect that has never been quantified. Unlike petroleum fuel and electricity production, which use minimal amounts of chemicals, agriculture and biorefining require large quantities of fertilizers, pesticides, herbicides, enzymes, acid, and other substances (*69, 86, 145, 147*). According to reference (*119*), the water recycling rate in the chemical manufacturing industry is low (28% on average), which translates to high withdrawals.

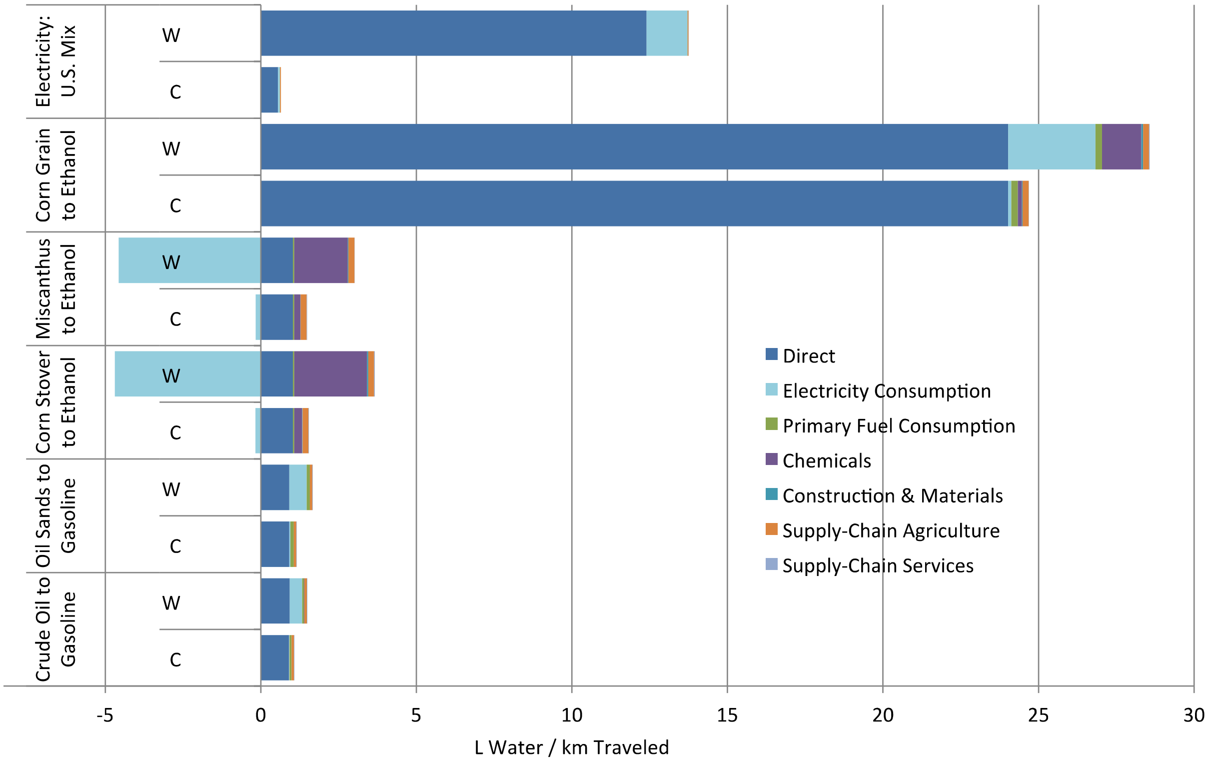

Figure 62: Life-Cycle Water Use for Transportation Fuel Production by Major Contributor

More important than the volumes of water used for each fuel production pathway is the resulting impact. This dissertation postulates that there are two main impacts associated with anthropogenic freshwater use: water resource depletion and GHG emissions. The former occurs when water resources are consumed at a rate greater than natural cycles can replenish them. The depletion may occur from pumping underground aquifers at a higher rate than they are naturally recharged, from diversion or consumption of surface water, or planting crops with a much greater evapotranspiration rate than naturally occurring vegetation. All of these water uses can result in a redistribution of freshwater resources that is likely to be unfavorable given that communities already unable to meet their needs with local freshwater are typically the same communities that experience net losses. If left unchecked, any population has the potential to grow beyond its available water resources. However, some regions are closer to exceeding their means than others. Figure 6 and Figure 7 serve to identify which parts of the

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country are at risk of experiencing surface or groundwater shortages, respectively. As this local depletion occurs, there are two options: the residents of communities that no longer have the local freshwater resources to support themselves can relocate to water water-rich regions or the communities can choose to supply freshwater through more energy-intensive means such as desalination, importation, and wastewater recycling. These methods can result in more than a three-fold increase in total GHG emissions per unit of water delivered (*16*).

The climate impacts associated with freshwater use are a result of GHG emissions from pumping and treating water for use in agriculture, industry, commercial facilities, and homes. The average GHG-intensity of freshwater supply in the United States is currently relatively low (see Figure 60), but the marginal unit of water in areas where desalination, importation, and wastewater recycling are taking place is likely to be much higher. California currently possesses the only large-scale, non-gravity-driven importation projects, but other technologies are present in a number of states (*160*). Florida contains the most installed desalination capacity at 2 million $m^3$/day, followed by California at approximately 0.9 million $m^3$/day, and Arizona and Texas with 0.5 million $m^3$/day each (*166*).

With these regional differences in mind, geospatial disaggregation of the life-cycle water use inventory serves two purposes: first, it allows for decision makers to identify areas where increased production of a particular transportation fuel may exacerbate surface or groundwater shortages and second, it serves to identify areas where high water use may have a large GHG footprint (in locations where desalination or importation are necessary, for example). The life-cycle water consumption and withdrawals for each fuel pathway as mapped to counties in the United States are shown in Figure 37 through Figure 48. Using these maps, combined with information from Chapters 4 and 5 regarding water resource vulnerability and GHG-intensity of water supplies, key areas of concern can be identified for each fuel production pathway.

### 6.1.1 Key Areas of Concern: Crude Oil to Gasoline

Based on the county-level analysis presented in Chapter 4, water use for gasoline production from crude oil is concentrated in three main locations: Southern California, Southeastern Texas, and Northern Alaska. Southern California is known to be a water-stressed region, relying heavily on importation and beginning to install desalination capacity. Southern California also has overpumped its groundwater resources, as clearly shown in Figure 35. From a surface water perspective, Figure 6 indicates that the region has spent between 10 and 15% of the previous 100 years in either severe, extreme, or exceptional drought, and Figure 34 predicts that Southern California will be subject to long-term drought conditions in the future.

Northern Alaska and Southeastern Texas are of less concern than California. By every indication, Alaska is not expected to experience shortages of ground or surface water, although groundwater monitoring does not appear to be particularly active judging by the small number of wells shown in Figure 35, so it is possible that groundwater levels are dropping, but have not been sufficiently measured. Southeastern Texas is shown as having only spent between 5 and 10% of the past 100 years in serious drought conditions according to Figure 6. Figure 34 indicates that water availability will actually improve in the long term for that area. However,

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Figure 35 indicates that groundwater levels have dropped. It should be noted that seawater has the potential to be used as injection water at some sites, although this may be technology and location-dependent (*5*). Seawater is already used for injection in offshore oil wells and could be pumped to onshore locations that are near the coast if local freshwater becomes too scarce.

### 6.1.2 Key Areas of Concern: Oil Sands to Gasoline

A large fraction of the water used for the oil sands-to-gasoline pathway is taken from outside the United States since all oil sands analyzed in this dissertation come from the Athabasca region of Canada. Although this does pose water availability concerns, it is outside the geospatial scope of this dissertation (*211*). Having excluded the water footprint of extraction, the water use for this pathway is essentially equal to that of the refining process. Unsurprisingly, a significant amount of refining capacity exists near crude oil extraction sites, so Southern California again emerges as bearing a portion of the water impacts. See Section 6.1.1 for concerns related to this region.

Wyoming, Montana, Kansas, Washington, and Illinois also contain refining capacity as shown in Figure 39. Of these states, Wyoming is by far of most concern. While groundwater monitoring in the state appears to be sparse according to Figure 35, it is flagged as being subject to more drought risk than almost any other location in the country in Figure 33 and Figure 34. Figure 33 indicates that the southwest portion of the state has spent more than 20% of the last 100 years in a serious drought and Figure 34 indicates that the same area is expected to experience D4 conditions in the long term, also known as exceptional drought (see Table 35 for explanation of D4). Should the petroleum industry continue to expand, it is inadvisable to build any additional water-using facilities in Wyoming, as such additions are likely to exacerbate a drought that is already predicted to be exceptionally severe.

### 6.1.3 Key Areas of Concern: Corn Grain to Ethanol

The primary location of concern for the corn grain to ethanol pathway is groundwater depletion in Nebraska. Although the state is technically drought-prone because it has spent between 10 and 15% of the past 100 years in severe, extreme, or exceptional drought (see Figure 6), Figure 34 indicates that surface water availability will increase in the long-term. In contrast, Figure 35 shows that the groundwater, which is heavily monitored in the state, is being overpumped and the water table has dropped dramatically as a result. Nebraska depends heavily on the High Plains Aquifer, whose water is in high demand by surrounding states as well; as the water table continues to drop, there will be water rights issues and pumping will be further restricted (*97*). To minimize the water footprint of the corn grain to ethanol pathway, it is imperative that the marginal unit be grown in states where little to no irrigation is used, avoiding Nebraska in particular.

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### 6.1.4 Key Areas of Concern: Corn Stover to Ethanol

The three locations that stand out in the map of the corn stover to ethanol pathway are Southern California, the Midwest, and Southeast Texas. The Midwest bears a large fraction of the water footprint because this dissertation makes the assumption that future corn stover biorefining capacity will be added to existing corn grain biorefineries since the two feedstocks are produced from the same crop. Of the Midwestern states, Nebraska again stands out as the most at-risk location for reasons described in Section 6.1.3. Much of the Midwest is categorized as drought-prone based on Figure 6, but Figure 34 indicates that those same states will experience increases in freshwater availability in the long-term. Southeast Texas appears significant because of the concentration of chemical manufacturing plants in that area. However, it should be noted that each chemical used for agriculture and biorefining was mapped based on a generic distribution of all chemical manufacturing facilities in the United States, so many of the facilities in Texas may be petrochemical facilities that do not produce the specific chemicals used in the corn stover to ethanol production pathway. Southern California is also significant for indirect reasons. Because agriculture on average is very water-intensive, even small amounts of agricultural products within a supply chain may emerge as being significant contributors to the overall life-cycle water use. California is home to a large fraction of heavily irrigated agricultural production in the United States and hence it appears as a non-negligible portion of ethanol's water footprint. For a discussion of water concerns in Southern California, see Section 6.1.1.

### 6.1.5 Key Areas of Concern: Miscanthus to Ethanol

The mapping of water use for the Miscanthus to ethanol pathway should be taken with the proverbial grain of salt. Because no Miscanthus crops currently exist and it is thus far unclear where the crop will ultimately be grown, it was assumed to be grown and processed in the same locations as corn grain and corn stover. In recent months, it has come to light that Miscanthus may ultimately be grown in the Southeastern United States rather than the Midwest (*212*), although the exact locations are as of yet undetermined. If this is in fact the case, Florida will almost certainly be the location of most concern. Florida has installed more desalination capacity than any other state, implying that its marginal unit of freshwater may be very GHG-intensive (*166*). The state is also likely to experience long-term severe drought conditions in the northern half according to Figure 34. Lastly, Florida monitors its groundwater carefully and a number of groundwater wells are flagged as being significantly below normal, as shown in Figure 35.

### 6.1.6 Key Areas of Concern: Electricity

Unlike the other fuel production pathways, electricity production is not concentrated in one or a few states, but rather is spread throughout the entire country. This is because transmission line losses prevent utilities from building generation capacity too far from population centers (*131*). However, from a consumption perspective, there is a higher concentration of water use in the western half of the country, particularly in Southern California, Arizona, Colorado, and Wyoming. Ironically, closed-loop cooling systems are the technology of choice in water-

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stressed regions due to their much lower withdrawals relative to open-loop systems, but closed-loop systems result in higher water consumption (*31*). Because surface water is much more commonly used than groundwater for power plant cooling, surface water availability is the main impact of concern for electricity generation (*12*). Wyoming, California, and a small portion of Colorado are all flagged in Figure 34 as being at risk for long-term drought conditions. These plants also may also end up using recycled wastewater for cooling if local water resources are unavailable, which may increase their total GHG footprint (*16, 213*).

## 6.2 Uncertainty and Sensitivity

Having discussed the main conclusions that can be derived from this dissertation's results, there are a number of caveats that must also be addressed. Inevitably, there is uncertainty associated with LCA whether it is due to input data quality, methodological choices, or simply humans' inability to perfectly predict future outcomes. The analysis presented in this dissertation is no exception and it is imperative that sources of uncertainty and their impacts on the results be explored so as not to be misleading.

The concepts of sensitivity and uncertainty are fundamentally connected. Uncertainty refers to any instance in which an outcome cannot be accurately and consistently predicted (*214*). There is at least some uncertainty associated with all of the input data used in this dissertation. For example, it is impossible to predict with 100% certainty what the source of the marginal liter of gasoline will be or where future cellulosic biorefineries will be located. Assumptions must be made for these and other variables in order to complete the analysis. Sensitivity refers to the impact each of these assumptions has on the final results. Water use for dust control during construction is highly uncertain due to its dependence on local climate, the season during which construction is taking place, length of the construction process, and the general contractor's concern for their workers' safety, for instance. However, dust control proves to be an insignificant contributor to the overall water footprint of such facilities as biorefineries, petroleum refineries, and power plants. In other words, the results are not sensitive to assumptions about water needs for dust control.

### 6.2.1 Uncertainty

There are two major types of uncertainty that will be discussed here: epistemic and aleatory (*215*). Epistemic uncertainty refers to some lack of ascertainable knowledge about the system of interest. Aleatory uncertainty refers to natural, unpredictable variation within the system of interest. Both types play a role in this dissertation. In order to gauge the level of uncertainty, a data quality assessment is performed and key assumptions are discussed.

#### *6.2.1.1 Aleatory Uncertainty*

Aleatory uncertainty comes from systems whose behavior cannot be perfectly predicted, regardless of how much time and effort are expended. Because this dissertation attempts to predict the behaviors of markets that do not yet exist, such as cellulosic ethanol, aleatory uncertainty plays a major role. Markets for ethanol from Miscanthus and corn stover are highly

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uncertain, in part because technological innovation and policy will significantly influence where and how the fuel is produced, if at all. The results for electricity are also plagued by aleatory uncertainty because a scale-up of power generation to supply transportation needs in addition to the existing needs of society will inevitably change both the average and marginal fuel mixes, but this change is again dependent on policy, technological innovation, geospatial distribution of transportation-related demand, and fuel prices.

There is also aleatory uncertainty associated with water resource vulnerability data because it is dependent on climate predictions, which are inherently uncertain. Precipitation rates, temperatures, groundwater flows, and other factors that impact freshwater availability are subject to unpredictable, natural variation and this variation should be acknowledged when making predictions about water stress in any region.

#### *6.2.1.2 Epistemic Uncertainty*

Epistemic uncertainty refers to limitations in knowledge about a system that could theoretically be understood. For example, the water use in petroleum refineries operating in the United States could be measured at a facility level, thus producing an accurate accounting of the average amount of water required to produce a unit of gasoline. However, this task would be time and labor-intensive for a researcher, so instead, he/she may choose to estimate a range or average value based on engineering concepts and existing literature. The uncertainty associated with this estimate is categorized as epistemic uncertainty. In LCA, a great deal of data are collected for a variety of engineered and natural systems, so researchers often use estimates in favor of exact measurements to prevent the task of data collection from becoming insurmountable. There are two strategies that are used in this research to address epistemic uncertainty. First, a data quality matrix, discussed further in Section 6.2.1, is used to assess data that are used for analysis. Second, a sensitivity analysis is performed to gauge how uncertainty can impact the final results, shown in Section 6.2.2.

#### *6.2.1.3 Data Quality Assessment*

One method for addressing data-related uncertainty is a data quality matrix, also known as a pedigree matrix (shown in Table 49). The data quality matrix allows for a general indication of how accurate input data are. Using the scoring system, a reader should quickly be able to determine how reliable results are given the quality of their inputs. The scoring system also makes it possible to highlight future data needs. If certain data points have exceptionally low scores, it indicates that future studies should seek to collect better information for that particular process/system. The data quality matrix does, however, have limitations as well. The actual process for assigning scores in each category is relatively subjective, and two equally qualified authors may assign different scores in some cases. This is in part due to the fact that scores are often assigned not just to one data point, but rather to a collection of data. In this case, the author must make judgments about the quality of many data points at once and how important each one is relative to the others. For example, if one particular data point is a much larger contributor to the total for a category and its data quality is low, the category should be

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assigned a low data quality score regardless of how accurate some of the less important data points may be.

| **Indicator Score** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Independence of Data Supplier | Verified data based on measurements | Verified data partly based on assumptions or non-verified data based on measurements | Non-verified data partly based on assumptions | Qualified estimate (e.g. by industrial expert) or generally accepted industry average | Non-qualified estimate |
| Representation | Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations | Representative data from a smaller number of sites but from shorter periods | Representative data from an adequate number of sites but from shorter periods | Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods | Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods |
| Temporal Correlation | < 3 years of difference to year of study | < 6 years difference | < 10 years difference | < 15 years difference | Age of data unknown or > 15 years difference |
| Geographical Correlation | Data from area under study | Average data from larger area in which the area under study is included, same country | Data from different area within same country, similar production conditions | Data from a different country, somewhat similar production conditions | Data from unknown area or area with very different production conditions |
| Technological Correlation | Data from enterprises, processes, and materials under study | Data from processes and materials under study but from different enterprises | Data from processes and materials under study but from different technology | Data on related processes or materials but same technology | Data on related processes or materials but different technology |
| Range of Variation | Estimate is a fixed and deterministic number or a probability distribution is provided | Estimate is likely to vary by < 10% | Estimate is likely to vary by > 10% | Small range (+/- < 50% of midpoint) provided with no mean | Large range (+/- > 50% of midpoint) provided with no mean |

Table 49: Data Quality Matrix (Adapted from (*66, 216-219*))

Additionally, the scores from each data quality category are typically averaged or added together to produce a single data quality score. While this practice does make the results simpler for the reader to process, it also comes with the inherent assumption that each category is of equal importance. Temporal correlation, for example, is relatively unimportant for industries that have not changed significantly in the past few decades such as petroleum refining, whereas temporal correlation is very important for cellulosic biorefineries and other new technologies that are still maturing. The differences in the importance of each category are very case-specific, so it is impossible to develop some sort of universally accepted weighting scheme. In this dissertation, a simple average of the categories is taken to determine data quality scores for each fuel pathway with the acknowledgement that these averages are not ideal measures of data quality. The data quality matrices and resulting data quality scores are shown in Table 50 through Table 56.

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| **Crude Oil to Gasoline** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 1 | 1 | 1 | 1 | 5 |
| Electricity Consumption | 3 | 1 | 1 | 1 | 1 | 2 |
| Primary Fuel Consumption | 3 | 1 | 1 | 1 | 1 | 3 |
| Chemicals | 4 | 2 | 3 | 2 | 1 | 5 |
| Construction & Materials | 3 | 1 | 1 | 1 | 1 | 3 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 3.4 | 1.1 | 1.6 | 1.1 | 2.1 | 4 |

Table 50: Data Quality Matrix for the Crude Oil-to-Gasoline Pathway

| **Oil Sands to Gasoline** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 1 | 1 | 1 | 1 | 3 |
| Electricity Consumption | 3 | 1 | 1 | 1 | 1 | 2 |
| Primary Fuel Consumption | 3 | 1 | 1 | 1 | 1 | 3 |
| Chemicals | 4 | 2 | 1 | 3 | 4 | 3 |
| Construction & Materials | 3 | 1 | 1 | 1 | 1 | 3 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 3.4 | 1.1 | 1.3 | 1.3 | 2.6 | 3.4 |

Table 51: Data Quality Matrix for the Oil Sands-to-Gasoline Pathway

| **Corn Stover to Ethanol** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 4 | 2 | 1 | 2 | 3 |
| Electricity Consumption | 1 | 4 | 2 | 1 | 2 | 3 |
| Primary Fuel Consumption | 1 | 4 | 2 | 1 | 2 | 3 |
| Chemicals | 1 | 4 | 2 | 1 | 2 | 3 |
| Construction & Materials | 5 | 5 | 2 | 2 | 5 | 5 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 2.7 | 3.3 | 2 | 1.1 | 3.3 | 3.9 |

Table 52: Data Quality Matrix for the Corn Stover-to-Ethanol Pathway

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| **Miscanthus to Ethanol** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 4 | 1 | 1 | 2 | 3 |
| Electricity Consumption | 1 | 4 | 1 | 1 | 2 | 3 |
| Primary Fuel Consumption | 1 | 4 | 1 | 1 | 2 | 3 |
| Chemicals | 1 | 4 | 1 | 1 | 2 | 3 |
| Construction & Materials | 5 | 5 | 2 | 2 | 5 | 5 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 2.7 | 3.3 | 1.4 | 1.1 | 3.3 | 3.9 |

Table 53: Data Quality Matrix for the Miscanthus-to-Ethanol Pathway

| **Corn Grain to Ethanol** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 2 | 2 | 1 | 1 | 3 |
| Electricity Consumption | 3 | 1 | 1 | 1 | 1 | 3 |
| Primary Fuel Consumption | 3 | 1 | 1 | 1 | 1 | 3 |
| Chemicals | 3 | 4 | 2 | 1 | 4 | 3 |
| Construction & Materials | 5 | 5 | 2 | 2 | 5 | 5 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 3.6 | 2.1 | 1.7 | 1.1 | 3.1 | 3.9 |

Table 54: Data Quality Matrix for the Corn Grain-to-Ethanol Pathway

| **Electricity (U.S. & All NERC Regions)** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Direct | 1 | 1 | 3 | 1 | 1 | 3 |
| Electricity Consumption | 1 | 1 | 3 | 1 | 1 | 2 |
| Primary Fuel Consumption | 1 | 1 | 2 | 1 | 1 | 2 |
| Chemicals | 4 | 5 | 2 | 1 | 3 | 3 |
| Construction & Materials | 2 | 4 | 3 | 3 | 1 | 3 |
| Supply-Chain Agriculture | 5 | 1 | 2 | 1 | 5 | 5 |
| Supply-Chain Services | 5 | 1 | 2 | 1 | 5 | 5 |
| Average | 2.7 | 2 | 2.4 | 1.3 | 2.4 | 3.3 |

Table 55: Data Quality Matrix for U.S. & NERC Region-Specific Electricity

| **GHG Footprint of Water** | Independence of Data Supplier | Representation | Temporal Correlation | Geographical Correlation | Technological Correlation | Range of Variation |
|---|---|---|---|---|---|---|
| Local Groundwater | 2 | 1 | 3 | 1 | 1 | 3 |
| Local Surface Water | 2 | 1 | 3 | 1 | 1 | 3 |
| Imported Freshwater | 1 | 4 | 2 | 1 | 2 | 3 |
| Desalinated Seawater | 1 | 2 | 2 | 1 | 2 | 3 |
| Desalinated Brackish Water | 1 | 2 | 2 | 1 | 2 | 3 |
| Recycled Wastewater | 1 | 2 | 2 | 1 | 2 | 3 |
| Average | 1.3 | 2 | 2.3 | 1 | 1.7 | 3 |

Table 56: Data Quality Matrix for the GHG Footprint of Water Use

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Although each pathway produces different results, the "range of variation" category is consistently poor. This is due to the fact that water use data are often reported as a range with no mean, or if a mean is reported, the marginal unit is likely to vary significantly from that average depending on location and technological choices. Particularly for technology that does not yet exist at commercial scale such as cellulosic ethanol production, water use may ultimately be very different than the average values measured at pilot plants or predicted by computer models.

#### *6.2.1.4 Uncertainty in Economic Input-Output Life-Cycle Assessment Water Data*

There is one source of uncertainty that necessitates treatment separate from the data quality matrix: results from the Economic Input-Output Life-Cycle Assessment (EIO-LCA) tool (*66*). The sheer volume of data that go into generating results in EIO-LCA makes it nearly impossible to estimate data quality with single rankings as done in Section 6.2.1. As discussed in Chapter 2, EIO-LCA utilizes economic input-output data, combined with what are known as impact vectors to generate life-cycle inventory results. Water use was not present in the 1997 version of the tool, but has been added to the most up-to-date version (2002) (*220*). Already, the water use results from EIO-LCA have been arguably misused; reference (*9*) presents the results as if they represent water consumption, while the tool documentation makes it clear that the tool only produces total withdrawals (*220*). In order to avoid such missteps in the future, it is important to understand the limitations of both EIO-LCA as a whole and of the water use results, specifically. Table 57 shows the methodological, temporal, geospatial, and water data quality constraints.

| **Methodological Constraints** | **Temporal Constraints** | **Geospatial Constraints** | **Water Use Data Constraints** |
|---|---|---|---|
| • Assumes constant returns to scale<br>• Inherently attributional<br>• Imports and exports not included<br>• Environmental impacts assumed to scale linearly with dollar value of output<br>• Sectors are often highly aggregated | • 8-year-old sector data cannot reflect changes of rapidly evolving sectors<br>• New industries such as cellulosic ethanol are not included in existing sectors | • Outputs are only offered on a total U.S. basis<br>• All sectors assumed to use the average U.S. electricity mix regardless of location | • Only water withdrawals are quantified, consumption is excluded<br>• Industrial and mining water use data is taken from Canada on a per employee basis – all industrial sectors assumed to have the same water use per employee<br>• The price of public water supplied for non-domestic uses assumed to be constant throughout United States |

Table 57: EIO-LCA Uncertainty (Partially Based on Reference (*221*))

The limitations put forth in Table 57 can be used as guidance in a hybrid LCA for determining when EIO-LCA should and should not be used. For example, cellulosic ethanol cannot be effectively modeled with EIO-LCA because there is no sector to represent the so far-largely non-existent industry, nor is there a sector for major inputs such as Miscanthus or switchgrass production. Additionally, because EIO-LCA only quantifies withdrawals, it should not be used to represent water consumption for any process that is known to withdraw significantly more

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water than it consumes.  Chemical manufacturing is a prime example of a sector that is not appropriate for modeling in EIO-LCA because of its high withdrawals relative to consumption (*119*).

However, process LCAs cannot quantify the total supply-chain effect that some water-intensive industries may have on the life-cycle water footprint of a particular product.  To include supply-chain effects reliably with EIO-LCA, it must only be used for industries that have remained relatively static in the past 8 years and have total water consumption that is roughly equal to withdrawals.  For this reason, only agriculture and commercial water use are modeled using EIO-LCA.  All agricultural water use is assumed to be consumptive, although it is possible that water not consumed through evapotranspiration could run off or percolate down to its original source.  Commercial sectors, labeled as “supply-chain services”, are also assumed to have a 100% consumption rate because.  The assumption is justified because commercial wastewater is almost certainly treated by a municipal wastewater treatment facility, which will subsequently discharge the treated wastewater into a body of water other than its initial source.

As EIO-LCA water use data inevitably become more widely used, researchers should exercise caution in how the results are incorporated into LCAs, hopefully taking into account the concerns raised in Table 57.

#### *6.2.1.5 Uncertainty in Impact Assessment Data*

There are two main elements of the water use impact assessment that may contribute to uncertainty in the final results: the geospatially-disaggregated water inventory, as well as the drought and groundwater vulnerability data.  For the most part, uncertainty associated with mapping is epistemic, suffering from a lack of information about where the marginal unit of various products comes from, for example.  However, there is some aleatory uncertainty in predicting the future locations of corn stover and Miscanthus crops, as well as biorefineries that have yet to be established.  Table 58 lists each industry that has been mapped along with the sources of uncertainty for each one.  Although there is a great deal of uncertainty in the mapping of minor contributors such as glass, sand, and clay mining, the more significant industries have been carefully assigned to counties throughout the United States.

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| Industry | Limitations of Geospatial Mapping |
|---|---|
| Crude Oil Extraction | • Average production data used in absence of marginal data<br>• Field-specific production data is 3 years old<br>• Water use assumed to be constant within each PADD (except for offshore wells)<br>• Some fields span multiple counties and production is assumed to be equally split between counties |
| Oil Sands Extraction/Upgrading | • All oil sands upgrading is assumed to occur in Canada |
| Petroleum Refining | • Average production data used in absence of marginal data<br>• All refineries assumed to be operating at capacity<br>• SCO refining assumed to have same geospatial distribution as conventional crude refining |
| Corn Grain & Stover Agriculture | • Average production data used in absence of marginal data<br>• Irrigation rates assumed to be constant within each state<br>• Stover assumed to have identical geospatial distribution to corn grain production |
| Miscanthus Agriculture | • Miscanthus assumed to have geospatial distribution identical to corn grain and stover |
| Corn Grain Biorefining | • Average production data used in absence of marginal data<br>• All biorefineries assumed to be operating at capacity |
| Corn Stover Biorefining | • Stover biorefineries assumed to have geospatial distribution identical to corn grain biorefineries |
| Miscanthus Biorefining | • Miscanthus biorefineries assumed to have geospatial distribution identical to corn grain biorefineries |
| Electricity Generation | • Average generation used in absence of marginal data<br>• Some counties fall into two or NERC regions, but each county is assigned one NERC region for this analysis – results in some power plants being allocated to the incorrect NERC region |
| Coal Mining | • Average production data used in absence of marginal data<br>• All mines assumed to require identical amount of water for revegetation<br>• Mine-specific production data is 3 years old |
| Natural Gas Extraction | • Average production data used in absence of marginal data<br>• Some fields span multiple counties and production is assumed to be equally split between counties |
| Nuclear Fuel Extraction & Processing | • Average production data used in absence of marginal data<br>• One mine spans multiple counties and production is assumed to be equally split between counties |
| Chemical Manufacturing | • Water-borne toxic releases data used as a proxy for water use<br>• Each chemical is mapped using the locations of all chemical manufacturing facilities in the United States |
| Steel Manufacturing | • Average production data used in absence of marginal data<br>• All plants assumed to be operating at capacity |
| Glass, Sand, & Clay Mining | • Water-borne toxic releases data used as a proxy for water use<br>• Each material is mapped using the locations of all mineral mining |
| Plastics & Rubber Manufacturing | • Water-borne toxic releases data used as a proxy for water use<br>• Each material is mapped using the locations of all plastics and rubber manufacturing facilities |

Table 58: Sources of Uncertainty in Geospatial Disaggregation of Water Use Inventory

In addition to geospatial disaggregation of each industry, there is uncertainty associated with the ground and surface water vulnerability metrics. First, the drought incidence data is inherently subjective. Severity is judged using non-quantitative guidelines as shown in Table 35 and it is entirely possible that two experts could categorize the same drought differently. Second, counties are assumed to be either vulnerable or not vulnerable based on whether they have spent more than 10% of the previous 100 years in severe or extreme drought. This choice is made for the sake of simplicity and has no basis in climate science. Using data from the previous 100 years rather than future projections also ignores the impact that climate change and other long-term trends may have on water availability. For example, reference (*94*) suggests that water availability may increase in some parts of the United States as a result of climate change, increasing yields of rain-fed agriculture. Lastly, the Palmer Drought Index (PDI), although common, is only one of many different systems for measuring drought severity and vulnerability. The alternate metric shown in Figure 34 proves very different from the PDI

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(Figure 33), thus implying that a different drought vulnerability metric could change the impact assessment results for surface water significantly.

For groundwater vulnerability, although the source data are far less precise and complete than drought incidence data, there is greater agreement among studies that highlight overpumping and the resulting impacts. Figure 35, which maps groundwater monitoring wells that indicate water levels in the 10th percentile of the well's overall distribution, and Figure 36, which shows the state-level groundwater vulnerability mapping used in this dissertation, appear to be in agreement. In part, this is because any groundwater data source is limited to those states that actively monitor groundwater levels and other impacts such as subsidence and saltwater intrusion (*26*). It is likely, however, that any state or watershed experiencing significant negative impacts as a result of groundwater overpumping has established some form of monitoring, so there is a natural correlation between states/watersheds subject to groundwater depletion and monitoring network locations.

### 6.2.2 Sensitivity Analysis and External Validation

In the absence of probability distributions for input data, the most effective method of dealing with uncertainty is sensitivity analysis. In this section, the life-cycle water use inventory is recalculated using both extreme lows and highs for the most uncertain input variables to determine the practical maximums and minimums, thus providing a sense for how the marginal unit of each good or service may differ from the national average. For example, depending on economic and policy factors, the marginal unit of corn may come from parts of the Midwest where no irrigation is required or it may be grown in heavily irrigated regions such as California or Arizona. Unfortunately, because alternative metrics for both surface and groundwater are not available, the sensitivity analysis will focus exclusively on the water use inventory. After the sensitivity analysis is completed, these ranges and average values are compared to existing literature. Making this comparison and discussing the factors that are responsible for any differences in results between this and other studies sheds light on what impact the methodological and input data choices made in this dissertation have on the final results.

The sensitivity analysis is presented in two parts. The first deals only with the inclusion of hydroelectricity-related water use. The issue that some hydroelectric dams result in an increase in water surface area, and thus total evaporation, was first raised by reference (*27*) and is discussed in more detail in Chapter 3. Reference (*27*) chooses to attribute all water impacts to the generation of electricity, but dams often provide other services such as water storage, recreation, and flood prevention, which could be considered valuable co-products of the system. Unfortunately, the National Inventory of Dams provided by the U.S. Army Corps of Engineers only displays one function for each dam in the United States (*222*). Because no reliable information about the multiple functions of dams is available and, even if it were, the process of allocating impacts to these functions would be difficult given that monetary values of such services as flood protection and recreation are typically unavailable, the water footprint of hydroelectricity is not included in the final results of this dissertation. Instead, a sensitivity analysis is performed where each hydroelectric power plant in a given state is assigned the

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average water-intensity factor for hydroelectricity for that state as calculated by reference (*27*). Figure 63 shows how the inclusion of hydroelectricity-related water use changes the life-cycle water footprint of electricity production in each NERC region. The baseline water withdrawals and consumption are equal to the life-cycle water use, excluding hydroelectricity-related evaporative losses, as shown in Figure 30, and the error bars represent the additional water use resulting from hydroelectricity. The effect on withdrawals and consumption is identical since water is directly evaporated from the water body's surface.

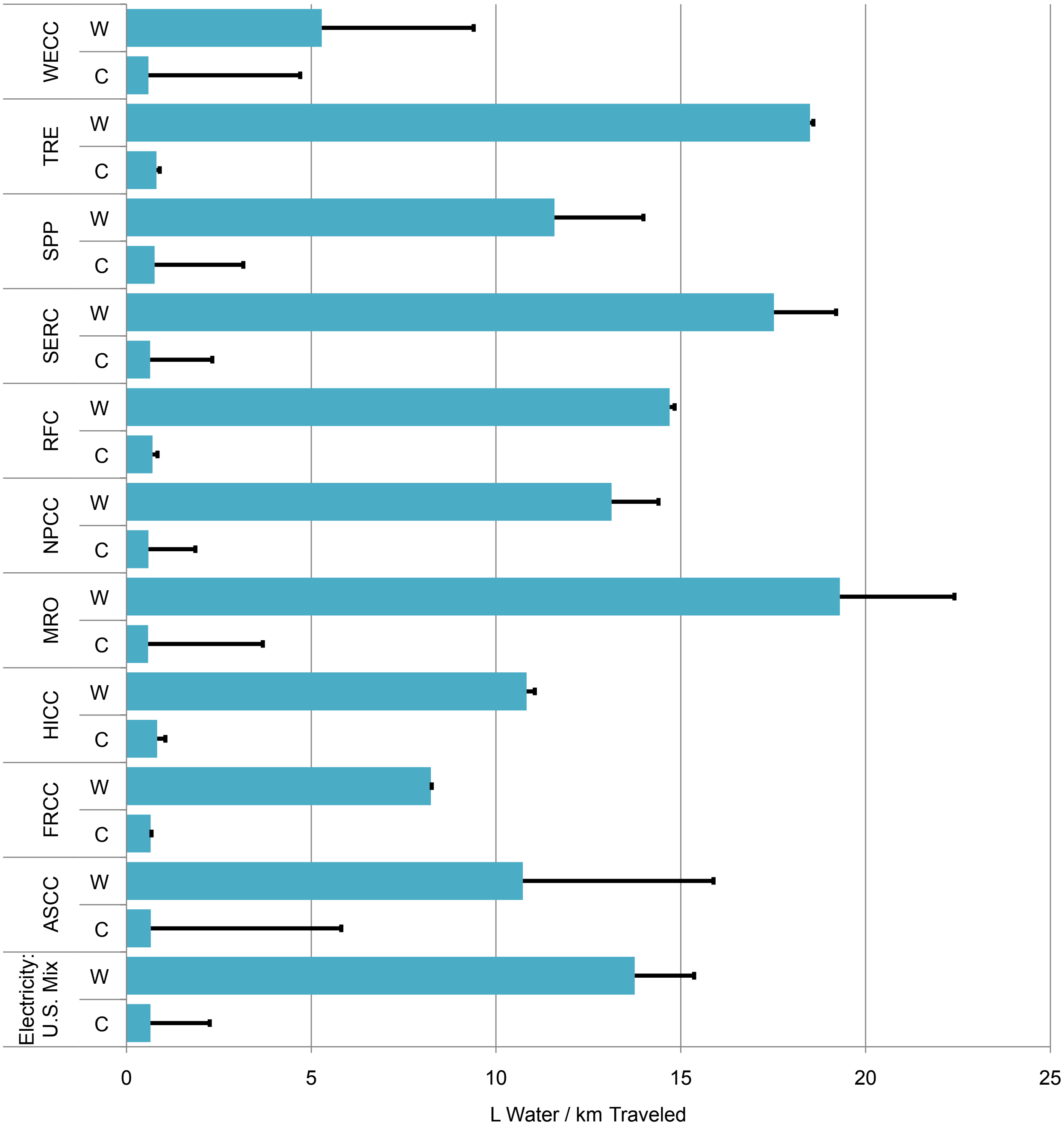

Figure 63: Impact of Hydroelectricity on the Life-Cycle Water Footprint of Electricity

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As Figure 63 shows, the inclusion of hydroelectricity dramatically increases the water footprint of electricity in some NERC regions. The largest increase occurs in Alaska (ASCC), where life-cycle water consumption increases by almost eight-fold. The WECC region consumption experiences an almost 700% increase and the average U.S. mix more than doubles its consumptive use. The relative increase in withdrawals is smaller because water withdrawals for electricity generation are already quite high. WECC experiences the largest increase in withdrawals, at 78% and withdrawals for the U.S. average mix increase by 12%.

Because electricity is ubiquitous in LCA, playing a role in every supply chain (at least in the United States), the increase in its water footprint also has a ripple effect, increasing the water footprint of all other products and services. Figure 64 shows the change in the life-cycle water use inventory of transportation fuels resulting from the inclusion of hydroelectricity-related water use. The more dependent a particular pathway is on electricity, the larger the resulting change. The oil sands to gasoline pathway, for example, relies heavily on electricity and the inclusion of hydroelectricity increases its total water withdrawals by 12% and its consumption by 18%. Corn stover and Miscanthus to ethanol experience the opposite effect: because cellulosic biorefineries displace electricity production by exporting their excess electricity to the grid, an increase in the water-intensity of grid electricity production lowers the water footprint of these fuel pathways. As shown in Figure 64, the change is significant. Total consumption for corn stover to ethanol decreases by 46% and withdrawals decrease by 61%. The results for Miscanthus are similar: consumption is lowered by 48% and withdrawals are reduced by 41%. These results indicate that the inclusion of hydroelectricity-related water use can substantially change the results of any LCA. Hopefully future studies will explore potential options for appropriately accounting for hydroelectricity in water use inventories.

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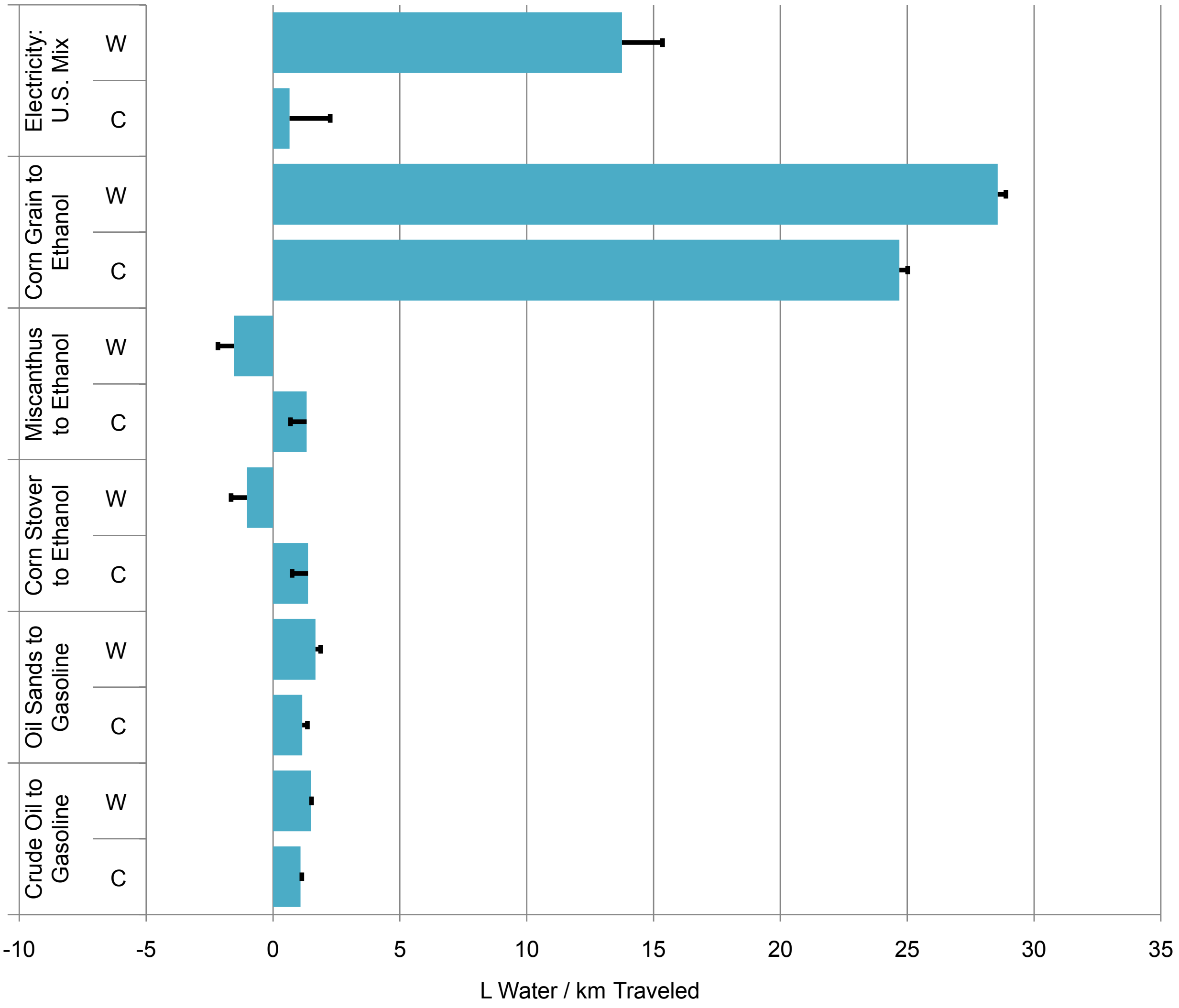

Figure 64: Impact of Hydroelectricity on the Water Footprints

Having explored the impact of hydroelectricity, the second sensitivity analysis deals with epistemic and aleatory uncertainty associated with all other input data for the water use inventory. By changing technologies, locations, and methodologies, the results provide an indication of how the water footprint of each fuel pathway may vary depending on what makes up the marginal unit of production. Table 59 shows the factors that are varied to develop low, average, and high scenarios. For the actual data points used in these scenarios, refer to Appendix E.

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| Pathway | Feedstock Extraction/Production | Feedstock Transportation | Refining/Fuel Production | Fuel Transportation, Storage & Distribution |
|---|---|---|---|---|
| Crude Oil to Gasoline | -Extraction method | N/A | -Direct water use | N/A |
| Oil Sands to Gasoline | -Extraction method | N/A | -Direct water use | N/A |
| Corn Stover to Ethanol | -Water embodied in chemicals | N/A | -Direct water use<br>-Water embodied in chemicals<br>-Electricity co-product credit | N/A |
| Miscanthus to Ethanol | -Green water consumption<br>-Water embodied in chemicals | N/A | -Direct water use<br>-Water Embodied in chemicals<br>-Electricity co-product credit | N/A |
| Corn Grain to Ethanol | -Irrigation<br>-Water embodied in chemicals | N/A | -Direct water use | N/A |
| U.S. Electricity | -Variation Among NERC Regions | -Variation Among NERC Regions | -Variation Among NERC Regions | -Variation Among NERC Regions |

Table 59: Factors Considered in the Sensitivity Analysis

Figure 65 shows the sensitivity analysis results for life-cycle water consumption and Figure 66 shows withdrawals. The numerical results can be found in Appendix E. From a consumption perspective, irrigation and net changes in green water consumption dominate any other factors. Relative to the average scenario, the most water-intensive corn in the United States results in an increase of more than a factor of 10 and the least water-intensive corn results in a decrease of 95%. Including an estimate for the net increase in green water consumption due to Miscanthus (relative to corn on a per hectare basis) raises the total life-cycle water consumption by a factor of 20. The changes in consumption for other pathways are more modest. Corn stover to ethanol differs by approximately 60% above and below the average due to changes in the assumed electricity imports from cellulosic biorefining and the water intensity of biorefining and chemical production. Changing assumptions about technology and direct water use at the petroleum refinery results in variances relative to the average of between 20 and 50% for petroleum pathways. Electricity is varied based on different NERC regions, which also produces modest results: 10% decrease relative to the average for the lowest possible consumption and 37% increase for the highest.

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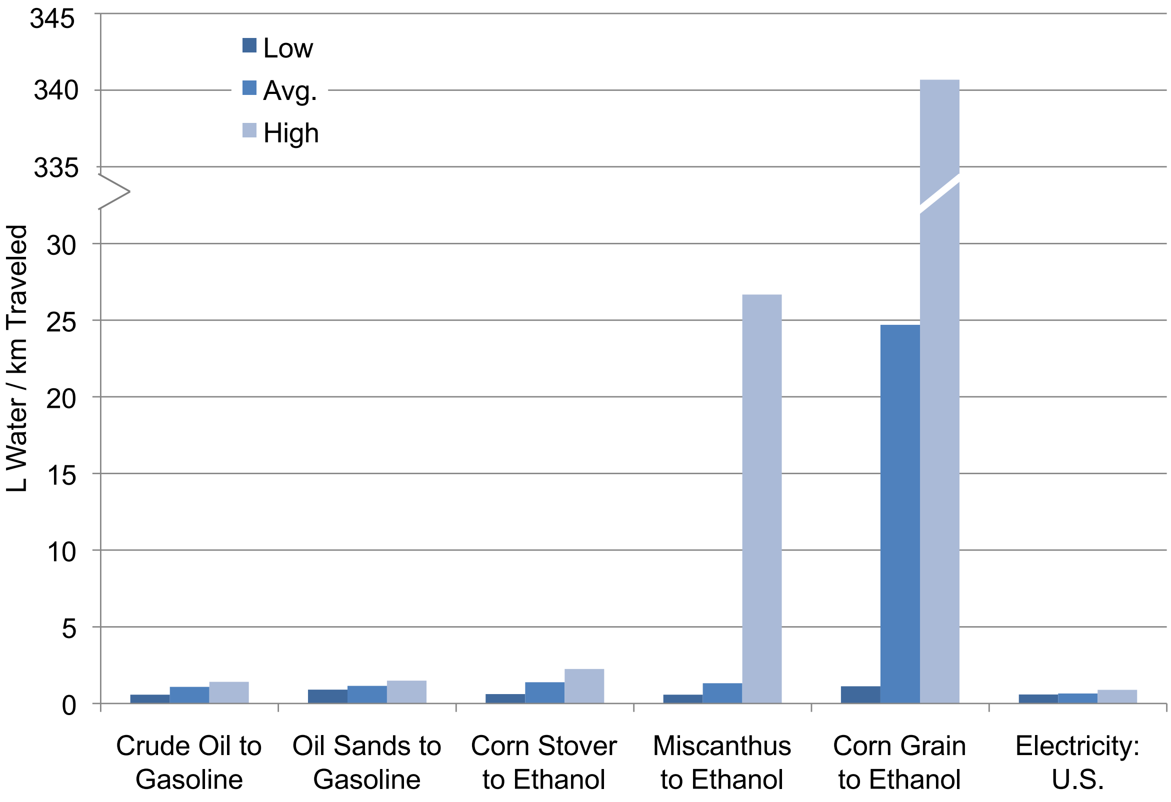

Figure 65: Life-Cycle Water Consumption Sensitivity Analysis

Whereas changes in assumptions about agricultural water made the most noticeable differences in Figure 65, withdrawals are dominated by two factors: agricultural water and electricity. As demonstrated in Figure 66, the green and irrigation water assumptions for corn grain and Miscanthus are still significant, but now corn stover and electricity also stand out. Because it is possible that cellulosic biorefineries may be unable to export their excess electricity, either due to location constraints or disputes with local utilities, the high scenarios for corn stover and Miscanthus both assume that no electricity is exported. This removes the electricity displacement credit, which for withdrawals is quite large. Without the electricity credit, cellulosic ethanol becomes significantly more water-intensive than its petroleum counterparts and if the planting of Miscanthus results in a net increase in green water consumption, its withdrawals will be more than 22 times higher than the average withdrawals for crude oil to gasoline.

Electricity withdrawals also vary more significantly than for consumption. This is due to the concentration of open-loop cooling systems in NERC regions where water is plentiful and closed-loop cooling systems in regions with less available water. The NERC regions with the lowest withdrawals (WECC) totals to 62% less than the average U.S. mix and that with the highest has withdrawals (MRO), 40% higher than the average.

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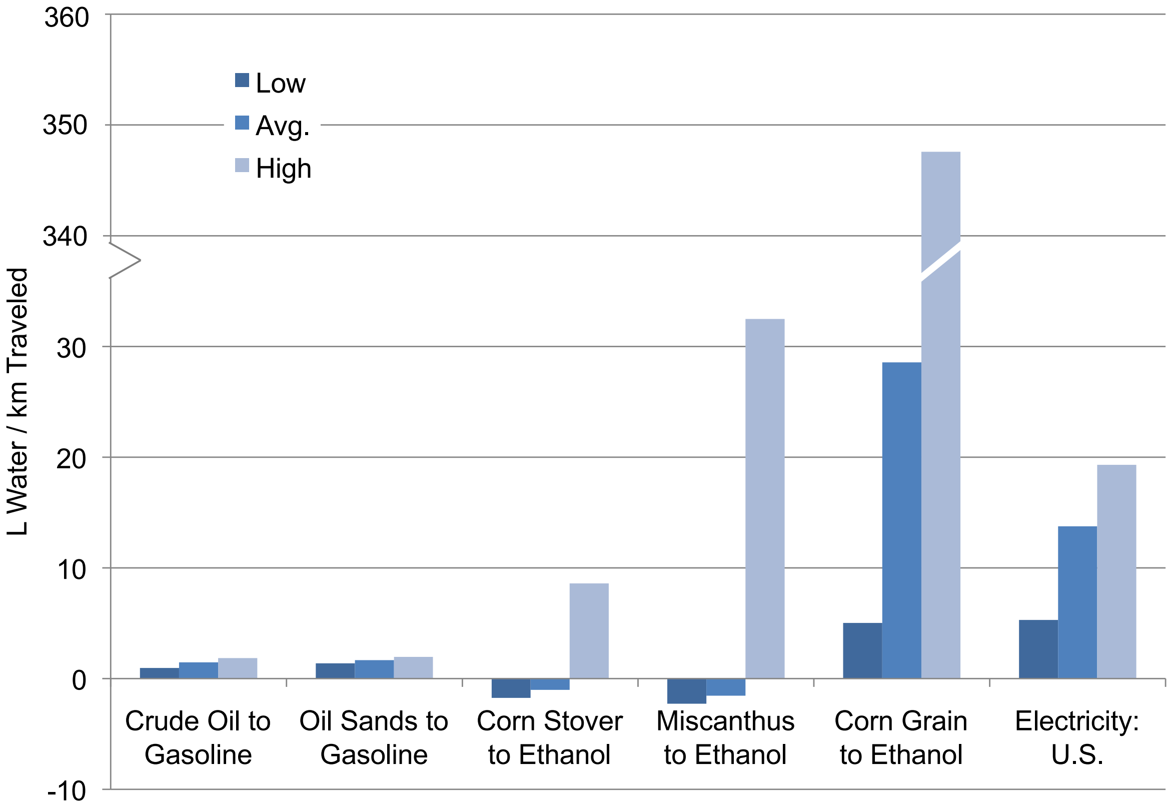

Figure 66: Life-Cycle Water Withdrawals Sensitivity Analysis

Having established ranges for the water footprint of each fuel pathway, these results can now be compared to existing literature. Figure 67 shows how the water use inventory in this dissertation compares to other recent studies, including references (*8*) (labeled as King and Webber 2008), (*5*) (labeled as Wu et al. 2009), and (*9*) (labeled as Harto et al. 2010). Some bars are missing because the study in question did not analyze the particular pathway or did not consider both consumption and withdrawals. The numerical results for each pathway are shown in Appendix E. Since no studies examine Miscanthus, the results for switchgrass in references (*9*) and (*5*) were assumed to be sufficiently similar. Where only a range was provided, the average value is assumed to be the mean of the high and low values.

For water withdrawals, the only study available for comparison is reference (*8*). The results for petroleum pathways and electricity are very similar, differing by no more than approximately 20%. For the biofuel pathways, however, the results are vastly different. Reference (*8*) makes three key assumptions that result in much higher water footprints. First, they assume a 79.7% conveyance loss rate for irrigation water, whereas this dissertation assumes that conveyance losses ultimately return to their source and are thus unimportant, which is consistent with reference (*3*). The conveyance loss assumption results in total withdrawals 5.3 times higher than what is reported in this dissertation. Second, reference (*8*) makes no attempt at any sort of allocation between ethanol and electricity produced at the biorefinery and uses a high, likely outdated estimate of 9.8 L of water used per L of ethanol produced. This estimate is approximately twice what has been modeled for this dissertation. Lastly, reference (*8*) chooses

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to allocate 54% of the total impacts of growing corn to stover, whereas it is argued in this dissertation that in the short to medium term, corn stover will continue to have no market price and thus remains a waste product.

Unlike reference (*8*), references (*9*) and (*5*) explore only water consumption. Reference (*9*) reports high water consumption for switchgrass (compared here to Miscanthus) because it includes a "drought" scenario in which rainfall is significantly lower than normal. These irrigation data have no basis in the United States, but rather are taken from a study conducted in Germany and Italy, so they are likely not indicative of actual drought-condition irrigation requirements in the United States. Both references (*9*) and (*5*) report significantly smaller ranges for the water footprint of the corn grain to ethanol pathway. This is because, rather than taking the absolute maximum of the USDA FRIS data, as is done in this dissertation and reference (*8*), they examine the highest corn-producing USDA regions (5, 6, and 7) and take the highest irrigation rate. Both methods have merit, and some could argue that taking a more reasonable maximum irrigation rate provides a better picture of what the water footprint of the marginal unit of corn may be since it is unlikely that corn production in states like California and Arizona will be scaled up significantly.

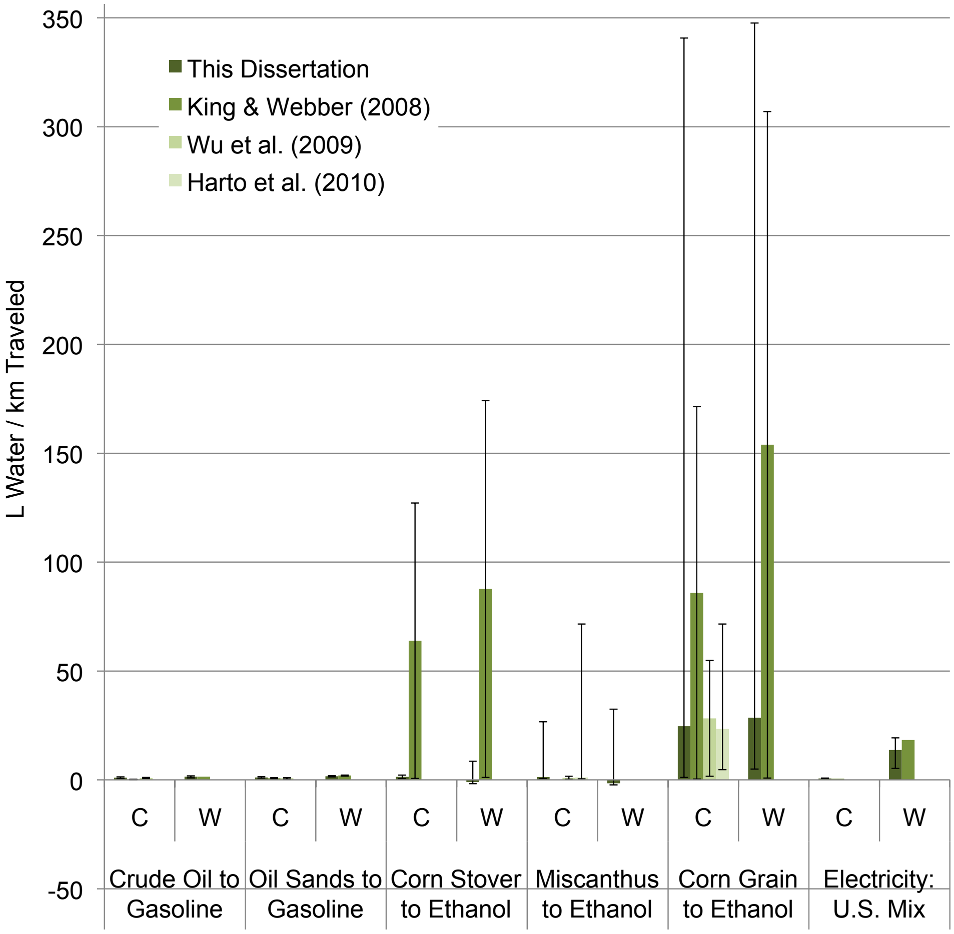

Figure 67: Comparison of Inventory Results to Recent Studies (*5, 8, 9*)

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# 7. Contributions and Future Work

Understanding how the production and consumption of fuels impacts freshwater resources is absolutely critical as humans attempt to transition into a more sustainable energy future. This is particularly true for transportation energy, which is already poised to become more reliant on sectors such as electricity and agriculture that are known to be water-intensive such as electricity and agriculture. Society has the tools to ensure that, in the process of reducing GHG emissions, water scarcity is not created or exacerbated. However, due to the complexity of tracking and modeling water use and its ultimate effect on resource availability, the existing literature leaves many questions unanswered.

This dissertation advances the field of water use LCA through methodological contributions and contributions to knowledge about the water impacts of existing and near-future transportation fuel production pathways in the United States. There are three main questions that have been answered in this dissertation:

1. What is the life-cycle water footprint of current and future transportation fuel production in the United States?

2. How might U.S. transportation fuel production pathways impact freshwater availability in the future?

3. What is the GHG-intensity of the water required for transportation fuel production and how do these emissions impact the overall transportation fuel GHG footprints?

The answers to each question, along with an assessment of how the results contribute to academic knowledge are laid out on this chapter. Much work still remains both to provide more robust answers to the above questions and to better understand the implications of water use. In an effort to identify key areas for additional work, recommendations for future research are laid out in Section 7.3 of this chapter.

## 7.1 Methodological Contributions

There are two LCA methodological issues that have been advanced in this dissertation: impact allocation and water use impact assessment. Both play critical roles in producing reliable results in water use LCAs. Each one is discussed in more detail in the following sections.

### 7.1.1 Impact Allocation

The first contribution to the area of impact allocation made in this dissertation is the summary and critical review performed of existing literature on multi-output allocation and open-loop recycling allocation. After the existing literature is synthesized, this dissertation makes strong recommendations for how researchers should prioritize different allocation methodologies. The important link between consequential and attributional LCA, and allocation methodology

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choices (which has been ignored in previous studies) is articulated to further assist researchers in choosing the most appropriate allocation strategies for future studies. For multi-output systems, the literature typically falls into one of two categories. Some studies oversimplify the problem, proposing entirely arbitrary allocation methods such as mass or energy content. Other studies present opaque methods such as linear programming models for complex systems like petroleum refineries, requiring proprietary operating cost data that are rarely available to researchers in academia. For open-loop recycling, existing literature asserts that the allocation method must inherently be arbitrary, and instead chooses to make practical arguments to support one arbitrary method over the others.

Most surprisingly, all of these studies ignore the important link between consequential/attributional approaches and the allocation methodology choice. Consequential LCA refers to an approach that measures the net change in environmental impacts as a result of an increase or decrease in production, and attributional refers to quantification of the average impacts for a given product or service. The optimal allocation strategy is dependent on whether the LCA in question is consequential or attributional, yet existing literature attempts to develop frameworks for choosing allocation methods as if this distinction is irrelevant. By neglecting the importance of the LCA's overall approach, studies often make blanket recommendations about which allocation methods are best while, in reality, some of the methods are only appropriate in a consequential LCA.

A prime example is system expansion, which is touted as being preferable to allocation by mass, energy content, or market value in most of the literature, including ISO 14044 (*54*). System expansion is performed by measuring the net change in a system's environmental impacts as a result of introducing a co-product and is thus inherently consequential. As is the case for total water withdrawals resulting from cellulosic biorefining, the impacts displaced by the co-product can be so large in some cases that the result is net negative. In an attributional LCA, which is essentially an impact accounting practice, the result should never be negative. The same criticism can be made of open-loop recycling literature, which attempts to both achieve the decision support goals of a consequential LCA and the accurate accounting goals of an attributional LCA. Separating methods appropriate for consequential LCA and those appropriate for attributional simplifies the allocation problem significantly. In a consequential LCA, double-counting recycling credits is a non-issue because consequential LCAs are not intended to be additive, but rather measure the net change in system-wide impacts as a result of a given activity.

### 7.1.2 Freshwater Use Impact Assessment

While impact allocation has been heavily studied with no completely satisfactory results, water use impact assessment faces the opposite problem: significant strides have been made in the past few years and the debate about how this impact assessment should be carried out is only now gaining momentum (*35, 93*). One study other than this dissertation has tackled the difficult task of freshwater use impact assessment (*10*). Although novel in its approach, this study contains a few major problems. First, it relies on water use data at the watershed level,

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whereas most data used in LCA are collected based on political boundaries such as counties, states, and nations. Relying on watershed-level results makes integrating the impact assessment methodology with existing life-cycle water use inventories very challenging. Second, the results are reported in Eco-indicator-99 damage factors that only have meaning relative to one another, so while the results can be compared to one another, they cannot be compared to results in other impact assessments or easily translated into estimated damages that the general public can understand. Furthermore, their proposed methodology is very data and time-intensive. If it remains as the only option for water use impact assessment, other researchers are likely to ignore impact assessment altogether and report only inventory results.

This dissertation presents an entirely new and different approach to assessing the impacts of freshwater use. Instead of running the analysis on a watershed level, it analyzes U.S. counties because this is the finest granularity that can be reasonably achieved for U.S. data. The locations of power plants, petroleum refineries, and other facilities are typically reported by county. Second, unlike previous literature, water use is split into ground and surface water to allow for separate modeling of each resource. Although there is interaction between the two resources, they are also fundamentally different in their short and long-term responses to changes in climate and pumping for human usage. Finally, the methodology presented in this dissertation is far less time-consuming than the previously proposed method, requiring only publicly available data on groundwater overpumping and drought vulnerability. The results are more informative than simple water use estimates, but still in physical units, making them more accessible to decision makers and the general public. Leaving the results in physical units also allows users more flexibility in developing their own interpretation or using the results as inputs to future analyses. It should be noted, however, that this impact assessment method relies on data that is known to be available for the United States. If researchers choose to utilize it for assessment of other countries, the necessary supporting data on groundwater overpumping and drought vulnerability may not be sufficient.

## 7.2 Contributions to Knowledge of the Water Impacts of U.S. Transportation Fuels

In addition to the methodological contributions, the results from this dissertation add to society’s knowledge about the water impacts of existing and alternative transportation fuel production pathways. These results provide a glimpse into how incentivizing production of a particular fuel or set of fuels could alter freshwater availability in the United States. There are three main points that emerge as being both novel and important in the discussion about the water impacts of transportation fuels: (1) the choice between consequential and attributional may have a dramatic impact on the results, (2) the inclusion of indirect water is critical, particularly for cellulosic ethanol, and (3) the geospatial distribution of water use is key in determining its impact on ground and surface water.

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### 7.2.1 Marginal Units and Their Potential Impact on the Results

The importance of making a definitive choice between consequential and attributional LCA has been discussed to some extent in Section 7.1.1. In addition to dictating methodological choices such as impact allocation, it also dictates the input data and thus can change the results. In Chapter 6, a sensitivity analysis is run, exploring the lowest, average, and highest water intensities for production processes that occur along the life cycle of transportation fuels. The results prove that, if production at the margin is substantially different in terms of technology and/or location than the average, the total water use and associated impacts will also be substantially different. For example, the difference between the water footprint of irrigated corn grain grown in the arid west and that of rain-fed corn grain in parts of the Midwest is two orders of magnitude. The water-intensity of gasoline from crude oil may triple if the marginal unit requires more water-intensive technologies in wells where produced water is scarce. Electricity is also subject to large uncertainty associated with the difference between the average and marginal unit. If the average unit of electricity comes from a natural gas-fired plant with closed-loop cooling, for example, its water consumption will be higher than the average, but its water withdrawals will be far lower.

Having discussed the importance of the marginal vs. average distinction, it should be acknowledged that determining the origin of the marginal unit for any given product or service is difficult and depends on economic modeling to predict relative prices and availability. The difficulty of this type of analysis is likely the reason why so many LCAs take an attributional approach or claim to use a consequential approach, but use a great deal of attributional input data. While this dissertation does not provide a purely consequential LCA, it does serve to highlight the importance of making the distinction between the average and marginal unit. The results of the sensitivity analysis indicate that even a cursory attempt at establishing the difference between the average and marginal unit for transportation fuels would greatly improve researchers' understanding of the environmental impacts.

### 7.2.2 Indirect Impacts

The inclusion of indirect impacts is something that has only been done in a handful of studies (see references (*8, 9*)), and none have gone beyond the water use inventory to quantify the impacts on resource availability. As discussed in Chapter 6, including indirect water use has a significant impact on the overall results, particularly for withdrawals. This is because water withdrawals for electricity production are largely due to the use of open-loop cooling systems at many power plants in the United States (*31*). In no other pathway is this as pronounced as it is for cellulosic ethanol production (in this case, corn stover and Miscanthus to ethanol). For no obvious reason, even the literature that includes indirect water use ignores the effect that electricity exports have on water use as a whole. By using system expansion to account for the electricity generation displaced by cellulosic biorefineries' exports to the grid, total consumption for those pathways drops considerably and the total withdrawals actually becomes a net negative number. If the evaporative losses associated with hydroelectricity

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production are included in the water footprint of electricity generation, as discussed in Chapter 6, the impacts of including indirect water use would be even more pronounced.

### 7.2.3 The Importance of Geospatial Disaggregation

Stopping at the life-cycle inventory stage, as all other transportation fuel water use studies have done so far, leaves the reader wondering what the results mean for the availability of freshwater resources. Geospatial disaggregation of inventory results, which has not been done for any water use LCAs of transportation fuels in the United States, proves to be invaluable in determining the potential impacts on freshwater availability. As long as water use is mapped at a reasonably small granularity, such as watershed, or even state, some conclusions can be drawn based on general knowledge about the state of surface and groundwater in those locations. For example, this dissertation is able to match up geospatially disaggregated results with drought and groundwater vulnerability data in order to draw important conclusions about how each fuel production pathway might impact water resources, and what locations are at risk of experiencing additional water stress. Corn ethanol clearly places a large burden on already overpumped groundwater in Nebraska, crude oil extraction may contribute to surface and groundwater scarcity in Southern California, and petroleum refineries place a disproportionate amount of water burden on drought-prone Wyoming. Depending on the particular goals of future studies, the impact assessment methods may change, but this dissertation demonstrates that a great deal of information can be gathered simply by geospatially disaggregating life-cycle water use.

## 7.3 Future Work Recommendations

Life-cycle assessment of water use is a relatively undeveloped field compared to those dealing with air emissions and energy use, so this dissertation serves as a first step in what will hopefully be the path to better, more robust water use inventories and impact assessments. In addition to the methodological contributions and results, a number of areas in need of further work have revealed themselves over the course of this research, the most important of which are described in the following sections.

### 7.3.1 Establishment of Marginal Units

As discussed in Section 7.2.1, the disparity between marginal units and average units can make a significant difference in the results of an LCA. In the case of transportation fuels, this is especially true because the geographic location of crop production and crude oil extraction, for example, has a major impact on the how much water is required. Although many studies claim to take a consequential approach, attributional data is used when information about the marginal unit is unavailable. A classic example is electricity; it is common practice in LCA to use the average electricity mix in a consequential LCA because information on what electricity is generated at the margin is not readily available or requires time and data-intensive grid modeling. However, based on the large ranges shown in the sensitivity analysis in Chapter 6, even a rough estimate of what makes up the marginal unit of a given product or service would be extremely valuable.

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### 7.3.2 Scenario Development for Alternative Transportation Fuels

For cellulosic biofuels, there is no average or marginal unit because the industry is essentially non-existent. Until costs are reduced and/or policy becomes more aggressive in incentivizing the production of these fuels, production will continue to be negligible (*87*). In a sense, this is an ideal scenario because the environmental impacts can be modeled, thus screening the technology before any major investments are made. However, this also requires that any environmental assessment make predictions about the future market: where the biomass crops will be grown, where and how they will be processed, and where they will ultimately be consumed. One of the major shortcomings of this dissertation and other comparable literature is that they lack data for potential Miscanthus crop and biorefinery locations, which are particularly critical when attempting to model local water impacts. The same is true of electricity, for which production would significantly increase if it were to supply energy for transportation. Predicting where consumption would be and what types of power plants are likely to be built in order to meet the additional demand is crucial in effectively modeling water and other environmental impacts.

### 7.3.3 Land Use Change

Land use change is typically discussed in the context of greenhouse gas emissions (*47*). However, it has an impact on water use as well. In previous attempts to quantify green water use, researchers simply total up the fraction of rainwater and soil moisture that is consumed through evapotranspiration, ignoring the fact that whatever biofuel crop is planted has replaced some other land use that inevitably had its own green water footprint (*17*). In order to responsibly calculate the green water impact of biofuel crops, it is critical that researchers gain a better understanding of what land will likely be used to grow biofuel crops and what currently exists on that land. Only then will it be possible to calculate the net change in green water consumption as a result of increased biofuel (or any agricultural) production.

### 7.3.4 Water Use Efficiency and Interaction with Other Inputs

Lastly, a useful next step in the study of water use for transportation-fuel production is the exploring of how water impacts can be reduced and with what tradeoffs. Even simple water use factors for many agricultural, industrial, and fuel products are difficult to obtain and water efficiency measurements are even scarcer. As the role of water in human activities becomes better understood, researchers should include assessments of efficiency in LCAs, pinpointing areas in which water use can be reduced and at what cost (both monetary and environmental). For example, some water-stressed locations utilize dry cooling in power plants despite its negative impact on energy efficiency (*31*). One potential tradeoff in the realm of biofuels is the ability to increase biomass crop yields by increasing irrigation (*223*). Increased yields leads to less energy use for feedstock transportation to the biorefinery and thus may have a non-negligible impact on the overall GHG footprint of biofuels. Exploring these tradeoffs will help to go beyond simply understanding the water impacts of transportation fuels by providing decision-makers with the tools to manage natural resources in the most sustainable fashion.

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(223) Ercoli, L.; Mariotti, M.; Masoni, A.; Bonari, E. Effect of Irrigation and Nitrogen Fertilization on Biomass Yield and Efficiency of Energy Use in Crop Production of *Miscanthus*. *Field Crops Research* **1999,** *63* (1), 3-11.

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# Appendix A: Methodology

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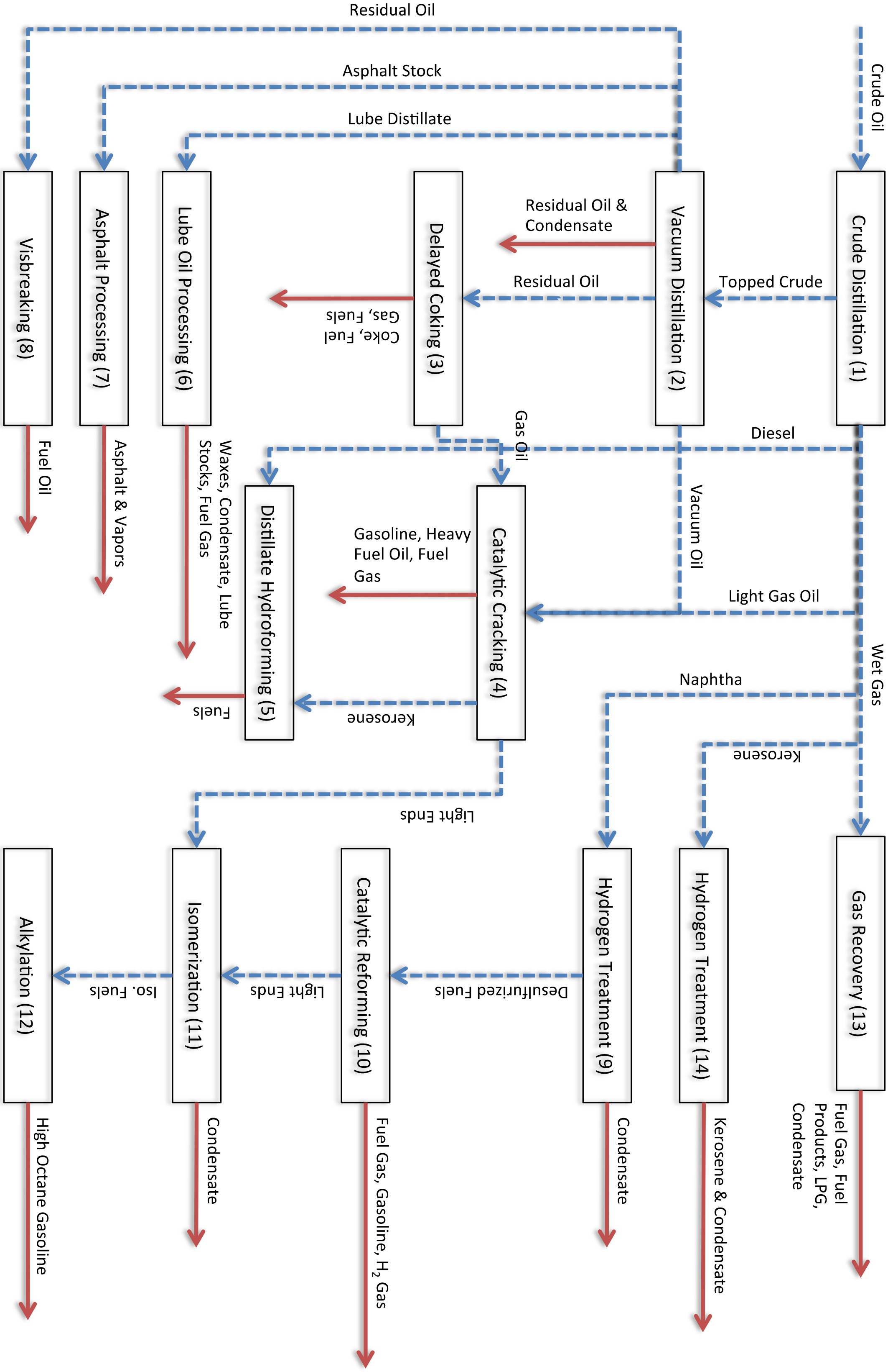

Figure 68: Example Petroleum Refining Process (Recreated from (*1*))

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# References

(1) Brown, H. L.; Hamel, B. B.; Hedman, B. A., *Energy Analysis of 108 Industrial Processes*. The Fairmont Press, Inc.: Lilburn, GA, 1996; p 314.

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# Appendix B: Water Use Inventory Calculations

## B.1 Agricultural Systems

$ET_o$ = Reference evapotranspiration (mm/day)

$R_n$ = Net solar radiation at the crop surface (MJ/m$^2$-day)

$G$ = Soil heat flux density (MJ/m$^2$-day)

$T$ = Mean daily air temperature at 2 m height (°C)

$u_2$ = Wind speed at 2 m height (m/s)

$e_s$ = Saturation vapor pressure, average of $e°(T_{max})$ and $e°(T_{min})$ (kPa)

$e_a$ = Actual vapor pressure (kPa)

$(e_s - e_a)$ = Saturation vapor pressure deficit (kPa)

$\Delta$ = Slope vapor pressure curve (kPa/°C)

$\gamma$ = Psychrometric constant (kPa/°C)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Equation 14: FAO Version of the Penman-Monteith Equation (Source: (*1*))

This equation appears daunting, but the psychrometric constant, vapor pressure curve slope, saturation vapor pressure, and actual vapor pressure depends only on altitude z (m), daily maximum and minimum temperatures $T_{max}$, $T_{min}$ (°C), and maximum and minimum relative humidity $RH_{max}$, $RH_{min}$, as shown in Equation 15 through Equation 18:

$$\gamma = 7.124 \times 10^{-15}(293 - 0.0065z)^{5.26}$$

Equation 15: Psychrometric Constant as a Function of Altitude (z) (Source: (*1*))

$$\Delta = \frac{2503e^{\frac{17.277}{T+237.3}}}{(T+237.3)^2}$$

Equation 16: Vapor Pressure Curve Slope as a Function of Temperature (T) (Source: (*1*))

$$e^o(T) = 0.6108e^{(\frac{17.277}{T+237.3})}$$

Equation 17: Saturation Vapor Pressure as a Function of Temperature (T) (Source: (*1*))

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$$e_a = \frac{e^o(T_{\min})\frac{RH_{\max}}{100} + e^o(T_{\max})\frac{RH_{\min}}{100}}{2}$$

Equation 18: Actual Vapor Pressure as a Function of Relative Humidity (RH) and Temperature (T) (Source: (*1*))

For large-scale evapotranspiration (ET) modeling, some of the weather data necessary for use of Equation 14 may not be available. In this case, the FAO suggests a simplified version (Equation 19) that requires only three pieces of information: daily minimum temperature, maximum temperature, and net solar radiation.

$$ET_o = 0.0023(T + 17.8)(T_{\max} - T_{\min})^{0.5} R_n$$

Equation 19: FAO-Suggested Simplified Penman-Monteith Equation (Source: (*1*))

Finally, the reference ET must be adjusted for the specific crop of interest. Many factors cause ET for crops to vary, including plant size and surface area, and the physical structure. For example, *Miscanthus x Giganteus* is a tall grass that forms a dense canopy, causing 20-30% of the rainfall to be intercepted and evaporated instead of reaching the soil below (*2*). To make this adjustment, an empirical constant, $K_c$, is used as shown in Equation 20 (*3*). Values for $K_c$ can be found in reference (*1*).

$$ET_c = K_c ET_o$$

Equation 20: Adjustment of Reference ET for Specific Crops (Source: (*1*))

The Penman-Monteith Equation is very useful for estimating consumptive water use, including both green and blue water. Because ET includes evaporative losses from the plants themselves and the surrounding soil, the only consumptive use theoretically not included in ET is the water that is incorporated into the product (in this case, biomass). Therefore, the equation for total consumptive water use is as shown in Equation 21, where $\%_{\text{moisture}}$ equals the biomass moisture content and $M_{\text{harvested}}$ is the total biomass harvested, t is the total time of analysis measured in days, and $A_{\text{crop}}$ equals the total surface area of the crop.

$$\text{Consumptive Water Use} = (A_{crop}\sum_{0}^{t} ET_c) + (\%_{moisture})(M_{harvested})$$

Equation 21: Total Consumptive Water Use

| **Crop** | **Variable** | **Initial** | **Development** | **Mid-Season** | **Late-Season** | **Total** |
|---|---|---|---|---|---|---|
| **Corn (Idaho, USA)** | Stage Length (days) | 30 (Plant Date: April 1st) | 40 | 50 | 50 (Harvest Date: Sept. 17th) | 170 |
| | $K_c$ | 0.3 | - | 1.2 | 0.5 | - |
| | Rooting Depth (m) | 0.3 | - | - | 1.00 | |
| | Critical Depletion (fraction) | 0.5 | 0.5 | 0.5 | 0.8 | - |
| | Yield Response Factor | 0.4 | 0.4 | 1.3 | 0.5 | 1.25 |
| | Crop Height (m) | - | - | $2^2$ | - | - |

Table 60: CropWat Parameters for U.S. Corn Production

| **State** | **Station Location** | **Corn** |
|---|---|---|

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| | | |
|---|---|---|
| AK | Anchorage | N/A |
| | Juneau | N/A |
| | Nome | N/A |
| AL | Montgomery | X |
| AR | Fort Smith | X |
| AZ | Phoenix | |
| | Tucson | X |
| | Yuma | |
| CA | San Diego | |
| | Fresno | X |
| | Sacramento | |
| CO | Denver | X |
| | Grand Junction | |
| | Pueblo | |
| CT | Hartford | X |
| DA | N/A | N/A |
| FL | Fort Wayne | |
| | Jacksonville | X |
| | Key West | |
| | Miami | |
| | Tampa | |
| GA | Atlanta | |
| | Macon | |
| | Savannah | X |
| HI | Hilo | N/A |
| | Honolulu | N/A |
| | Kahului | N/A |
| | Lihue | N/A |
| IA | Des Moines | X |
| | Sioux City | |
| ID | Boise | X |
| | Pocatello | |
| IL | Peoria | X |
| | Chicago | |
| | Moline | |
| | Springfield | |
| IN | Evansville | |
| | Indianapolis | X |
| KS | Concordia-Blosser | |
| | Dodge City | |
| | Kansas City | X |
| | Topeka | |
| | Wichita | |
| KY | Louisville | X |
| LA | New Orleans | X |
| | Shreveport | |
| MA | Boston | X |
| MD | Baltimore/Washington, DC | X |
| MI | Detroit | |
| | Grand Rapids | |
| | Sault Ste Marie | X |
| MN | Duluth | |
| | Minneapolis | X |
| MO | Columbia | X |
| | Springfield | |
| | St. Louis | |
| MS | Jackson | X |
| | Billings | |
| | Great Falls | |
| | Helena | |
| | Missoula-Johnson-Bell | |
| NC | Asheville | |
| | Cape Hatteras | X |
| | Charlotte | |
| | Greensboro | |

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|  |  |  |
|---|---|---|
|  | Raleigh |  |
| ND | Bismarck |  |
|  | Fargo | X |
|  | Williston-Sloulin |  |
| NE | Lincoln | X |
|  | North Platte |  |
|  | Valentine |  |
| NJ | Atlantic City | X |
| NM | Albuquerque |  |
|  | Roswell | X |
| NV | Ely-Yelland | Avg. |
|  | Las Vegas |  |
|  | Reno |  |
|  | Winnemucca |  |
| NY | Albany |  |
|  | Binghamton/Broome County |  |
|  | Buffalo |  |
|  | Rochester | X |
|  | Syracuse |  |
| OH | Cleveland |  |
|  | Cincinnati |  |
|  | Columbus |  |
|  | Dayton | X |
|  | Huron |  |
|  | Toledo |  |
| OK | Oklahoma City |  |
|  | Tulsa | X |
| OR | Portland | X |
| PA | Philadelphia | X |
|  | Pittsburgh |  |
|  | Wilkes-Barre |  |
| RI | Providence | X |
| SC | Charleston |  |
|  | Columbia | X |
|  | Greenville |  |
| SD | Alpena | X |
|  | Rapid City |  |
| TN | Chattanooga | X |
|  | Knoxville |  |
|  | Memphis |  |
|  | Nashville |  |
| TX | Abilene |  |
|  | Amarillo | X |
|  | Austin-Robert-Mueller |  |
|  | Brownsville |  |
|  | Corpus Christi |  |
|  | Dallas-Fort Worth |  |
|  | El Paso |  |
|  | Houston |  |
|  | Lubbock |  |
|  | Port Arthur |  |
|  | San Antonio |  |
| UT | Salt Lake City | X |
| VA | Lynchburg | X |
|  | Norfolk |  |
|  | Richmond |  |
|  | Washington Nat'l Airport |  |
| VT | Burlington | X |
| WA | Seattle |  |
|  | Spokane | X |
| WI | Green Bay |  |
|  | Madison | X |
|  | Milwaukee |  |
| WY | Cheyenne |  |
|  | Lander Hunt |  |

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| | |
|---|---|
| Sheridan | X |

Table 61: Representative ClimWat Stations for Corn Agriculture by State

| State | Climate Monitor Location | USDA-Measured State Annual Corn Production (bushels) | Etc Predicted by CropWat (mm) | Rainfall Predicted by CropWat (mm) | Irr Requirement Prediced by CropWat (mm) | 2003 FRIS Irrigation Applications (irrigated land only) (mm) | Green Water Requirement (mm) |
|---|---|---|---|---|---|---|---|
| AL | Montgomery | 2.10E+07 | 7.50E+02 | 4.95E+02 | 3.20E+02 | 1.52E+02 | 5.98E+02 |
| AR | Fort Smith | 9.98E+07 | 8.33E+02 | 4.11E+02 | 4.54E+02 | 2.13E+02 | 6.20E+02 |
| AZ | Tucson | 4.08E+06 | 1.45E+03 | 1.46E+02 | 1.30E+03 | 1.04E+03 | 4.11E+02 |
| CA | Fresno | 3.46E+07 | 1.26E+03 | 3.74E+01 | 1.22E+03 | 7.32E+02 | 5.24E+02 |
| CO | Denver | 1.41E+08 | 9.75E+02 | 2.36E+02 | 7.37E+02 | 5.18E+02 | 4.56E+02 |
| FL | Jacksonville | 2.99E+06 | 8.08E+02 | 5.74E+02 | 2.76E+02 | 3.05E+02 | 5.03E+02 |
| GA | Savannah | 5.41E+07 | 7.90E+02 | 5.74E+02 | 2.51E+02 | 1.22E+02 | 6.68E+02 |
| IA | Des Moines | 2.29E+09 | 7.86E+02 | 4.60E+02 | 3.81E+02 | 1.52E+02 | 6.34E+02 |
| ID | Boise | 1.78E+07 | 1.08E+03 | 1.06E+02 | 9.72E+02 | 8.53E+02 | 2.27E+02 |
| IL | Peoria | 2.25E+09 | 4.57E+02 | 3.41E+02 | 1.64E+02 | 1.83E+02 | 2.74E+02 |
| IN | Indianapolis | 9.60E+08 | 7.41E+02 | 4.50E+02 | 3.47E+02 | 1.52E+02 | 5.89E+02 |
| KS | Kansas City | 5.01E+08 | 8.47E+02 | 5.02E+02 | 3.97E+02 | 4.27E+02 | 4.20E+02 |
| KY | Louisville | 1.67E+08 | 7.45E+02 | 4.71E+02 | 3.41E+02 | 1.52E+02 | 5.93E+02 |
| LA | New Orleans | 1.15E+08 | 7.34E+02 | 6.00E+02 | 2.16E+02 | 1.83E+02 | 5.51E+02 |
| MD | Baltimore/Washington, D.C. | 4.55E+07 | 7.81E+02 | 4.35E+02 | 3.85E+02 | 9.14E+01 | 6.89E+02 |
| MI | Sault Ste Marie | 2.88E+08 | 5.67E+02 | 3.70E+02 | 2.53E+02 | 1.52E+02 | 4.15E+02 |
| MN | Minneapolis | 1.14E+09 | 8.06E+02 | 4.07E+02 | 4.26E+02 | 1.83E+02 | 6.23E+02 |
| MO | Columbia | 4.39E+08 | 8.03E+02 | 4.73E+02 | 3.95E+02 | 1.83E+02 | 6.20E+02 |
| MS | Jackson | 1.28E+08 | 7.97E+02 | 5.01E+02 | 3.80E+02 | 1.83E+02 | 6.14E+02 |
| MT | Billings | 5.15E+06 | 9.92E+02 | 2.12E+02 | 7.84E+02 | 7.32E+02 | 2.60E+02 |
| NC | Cape Hatteras | 9.82E+07 | 6.35E+02 | 5.25E+02 | 1.86E+02 | 1.52E+02 | 4.83E+02 |
| ND | Fargo | 2.75E+08 | 8.21E+02 | 3.06E+02 | 5.28E+02 | 2.74E+02 | 5.47E+02 |
| NE | Lincoln | 1.43E+09 | 9.07E+02 | 4.19E+02 | 5.21E+02 | 3.66E+02 | 5.42E+02 |
| NJ | Atlantic City | 1.01E+07 | 7.13E+02 | 4.18E+02 | 3.47E+02 | 9.14E+01 | 6.21E+02 |
| NM | Roswell | 9.63E+06 | 1.22E+03 | 2.03E+02 | 1.01E+03 | 7.01E+02 | 5.15E+02 |
| NY | Rochester | 7.15E+07 | 6.68E+02 | 3.62E+02 | 3.44E+02 | 1.22E+02 | 5.46E+02 |
| OH | Dayton | 5.27E+08 | 7.81E+02 | 4.21E+02 | 4.12E+02 | 4.88E+02 | 2.93E+02 |
| OK | Tulsa | 3.86E+07 | 9.74E+02 | 4.75E+02 | 5.51E+02 | 4.57E+02 | 5.17E+02 |
| PA | Philadelphia | 1.19E+08 | 7.49E+02 | 4.55E+02 | 3.50E+02 | 6.10E+01 | 6.88E+02 |
| SC | Columbia | 3.51E+07 | 7.99E+02 | 5.22E+02 | 3.08E+02 | 1.22E+02 | 6.77E+02 |
| SD | Alpena | 5.19E+08 | 6.35E+02 | 3.62E+02 | 3.13E+02 | 3.05E+02 | 3.31E+02 |
| TN | Chattanooga | 8.36E+07 | 7.00E+02 | 4.84E+02 | 2.89E+02 | 1.52E+02 | 5.47E+02 |
| TX | Amarillo | 2.86E+08 | 1.28E+03 | 3.19E+02 | 9.59E+02 | 4.88E+02 | 7.96E+02 |
| UT | Salt Lake City | 3.25E+06 | 1.18E+03 | 1.72E+02 | 1.02E+03 | 8.53E+02 | 3.31E+02 |
| VA | Lynchburg | 3.48E+07 | 6.96E+02 | 4.34E+02 | 3.01E+02 | 9.14E+01 | 6.05E+02 |
| WA | Spokane | 2.46E+07 | 9.44E+02 | 1.37E+02 | 8.07E+02 | 6.40E+02 | 3.04E+02 |
| WI | Madison | 4.37E+08 | 6.93E+02 | 4.17E+02 | 3.24E+02 | 2.13E+02 | 4.80E+02 |
| WY | Sheridan | 6.86E+06 | 8.67E+02 | 2.07E+02 | 6.68E+02 | 3.66E+02 | 5.02E+02 |

Table 62: Green Water Consumption Estimates for Corn by State

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| State | Irr. Land (ha) | Non-Irr. Land (ha) | % Land Irr. | Total Irr. Prod. (bushels) | Total Non-Irr. Prod. (bushels) | Irr. Water App. to Irr. Land ($m^3$/ha) | Irr. Water App. to Avg. Land ($m^3$/ha) | Average Irr. App. ($m^3$/bushel) |
|---|---|---|---|---|---|---|---|---|
| AL | 7.84E+03 | 1.04E+05 | 7% | 3.14E+06 | 3.29E+07 | 6.17E+02 | 4.32E+01 | 1.34E-01 |
| AZ | 9.08E+03 | 9.17E+01 | 99% | 4.17E+06 | 4.21E+04 | 4.19E+03 | 4.15E+03 | 9.03E+00 |
| AR | 1.35E+05 | 1.02E+05 | 57% | 5.00E+07 | 2.87E+07 | 8.63E+02 | 4.92E+02 | 1.48E+00 |
| CA | 7.69E+04 | 0.00E+00 | 100% | 3.36E+07 | 0.00E+00 | 2.96E+03 | 2.96E+03 | 6.77E+00 |
| CO | 3.76E+05 | 5.12E+04 | 88% | 1.63E+08 | 3.80E+06 | 2.10E+03 | 1.85E+03 | 4.71E+00 |
| DE | 1.95E+04 | 5.55E+04 | 26% | 7.23E+06 | 1.76E+07 | 6.17E+02 | 1.60E+02 | 4.85E-01 |
| FL | 3.43E+03 | 1.03E+04 | 25% | 1.06E+06 | 1.27E+06 | 1.23E+03 | 3.08E+02 | 1.82E+00 |
| GA | 6.18E+04 | 1.20E+05 | 34% | 2.41E+07 | 3.38E+07 | 4.93E+02 | 1.68E+02 | 5.26E-01 |
| ID | 1.18E+03 | 2.42E+01 | 98% | 5.00E+05 | 5.97E+03 | 3.45E+03 | 3.38E+03 | 8.08E+00 |
| IL | 1.06E+05 | 5.19E+06 | 2% | 4.56E+07 | 2.09E+09 | 7.40E+02 | 1.48E+01 | 3.67E-02 |
| IN | 7.72E+04 | 2.50E+06 | 3% | 3.23E+07 | 8.83E+08 | 6.17E+02 | 1.85E+01 | 5.21E-02 |
| IA | 5.60E+04 | 5.55E+06 | 1% | 2.37E+07 | 2.00E+09 | 6.17E+02 | 6.17E+00 | 1.71E-02 |
| KS | 7.74E+05 | 7.15E+05 | 52% | 3.41E+08 | 1.01E+08 | 1.73E+03 | 8.98E+02 | 3.03E+00 |
| KY | 5.31E+03 | 5.26E+05 | 1% | 2.10E+06 | 1.64E+08 | 6.17E+02 | 6.17E+00 | 1.98E-02 |
| LA | 7.02E+04 | 2.22E+05 | 24% | 2.76E+07 | 4.45E+07 | 7.40E+02 | 1.78E+02 | 7.21E-01 |
| MD | 1.49E+04 | 1.71E+05 | 8% | 6.04E+06 | 5.67E+07 | 3.70E+02 | 2.96E+01 | 8.78E-02 |
| MI | 8.56E+04 | 8.66E+05 | 9% | 3.49E+07 | 2.61E+08 | 6.17E+02 | 5.55E+01 | 1.78E-01 |
| MN | 9.47E+04 | 3.06E+06 | 3% | 3.96E+07 | 9.84E+08 | 7.40E+02 | 2.22E+01 | 6.85E-02 |
| MS | 8.13E+04 | 2.72E+05 | 23% | 3.30E+07 | 7.67E+07 | 7.40E+02 | 1.70E+02 | 5.49E-01 |
| MO | 1.19E+05 | 1.20E+06 | 9% | 4.63E+07 | 3.55E+08 | 7.40E+02 | 6.66E+01 | 2.19E-01 |
| MT | 1.38E+04 | 1.54E+03 | 90% | 4.79E+06 | 0.00E+00 | 2.96E+03 | 2.66E+03 | 8.00E+00 |
| NE | 2.27E+06 | 1.45E+06 | 61% | 1.04E+09 | 5.05E+08 | 1.48E+03 | 9.03E+02 | 2.17E+00 |
| NJ | 1.98E+03 | 3.10E+04 | 6% | 7.73E+05 | 2.76E+06 | 3.70E+02 | 2.22E+01 | 2.07E-01 |
| NM | 2.14E+04 | 4.36E+02 | 98% | 1.03E+07 | 1.26E+05 | 2.84E+03 | 2.78E+03 | 5.82E+00 |
| NY | 2.23E+03 | 2.21E+05 | 1% | 9.76E+05 | 6.61E+07 | 4.93E+02 | 4.93E+00 | 1.64E-02 |
| NC | 1.17E+04 | 3.79E+05 | 3% | 3.71E+06 | 1.01E+08 | 6.17E+02 | 1.85E+01 | 6.89E-02 |
| ND | 4.75E+04 | 9.03E+05 | 5% | 1.68E+07 | 3.12E+08 | 1.11E+03 | 5.55E+01 | 1.60E-01 |
| OH | 0.00E+00 | 1.46E+06 | 0% | 0.00E+00 | 4.15E+08 | 1.97E+03 | 0.00E+00 | 0.00E+00 |
| OK | 5.70E+04 | 5.26E+04 | 52% | 2.34E+07 | 1.63E+07 | 1.85E+03 | 9.62E+02 | 2.65E+00 |
| OR | 1.37E+04 | 5.71E+02 | 96% | 6.64E+06 | 0.00E+00 | 3.08E+03 | 2.96E+03 | 6.21E+00 |
| PA | 0.00E+00 | 3.97E+05 | 0% | 0.00E+00 | 9.66E+07 | 2.47E+02 | 0.00E+00 | 0.00E+00 |
| SC | 9.05E+03 | 1.42E+05 | 6% | 3.35E+06 | 3.89E+07 | 4.93E+02 | 2.96E+01 | 1.06E-01 |
| SD | 7.21E+04 | 1.73E+06 | 4% | 3.01E+07 | 5.65E+08 | 1.23E+03 | 4.93E+01 | 1.50E-01 |
| TN | 3.16E+03 | 3.13E+05 | 1% | 1.26E+06 | 3.94E+07 | 6.17E+02 | 6.17E+00 | 4.79E-02 |
| TX | 2.94E+05 | 5.01E+05 | 37% | 1.34E+08 | 1.72E+08 | 1.97E+03 | 7.30E+02 | 1.90E+00 |
| UT | 8.13E+03 | 5.19E+02 | 94% | 3.27E+06 | 0.00E+00 | 3.45E+03 | 3.25E+03 | 8.57E+00 |
| VA | 6.49E+03 | 1.56E+05 | 4% | 2.63E+06 | 1.96E+07 | 3.70E+02 | 1.48E+01 | 1.08E-01 |
| WA | 4.80E+04 | 0.00E+00 | 100% | 2.21E+07 | 0.00E+00 | 2.59E+03 | 2.59E+03 | 5.64E+00 |
| WI | 3.95E+04 | 1.28E+06 | 3% | 1.67E+07 | 3.59E+08 | 8.63E+02 | 2.59E+01 | 9.06E-02 |
| WY | 2.16E+04 | 4.42E+02 | 98% | 6.58E+06 | 0.00E+00 | 1.48E+03 | 1.45E+03 | 4.87E+00 |

Table 63: Corn Irrigation Water Application (Data Sources: (*4, 5*))

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## B.2 Electricity Generation

| Geothermal | Solar | Wind | Biomass | Hydro | Nuclear | Natural Gas | Oil | Coal | T&D Loss Adjustment Factors |
|---|---|---|---|---|---|---|---|---|---|
| 0.0% | 0.0% | 0.0% | 0.1% | 22.3% | 0.0% | 56.6% | 11.6% | 9.5% | 12.9% |
| 0.0% | 0.0% | 0.0% | 1.5% | 0.0% | 13.8% | 39.0% | 17.9% | 26.2% | 9.6% |
| 1.9% | 0.0% | 0.1% | 2.6% | 0.8% | 0.0% | 0.0% | 78.8% | 14.2% | 8.9% |
| 0.0% | 0.0% | 1.8% | 1.2% | 4.1% | 14.0% | 5.2% | 0.8% | 72.7% | 9.6% |
| 0.0% | 0.0% | 0.0% | 3.2% | 11.7% | 27.2% | 29.2% | 13.2% | 14.4% | 9.6% |
| 0.0% | 0.0% | 0.1% | 0.7% | 0.6% | 26.2% | 5.8% | 1.4% | 64.4% | 9.6% |
| 0.0% | 0.0% | 0.0% | 1.8% | 3.3% | 24.2% | 11.7% | 1.5% | 57.1% | 9.6% |
| 0.0% | 0.0% | 0.9% | 1.1% | 2.6% | 4.1% | 27.7% | 0.7% | 62.6% | 9.6% |
| 0.0% | 0.0% | 1.2% | 0.1% | 0.3% | 11.9% | 47.5% | 0.5% | 37.1% | 16.0% |
| 2.1% | 0.1% | 1.1% | 1.3% | 24.7% | 10.1% | 26.3% | 0.5% | 33.4% | 8.4% |
| 0.4% | 0.0% | 0.4% | 1.3% | 6.5% | 19.3% | 18.8% | 3.0% | 49.6% | 9.9% |
| (7) | (7) | (7) | (7) | (7) | (7) | (7) | (7) | (7) | (6) |

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| **Region** | **Other/ Unknown** | **Other Fossil** |
|---|---|---|
| ASCC | 0.0% | 0.0% |
| FRCC | 0.8% | 0.6% |
| HICC | 0.0% | 1.6% |
| MRO | 0.0% | 0.2% |
| NPCC | 0.0% | 1.1% |
| RFC | 0.1% | 0.7% |
| SERC | 0.1% | 0.4% |
| SPP | 0.1% | 0.2% |
| TRE | 0.2% | 1.2% |
| WECC | 0.0% | 0.4% |
| U.S. Avg | 0.1% | 0.6% |
| Data Source | (*7*) | (*7*) |

Table 64: Electricity Mixes by NERC Region

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| Fuel | Cooling System | Boiler Type/Plant Type | FGD System | Withdrawals (L/kWh) | Consumption (L/kWh) | Data Source |
|---|---|---|---|---|---|---|
| Coal | Once-Through | Subcritical | Wet | 1.0E+02 | 5.2E-01 | (*8*) |
| Coal | Once-Through | Subcritical | Dry | 1.0E+02 | 4.3E-01 | (*8*) |
| Coal | Once-Through | Subcritical | None | 1.0E+02 | 2.7E-01 | (*8*) |
| Coal | Once-Through | Supercritical | Wet | 8.6E+01 | 4.7E-01 | (*8*) |
| Coal | Once-Through | Supercritical | Dry | 8.6E+01 | 3.9E-01 | (*8*) |
| Coal | Once-Through | Supercritical | None | 8.5E+01 | 2.4E-01 | (*8*) |
| Coal | Once-Through | AVERAGE | AVERAGE | 9.8E+01 | 5.0E-01 | Calculated |
| Coal | Recirculating | Subcritical | Wet | 2.0E+00 | 1.7E+00 | (*8*) |
| Coal | Recirculating | Subcritical | Dry | 1.9E+00 | 1.7E+00 | (*8*) |
| Coal | Recirculating | Subcritical | None | 1.8E+00 | 1.5E+00 | (*8*) |
| Coal | Recirculating | Supercritical | Wet | 2.5E+00 | 2.0E+00 | (*8*) |
| Coal | Recirculating | Supercritical | Dry | 2.5E+00 | 1.9E+00 | (*8*) |
| Coal | Recirculating | Supercritical | None | 2.3E+00 | 1.7E+00 | (*8*) |
| Coal | Recirculating | AVERAGE | AVERAGE | 2.1E+00 | 1.8E+00 | Calculated |
| Coal | Cooling Pond | Subcritical | Wet | 6.8E+01 | 3.0E+00 | (*8*) |
| Coal | Cooling Pond | Subcritical | Dry | 6.8E+01 | 2.9E+00 | (*8*) |
| Coal | Cooling Pond | Subcritical | None | 6.8E+01 | 2.8E+00 | (*8*) |
| Coal | Cooling Pond | Supercritical | Wet | 5.7E+01 | 2.4E-01 | (*8*) |
| Coal | Cooling Pond | Supercritical | Dry | 5.7E+01 | 1.6E-01 | (*8*) |
| Coal | Cooling Pond | Supercritical | None | 5.7E+01 | 1.5E-02 | (*8*) |
| Coal | Cooling Pond | AVERAGE | AVERAGE | 6.5E+01 | 2.3E+00 | Calculated |
| Natural Gas | Once-Through | AVERAGE | N/A | 9.8E+01 | 5.0E-01 | Calculated |
| Natural Gas | Recirculating | AVERAGE | N/A | 2.1E+00 | 1.8E+00 | Calculated |
| Biomass | AVERAGE | AVERAGE | N/A | 2.7E+00 | 2.3E+00 | (*9*) |
| Nuclear | Once-Through | AVERAGE | N/A | 1.2E+02 | 5.2E-01 | (*10*) |
| Nuclear | Recirculating | AVERAGE | N/A | 4.2E+00 | 2.4E+00 | (*10*) |
| Nuclear | Cooling Pond | AVERAGE | N/A | 7.9E+01 | 5.4E+00 | Calculated |
| Oil | Once-Through | AVERAGE | N/A | 9.8E+01 | 5.0E-01 | Assumed to be same as coal |
| Oil | Recirculating | AVERAGE | N/A | 2.1E+00 | 1.8E+00 | Assumed to be same as coal |
| Geothermal | Once-Through | Vapor Dominated | N/A | 1.3E+01 | 1.3E+01 | (*9*) |
| Geothermal | Recirculating | Vapor Dominated | N/A | 6.8E+00 | 6.8E+00 | (*9*) |
| Geothermal | Recirculating | Water Dominated | N/A | 1.5E+01 | 1.5E+01 | (*9*) |

Table 65: Water Use for Thermoelectric Power Generation

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|  | Coal: L/MJ Electricity | Oil: L/MJ Electricity | Gas: L/MJ Electricity | Nuclear: L/MJ Electricity | Hydro: L/MJ Electricity | Biomass: L/MJ Electricity | Wind: L/MJ Electricity | Solar: L/MJ Electricity | Geothermal: L/MJ Electricity | Other Fossil: L/MJ Electricity | Unknown: L/MJ Electricity | Weighted Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ASCC** | 5.9E-01 | 6.7E-01 | 7.8E-01 | 8.6E-02 | N/A | 7.2E-01 | N/A | 3.1E-02 | 3.4E+00 | 7.8E-01 | 3.9E-01 | 5.8E-01 |
| **FRCC** | 5.6E-01 | 7.7E-01 | 6.5E-01 | 8.4E-02 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.5E-01 | 3.8E-01 | 5.7E-01 |
| **HICC** | 7.1E-01 | 6.7E-01 | 3.8E-01 | 8.3E-02 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 3.8E-01 | 3.8E-01 | 7.2E-01 |
| **MRO** | 5.6E-01 | 8.2E-01 | 7.1E-01 | 3.7E-01 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 7.1E-01 | 3.8E-01 | 5.1E-01 |
| **NPCC** | 2.9E-01 | 1.3E+00 | 6.6E-01 | 2.7E-01 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.6E-01 | 3.8E-01 | 5.0E-01 |
| **RFC** | 5.5E-01 | 4.0E-01 | 6.2E-01 | 8.3E-01 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.2E-01 | 3.8E-01 | 6.2E-01 |
| **SERC** | 5.8E-01 | 6.8E-01 | 6.6E-01 | 5.2E-01 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.6E-01 | 3.8E-01 | 5.6E-01 |
| **SPP** | 6.8E-01 | 8.0E-01 | 6.8E-01 | 1.0E+00 | N/A | 7.0E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.8E-01 | 3.8E-01 | 6.7E-01 |
| **TRE** | 6.5E-01 | 7.9E-01 | 7.1E-01 | 1.1E+00 | N/A | 7.4E-01 | N/A | 3.2E-02 | 3.5E+00 | 7.1E-01 | 4.0E-01 | 7.2E-01 |
| **WECC** | 7.5E-01 | 7.5E-01 | 6.5E-01 | 1.3E-01 | N/A | 6.9E-01 | N/A | 3.0E-02 | 3.3E+00 | 6.5E-01 | 3.8E-01 | 5.2E-01 |

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Table 66: Life-Cycle Water Consumption for U.S. Electricity Production

|  | U.S. Average | ASCC | FRCC | HICC | MRO | NPCC | RFC | SERC | SPP |
|---|---|---|---|---|---|---|---|---|---|
| Coal: L/MJ Electricity | 5.9E-01 | 1.5E+01 | 1.8E+00 | 8.1E-01 | 1.8E+01 | 1.6E+01 | 1.4E+01 | 1.8E+01 | 1.0E+01 |
| Oil: L/MJ Electricity | 4.8E-01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.3E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 |
| Gas: L/MJ Electricity | 6.6E-01 | 1.3E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 |
| Nuclear: L/MJ Electricity | 5.8E-01 | 8.6E-02 | 8.4E-02 | 8.3E-02 | 2.8E+01 | 1.6E+01 | 1.3E+01 | 1.9E+01 | 2.1E+01 |
| Hydro: L/MJ Electricity | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Biomass: L/MJ Electricity | 7.0E-01 | 8.6E-01 | 8.3E-01 | 8.3E-01 | 8.3E-01 | 8.3E-01 | 8.3E-01 | 8.3E-01 | 8.3E-01 |
| Wind: L/MJ Electricity | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Solar: L/MJ Electricity | 3.1E-02 | 3.1E-02 | 3.0E-02 | 3.0E-02 | 3.0E-02 | 3.0E-02 | 3.0E-02 | 3.0E-02 | 3.0E-02 |
| Geothermal: L/MJ Electricity | 3.4E+00 | 3.4E+00 | 3.3E+00 | 3.3E+00 | 3.3E+00 | 3.3E+00 | 3.3E+00 | 3.3E+00 | 3.3E+00 |
| Other Fossil: L/MJ Electricity | 6.6E-01 | 1.3E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 |
| Unknown: L/MJ Electricity | 3.8E-01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 | 1.2E+01 |
| Weighted Total | 5.7E-01 | 1.0E+01 | 7.6E+00 | 9.8E+00 | 1.8E+01 | 1.2E+01 | 1.4E+01 | 1.6E+01 | 1.1E+01 |

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| U.S. Average | WECC | TRE |
|---|---|---|
| 1.4E+01 | 3.9E+00 | 1.9E+01 |
| 1.2E+01 | 1.2E+01 | 1.3E+01 |
| 1.2E+01 | 1.2E+01 | 1.3E+01 |
| 1.6E+01 | 2.2E+00 | 3.1E+01 |
| N/A | N/A | N/A |
| 8.4E-01 | 8.3E-01 | 8.8E-01 |
| N/A | N/A | N/A |
| 3.1E-02 | 3.0E-02 | 3.2E-02 |
| 3.4E+00 | 3.3E+00 | 3.5E+00 |
| 1.2E+01 | 1.2E+01 | 1.3E+01 |
| 1.2E+01 | 1.2E+01 | 1.2E+01 |
| 1.3E+01 | 4.9E+00 | 1.7E+01 |

Table 67: Life-Cycle Withdrawals for U.S. Electricity Production

## B.3 Electricity Mixes Used for Inventory Processes

| Process: Crude Oil Extraction for Consumption in the United States | Electricity Breakdown | Water Consumption Breakdown | Water Withdrawals Breakdown |
|---|---|---|---|
| ASCC | 35% | 34% | 34% |
| FRCC | 0% | 0% | 0% |
| HICC | 0% | 0% | 0% |
| MRO | 6% | 5% | 11% |
| NPCC | 0% | 0% | 0% |
| RFC | 0% | 0% | 0% |
| SERC | 2% | 2% | 4% |
| SPP | 11% | 13% | 12% |
| TRE | 14% | 17% | 24% |
| WECC | 31% | 28% | 15% |
| | | | |
| Fraction Domestic | 43% | 44% | 40% |
| Fraction Imported | 57% | 56% | 60% |
| | | | |
| Total Water Consumption (L/MJ) = | 0.57 | 0.57 | 0.57 |
| | | | |
| Total Water Withdrawals (L/MJ) | 10.76 | 10.76 | 10.76 |

Table 68: Breakdown of Electricity Water Use by NERC Region and Foreign/Domestic for Crude Oil Extraction

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| **Process: Petroleum Refining for Consumption in the United States** | **Electricity Breakdown** | **Consumption Breakdown** | **Withdrawals Breakdown** |
|---|---|---|---|
| ASCC | 35% | 34% | 34% |
| FRCC | 0% | 0% | 0% |
| HICC | 0% | 0% | 0% |
| MRO | 6% | 5% | 11% |
| NPCC | 0% | 0% | 0% |
| RFC | 0% | 0% | 0% |
| SERC | 2% | 2% | 4% |
| SPP | 11% | 13% | 12% |
| TRE | 14% | 17% | 24% |
| WECC | 31% | 28% | 15% |
| | | | |
| Fraction Domestic | 43% | 44% | 40% |
| Fraction Imported | 57% | 56% | 60% |
| | | | |
| Total Water Consumption (L/MJ) = | 0.57 | 0.57 | 0.57 |
| | | | |
| Total Water Withdrawals (L/MJ) | 10.76 | 10.76 | 10.76 |

Table 69: Breakdown of Electricity Water Use by NERC Region and Foreign/Domestic for Petroleum Refining

| **Process: Oil Sands Extraction for Consumption in the United States** | **Electricity Breakdown** | **Consumption Breakdown** | **Withdrawals Breakdown** |
|---|---|---|---|
| ASCC | 0% | 0% | 0% |
| FRCC | 0% | 0% | 0% |
| HICC | 0% | 0% | 0% |
| MRO | 0% | 0% | 0% |
| NPCC | 0% | 0% | 0% |
| RFC | 0% | 0% | 0% |
| SERC | 0% | 0% | 0% |
| SPP | 0% | 0% | 0% |
| TRE | 0% | 0% | 0% |
| WECC | 100% | 100% | 100% |
| | | | |
| Fraction Domestic | 0% | 0% | 0% |
| Fraction Imported | 100% | 100% | 100% |
| | | | |
| Total Water Consumption (L/MJ) = | 0.52 | 0.52 | 0.52 |
| | | | |
| Total Water Withdrawals (L/MJ) | 4.86 | 4.86 | 4.86 |

Table 70: Breakdown of Electricity Water Use by NERC Region and Foreign/Domestic for Oil Sands Extraction

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| Process: SCO Refining for Consumption in the United States | Electricity Breakdown | Consumption Breakdown | Withdrawals Breakdown |
|---|---|---|---|
| ASCC | 1% | 1% | 1% |
| FRCC | 0% | 0% | 0% |
| HICC | 0% | 0% | 0% |
| MRO | 9% | 8% | 14% |
| NPCC | 0% | 0% | 0% |
| RFC | 38% | 40% | 42% |
| SERC | 15% | 15% | 20% |
| SPP | 17% | 19% | 15% |
| TRE | 1% | 1% | 1% |
| WECC | 19% | 17% | 7% |
| | | | |
| Fraction Domestic | 93% | 94% | 94% |
| Fraction Imported | 7% | 6% | 6% |
| | | | |
| Total Water Consumption (L/MJ) = | 0.59 | 0.59 | 0.59 |
| | | | |
| Total Water Withdrawals (L/MJ) | 11.77 | 11.77 | 11.77 |

Table 71: Breakdown of Electricity Water Use by NERC Region and Foreign/Domestic for SCO Refining

| Process: Steel Production for Consumption in the United States | Electricity Breakdown | Consumption Breakdown | Withdrawals Breakdown |
|---|---|---|---|
| ASCC | 0% | 0% | 0% |
| FRCC | 0% | 0% | 0% |
| HICC | 0% | 0% | 0% |
| MRO | 2% | 1% | 2% |
| NPCC | 0% | 0% | 0% |
| RFC | 67% | 69% | 65% |
| SERC | 26% | 24% | 30% |
| SPP | 1% | 1% | 1% |
| TRE | 1% | 2% | 2% |
| WECC | 2% | 2% | 1% |
| | | | |
| Fraction Domestic | 71% | 73% | 76% |
| Fraction Imported | 29% | 27% | 24% |
| | | | |
| Total Water Consumption (L/MJ) = | 0.59 | 0.59 | 0.59 |
| | | | |
| Total Water Withdrawals (L/MJ) | 12.58 | 12.58 | 12.58 |

Table 72: Breakdown of Electricity Water Use by NERC Region and Foreign/Domestic for Steel Production

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# B.4 Supply-Chain Agriculture and Services Calculations

| **Product** | **Electricity** | **Gasoline** | **Ethanol** |
|---|---|---|---|
| Sector | Power Generation & Supply | Petroleum Refineries | Basic Organic Chemical Manufacturing |
| 2002 Producer Price | \$0.02/MJ Electricity | \$0.01/MJ Gasoline | \$0.01/MJ EtOH |
| Adjustments | None | None | Water use for direct grain farming purchased subtracted out |
| Output: Indirect Agriculture | 0.007 L/MJ Electricity | 0.02 L/MJ Gasoline | 0.05 L/MJ Ethanol |
| Output: Indirect Services | 0.004 L/MJ Electricity | 0.003 L/MJ Gasoline | 0.004 L/MJ Ethanol |

Table 73: EIO-LCA Inputs for Agriculture and Service-Sector Water Use

# B.5 Data Sources for Ethanol and Gasoline Pathways

| **Pathway** | **Phase** | **Element** | **Spatial Disaggregation** | **Data Source** |
|---|---|---|---|---|
| Crude Oil to Gasoline | Extraction | Energy Use | Average | (*11*) |
| | | Water Use | PADD + Saudi Arabia | (*12*) |
| | | Chemical Use | Average | (44, 45) |
| | Refining | Energy Use | Average | (*13*) |
| | | Steel | Average | Calculated |
| | | Concrete | Average | Calculated |
| | | Water Use | Average | (*9, 12*) |
| | | Chemical Use | Average | (*14*) |
| | Transportation, Storage, & Distribution | Energy Use | Average | (*11*) |
| | Supply-Chain | Agriculture & Services | Average | (*15*) |
| Oil Sands to Gasoline | Extraction | Energy Use | Average | (*11*) |
| | | Water Use | Average | (*12*) |
| | Refining | Energy Use | Average | (*13*) |
| | | Steel | Average | Calculated |
| | | Concrete | Average | Calculated |
| | | Water Use | Average | (*9, 12*) |
| | | Chemical Use | Average | (*14*) |
| | Transportation, Storage, & Distribution | Energy Use | Average | (*11*) |

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| | | | | |
|---|---|---|---|---|
| | Supply-Chain | Agriculture & Services | Average | (*15*) |
| Corn Stover to Ethanol | Feedstock Production | Energy Use | U.S. Average | (*11*) |
| | | Steel | U.S. Average | (*11*) |
| | | Rubber | U.S. Average | (*11*) |
| | | Fertilizer | U.S. Average | (*11*) |
| | Fuel Production | Energy Use | U.S. Average | (*16*) |
| | | Steel | U.S. Average | Calculated |
| | | Concrete | U.S. Average | Calculated |
| | | Water Use | U.S. Average | (*16*) |
| | | Chemical Use | U.S. Average | (*16*) |
| | | Electricity Co-Product | U.S. Average | (*16*) |
| | Transportation, Storage, & Distribution | Energy Use | U.S. Average | (*11*) |
| | Supply-Chain | Agriculture & Services | U.S. Average | (*15*) |
| Miscanthus to Ethanol | Feedstock Production | Energy Use | Midwest Average | (*11*) |
| | | Steel | Midwest Average | (*11*) |
| | | Rubber | Midwest Average | (*11*) |
| | | Fertilizer | Midwest Average | (*17*) |
| | | Herbicide | Midwest Average | (*17*) |
| | Fuel Production | Energy Use | U.S. Average | ASPEN® model based on (*16*), adjusted for Miscanthus |
| | | Steel | U.S. Average | Calculated |
| | | Concrete | U.S. Average | Calculated |
| | | Water Use | U.S. Average | ASPEN® model based on (*16*), adjusted for Miscanthus |
| | | Chemical Use | U.S. Average | ASPEN® model based on (*16*), adjusted for Miscanthus |
| | Transportation, Storage, & Distribution | Energy Use | U.S. Average | (*11*) |

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| | | | | |
|---|---|---|---|---|
| | Supply-Chain | Agriculture & Services | U.S. Average | (*15*) |
| Corn Grain to Ethanol | Feedstock Production | Energy Use | U.S. Average | (*11*) |
| | | Water Use | State | (*4*) |
| | | Steel | U.S. Average | (*11*) |
| | | Rubber | U.S. Average | (*11*) |
| | | Fertilizer | U.S. Average | (*11*) |
| | | Pesticide | U.S. Average | (*11*) |
| | Fuel Production | Energy Use | U.S. Average | (*18*) |
| | | Steel | U.S. Average | (*19*) |
| | | Concrete | U.S. Average | (*19*) |
| | | Water Use | U.S. Average | (*12*) |
| | | Chemical Use | U.S. Average | (*19*) |
| | Transportation, Storage, & Distribution | Energy Use | U.S. Average | (*19*) |
| | Supply-Chain | Agriculture & Services | U.S. Average | (*15*) |

Table 74: Data Sources for Liquid Fuel Pathways

# B.6 Life-Cycle Inventory Results

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 9.26E-02 | 0.00E+00 | 1.35E-01 | 0.00E+00 | 2.27E-01 | L/MJ Gasoline | 83.96 % |
| Electricity | 2.03E-04 | 2.04E-04 | 4.08E-03 | 8.73E-05 | 4.58E-03 | L/MJ Gasoline | 1.69% |
| Petroleum Products & NG | 2.43E-03 | 2.98E-03 | 5.84E-03 | 2.09E-03 | 1.33E-02 | L/MJ Gasoline | 4.93% |
| Coal | N/A | N/A | 1.28E-03 | N/A | 1.28E-03 | L/MJ Gasoline | 0.47% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 8.01E-05 | N/A | 8.01E-05 | L/MJ Gasoline | 0.03% |
| Construction (Concrete Mix + Dust Control) | 0.00E+00 | N/A | 3.23E-05 | N/A | 3.23E-05 | L/MJ Gasoline | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.82E-04 | N/A | 1.39E-06 | N/A | 5.83E-04 | L/MJ Gasoline | 0.22% |
| Supply-Chain Agriculture | 8.58E-03 | 3.71E-04 | 1.15E-02 | N/A | 2.05E-02 | L/MJ Gasoline | 7.57% |
| Supply-Chain Services | 1.76E-03 | 1.55E-04 | 1.11E-03 | N/A | 3.03E-03 | L/MJ Gasoline | 1.12% |
| TOTAL | 1.06E-01 | 3.71E-03 | 1.59E-01 | 2.18E-03 | 2.71E-01 | L/MJ Gasoline | 100% |
| % | 39.23% | 1.37% | 58.60% | 0.81% | 100% | | |

Table 75: Life-Cycle Water Consumption for Crude Oil to Gasoline Pathway

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 9.26E-02 | N/A | 1.35E-01 | N/A | 2.27E-01 | L/MJ Gasoline | 61.85% |
| Electricity | 3.84E-03 | 4.57E-03 | 8.94E-02 | 1.95E-03 | 9.97E-02 | L/MJ Gasoline | 27.14% |
| Petroleum Products & NG | 2.43E-03 | 2.98E-03 | 5.84E-03 | 2.09E-03 | 1.33E-02 | L/MJ Gasoline | 3.63% |
| Coal | N/A | N/A | 1.28E-03 | N/A | 1.28E-03 | L/MJ Gasoline | 0.35% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.21E-04 | N/A | 2.21E-04 | L/MJ Gasoline | 0.06% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.23E-05 | N/A | 3.23E-05 | L/MJ Gasoline | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.08E-03 | N/A | 4.96E-06 | N/A | 2.08E-03 | L/MJ Gasoline | 0.57% |
| Supply-Chain Agriculture | 8.58E-03 | 3.71E-04 | 1.15E-02 | N/A | 2.05E-02 | L/MJ Gasoline | 5.57% |
| Supply-Chain Services | 1.76E-03 | 1.55E-04 | 1.11E-03 | N/A | 3.03E-03 | L/MJ Gasoline | 0.82% |
| TOTAL | 1.11E-01 | 8.07E-03 | 2.44E-01 | 4.05E-03 | 3.67E-01 | L/MJ Gasoline | 100% |
| % | 30.29% | 2.20% | 66.41% | 1.10% | 100% | | |

Table 76: Life-Cycle Water Withdrawals for Crude Oil to Gasoline Pathway

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 9.50E-02 | N/A | 1.35E-01 | N/A | 2.30E-01 | L/MJ Gasoline | 79.51% |
| Electricity | 4.96E-03 | 4.21E-04 | 4.03E-03 | 8.73E-05 | 9.49E-03 | L/MJ Gasoline | 3.29% |
| Petroleum Products & NG | 1.57E-02 | 1.16E-03 | 5.84E-03 | 2.09E-03 | 2.48E-02 | L/MJ Gasoline | 8.58% |
| Coal | N/A | N/A | 1.28E-03 | N/A | 1.28E-03 | L/MJ Gasoline | 0.44% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 7.86E-05 | N/A | 7.86E-05 | L/MJ Gasoline | 0.03% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.17E-05 | N/A | 3.17E-05 | L/MJ Gasoline | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | N/A | N/A | 1.36E-06 | N/A | 1.36E-06 | L/MJ Gasoline | 0.00% |
| Supply-Chain Agriculture | 8.58E-03 | 3.71E-04 | 1.15E-02 | N/A | 2.05E-02 | L/MJ Gasoline | 7.09% |
| Supply-Chain Services | 1.76E-03 | 1.55E-04 | 1.11E-03 | N/A | 3.03E-03 | L/MJ Gasoline | 1.05% |
| TOTAL | 1.26E-01 | 2.11E-03 | 1.59E-01 | 2.18E-03 | 2.89E-01 | L/MJ Gasoline | 100% |
| % | 43.61% | 0.73% | 54.90% | 0.75% | 100% | | |

Table 77: Life-Cycle Water Consumption for Oil Sands to Gasoline Pathway

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 9.50E-02 | N/A | 1.35E-01 | N/A | 2.30E-01 | L/MJ Gasoline | 54.90% |
| Electricity | 4.64E-02 | 9.43E-03 | 8.10E-02 | 1.95E-03 | 1.39E-01 | L/MJ Gasoline | 33.19% |
| Petroleum Products & NG | 1.57E-02 | 1.16E-03 | 5.84E-03 | 2.09E-03 | 2.48E-02 | L/MJ Gasoline | 5.92% |
| Coal | N/A | N/A | 1.28E-03 | N/A | 1.28E-03 | L/MJ Gasoline | 0.31% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.17E-04 | N/A | 2.17E-04 | L/MJ Gasoline | 0.05% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.17E-05 | N/A | 3.17E-05 | L/MJ Gasoline | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | N/A | N/A | 4.87E-06 | N/A | 4.87E-06 | L/MJ Gasoline | 0.00% |
| Supply-Chain Agriculture | 8.58E-03 | 3.71E-04 | 1.15E-02 | N/A | 2.05E-02 | L/MJ Gasoline | 4.90% |
| Supply-Chain Services | 1.76E-03 | 1.55E-04 | 1.11E-03 | N/A | 3.03E-03 | L/MJ Gasoline | 0.72% |
| TOTAL | 1.67E-01 | 1.11E-02 | 2.36E-01 | 4.05E-03 | 4.18E-01 | L/MJ Gasoline | 100% |
| % | 40.02% | 2.66% | 56.35% | 0.97% | 100% | | |

Table 78: Life-Cycle Water Withdrawals for Oil Sands to Gasoline Pathway

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 5.86E+00 | N/A | 1.27E-01 | N/A | 5.98E+00 | L/MJ Ethanol | 97.26% |
| Electricity | 1.17E-03 | N/A | 2.43E-02 | 2.03E-04 | 2.57E-02 | L/MJ Ethanol | 0.40% |
| Petroleum Products & NG | 5.48E-03 | 5.72E-03 | 3.33E-02 | 3.92E-03 | 4.84E-02 | L/MJ Ethanol | 0.70% |
| Coal | N/A | N/A | 4.38E-03 | N/A | 4.38E-03 | L/MJ Ethanol | 0.07% |
| Steel, Copper, & Aluminum Mfg | 4.78E-03 | N/A | 2.15E-04 | N/A | 5.00E-03 | L/MJ Ethanol | 0.08% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.93E-02 | N/A | 3.85E-03 | N/A | 3.31E-02 | L/MJ Ethanol | 0.54% |
| Supply-Chain Agriculture | 3.29E-03 | 2.16E-04 | 4.41E-02 | N/A | 4.76E-02 | L/MJ Ethanol | 0.77% |
| Supply-Chain Services | 2.18E-04 | 4.76E-04 | 3.23E-03 | N/A | 3.93E-03 | L/MJ Ethanol | 0.06% |
| TOTAL | 5.90E+00 | 6.41E-03 | 2.41E-01 | 4.12E-03 | 6.15E+00 | L/MJ Ethanol | 100% |
| % | 95.91% | 0.10% | 3.92% | 0.07% | 100% | | |

Table 79: Life-Cycle Water Consumption for Corn Grain to Ethanol Pathway

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 5.86E+00 | N/A | 1.27E-01 | N/A | 5.98E+00 | L/MJ Ethanol | 84.03% |
| Electricity | 2.61E-02 | N/A | 6.71E-01 | 4.55E-03 | 7.02E-01 | L/MJ Ethanol | 9.49% |
| Petroleum Products & NG | 5.48E-03 | 5.72E-03 | 3.33E-02 | 3.92E-03 | 4.84E-02 | L/MJ Ethanol | 0.60% |
| Coal | N/A | N/A | 4.38E-03 | N/A | 4.38E-03 | L/MJ Ethanol | 0.06% |
| Steel, Copper, & Aluminum Mfg | 1.32E-02 | N/A | 5.91E-04 | N/A | 1.38E-02 | L/MJ Ethanol | 0.19% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.83E-01 | N/A | 3.43E-02 | N/A | 3.17E-01 | L/MJ Ethanol | 4.45% |
| Supply-Chain Agriculture | 3.29E-03 | 2.16E-04 | 4.41E-02 | N/A | 4.76E-02 | L/MJ Ethanol | 0.67% |
| Supply-Chain Services | 2.18E-04 | 4.76E-04 | 3.23E-03 | N/A | 3.93E-03 | L/MJ Ethanol | 0.06% |
| TOTAL | 6.19E+00 | 6.41E-03 | 9.18E-01 | 8.47E-03 | 7.12E+00 | L/MJ Ethanol | 100% |
| % | 86.89% | 0.09% | 12.90% | 0.12% | 100% | | |

Table 80: Life-Cycle Water Withdrawals for Corn Grain to Ethanol Pathway

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | N/A | N/A | 2.59E-01 | N/A | 2.59E-01 | L/MJ Ethanol | 74.98% |
| Electricity | N/A | N/A | -4.27E-02 | 2.03E-04 | -4.25E-02 | L/MJ Ethanol | -12.31% |
| Petroleum Products & NG | 4.76E-03 | 1.21E-03 | 6.78E-06 | 3.92E-03 | 9.90E-03 | L/MJ Ethanol | 2.87% |
| Coal | N/A | N/A | N/A | N/A | N/A | L/MJ Ethanol | 0.00% |
| Steel, Copper, & Aluminum Mfg | 3.75E-03 | N/A | 2.15E-04 | N/A | 3.96E-03 | L/MJ Ethanol | 1.15% |
| Construction (Concrete Mix + Dust Control) | 0.00E+00 | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | 0.07% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.06E-02 | N/A | 4.27E-02 | N/A | 6.33E-02 | L/MJ Ethanol | 18.34% |
| Supply-Chain Agriculture | 3.29E-03 | 2.16E-04 | 4.41E-02 | N/A | 4.76E-02 | L/MJ Ethanol | 13.78% |
| Supply-Chain Services | 2.18E-04 | 4.76E-04 | 3.23E-03 | N/A | 3.93E-03 | L/MJ Ethanol | 1.14% |
| TOTAL | 3.26E-02 | 1.90E-03 | 3.07E-01 | 4.12E-03 | 3.45E-01 | L/MJ Ethanol | 100% |
| % | 9.45% | 0.55% | 88.81% | 1.19% | 100% | | |

Table 81: Life-Cycle Water Consumption for Corn Stover to Ethanol Pathway

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | N/A | N/A | 2.59E-01 | N/A | 2.59E-01 | L/MJ Ethanol | -100.80% |
| Electricity | N/A | N/A | -1.18E+00 | 4.55E-03 | -1.17E+00 | L/MJ Ethanol | 456.88% |
| Petroleum Products & NG | 4.76E-03 | 1.21E-03 | 6.78E-06 | 3.92E-03 | 9.90E-03 | L/MJ Ethanol | -3.85% |
| Coal | N/A | N/A | N/A | N/A | N/A | L/MJ Ethanol | 0.00% |
| Steel, Copper, & Aluminum Mfg | 1.03E-02 | N/A | 5.91E-04 | N/A | 1.09E-02 | L/MJ Ethanol | -4.25% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | -0.09% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.77E-01 | N/A | 4.08E-01 | N/A | 5.85E-01 | L/MJ Ethanol | -227.84% |
| Supply-Chain Agriculture | 3.29E-03 | 2.16E-04 | 4.41E-02 | N/A | 4.76E-02 | L/MJ Ethanol | -18.52% |
| Supply-Chain Services | 2.18E-04 | 4.76E-04 | 3.23E-03 | N/A | 3.93E-03 | L/MJ Ethanol | -1.53% |
| TOTAL | 1.96E-01 | 1.90E-03 | -4.63E-01 | 8.47E-03 | -2.57E-01 | L/MJ Ethanol | 100% |
| % | -76.27% | -0.74% | 180.30% | -3.30% | 100% | | |

Table 82: Life-Cycle Water Withdrawals for Corn Stover to Ethanol Pathway

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | N/A | N/A | 2.59E-01 | N/A | 2.59E-01 | L/MJ Ethanol | 78.24% |
| Electricity | N/A | N/A | -4.16E-02 | 2.03E-04 | -4.14E-02 | L/MJ Ethanol | -12.52% |
| Petroleum Products & NG | 4.76E-03 | 1.61E-03 | 6.78E-06 | 3.92E-03 | 1.03E-02 | L/MJ Ethanol | 3.11% |
| Coal | N/A | N/A | N/A | N/A | N/A | L/MJ Ethanol | 0.00% |
| Steel, Copper, & Aluminum Mfg | 1.71E-03 | 0.00E+00 | 2.15E-04 | N/A | 1.92E-03 | L/MJ Ethanol | 0.58% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | 0.07% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.45E-04 | N/A | 4.89E-02 | N/A | 4.95E-02 | L/MJ Ethanol | 14.95% |
| Supply-Chain Agriculture | 3.29E-03 | 3.08E-04 | 4.40E-02 | N/A | 4.76E-02 | L/MJ Ethanol | 14.38% |
| Supply-Chain Services | 2.18E-04 | 5.81E-04 | 3.13E-03 | N/A | 3.93E-03 | L/MJ Ethanol | 1.19% |
| TOTAL | 1.05E-02 | 2.50E-03 | 3.14E-01 | 4.12E-03 | 3.31E-01 | L/MJ Ethanol | 100% |
| % | 3.18% | 0.76% | 94.82% | 1.25% | 100% | | |

Table 83: Life-Cycle Water Consumption for Miscanthus to Ethanol Pathway

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | N/A | N/A | 2.59E-01 | N/A | 2.59E-01 | L/MJ Ethanol | -66.88% |
| Electricity | N/A | N/A | -1.15E+00 | 4.55E-03 | -1.14E+00 | L/MJ Ethanol | 295.43% |
| Petroleum Products & NG | 4.76E-03 | 1.61E-03 | 6.78E-06 | 3.92E-03 | 1.03E-02 | L/MJ Ethanol | -2.66% |
| Coal | N/A | N/A | N/A | N/A | N/A | L/MJ Ethanol | 0.00% |
| Steel, Copper, & Aluminum Mfg | 4.70E-03 | N/A | 5.91E-04 | N/A | 5.29E-03 | L/MJ Ethanol | -1.37% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 2.31E-04 | N/A | 2.31E-04 | L/MJ Ethanol | -0.06% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.26E-03 | 0.00E+00 | 4.25E-01 | N/A | 4.30E-01 | L/MJ Ethanol | -111.16% |
| Supply-Chain Agriculture | 3.29E-03 | 3.08E-04 | 4.40E-02 | N/A | 4.76E-02 | L/MJ Ethanol | -12.29% |
| Supply-Chain Services | 2.18E-04 | 5.81E-04 | 3.13E-03 | N/A | 3.93E-03 | L/MJ Ethanol | -1.01% |
| TOTAL | 1.82E-02 | 2.50E-03 | -4.16E-01 | 8.47E-03 | -3.87E-01 | L/MJ Ethanol | 100% |
| % | -4.71% | -0.65% | 107.54% | -2.19% | 100% | | |

Table 84: Life-Cycle Water Withdrawals for Miscanthus to Ethanol Pathway

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.55E-01 | N/A | 3.65E-01 | N/A | 5.20E-01 | L/MJ Electricity | 85.26% |
| Electricity | 3.91E-03 | N/A | 3.25E-05 | 5.14E-02 | 5.54E-02 | L/MJ Electricity | 9.09% |
| Petroleum Products & NG | 1.82E-03 | 1.78E-03 | 3.01E-07 | N/A | 3.60E-03 | L/MJ Electricity | 0.59% |
| Coal | 9.10E-05 | 1.23E-05 | N/A | N/A | 1.03E-04 | L/MJ Electricity | 0.02% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.48E-03 | N/A | 2.48E-03 | L/MJ Electricity | 0.41% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.42E-04 | N/A | 1.42E-04 | L/MJ Electricity | 0.02% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.37E-05 | N/A | 2.95E-05 | N/A | 4.32E-05 | L/MJ Electricity | 0.01% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.06% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.54% |
| TOTAL | 1.67E-01 | 3.96E-03 | 3.87E-01 | 5.14E-02 | 6.09E-01 | L/MJ Electricity | 100% |
| % | 27.36% | 0.65% | 63.55% | 8.44% | 100% | | |

Table 85: Life-Cycle Water Consumption for U.S. Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.55E-01 | N/A | 1.15E+01 | N/A | 1.16E+01 | L/MJ Electricity | 90.16% |
| Electricity | 7.82E-02 | N/A | 6.08E-04 | 1.15E+00 | 1.23E+00 | L/MJ Electricity | 9.54% |
| Petroleum Products & NG | 1.82E-03 | 1.78E-03 | 3.01E-07 | N/A | 3.60E-03 | L/MJ Electricity | 0.03% |
| Coal | 9.10E-05 | 1.23E-05 | N/A | N/A | 1.03E-04 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.70E-03 | N/A | 6.70E-03 | L/MJ Electricity | 0.05% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.42E-04 | N/A | 1.42E-04 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 4.90E-05 | N/A | 6.13E-04 | N/A | 6.62E-04 | L/MJ Electricity | 0.01% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.19% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.03% |
| TOTAL | 2.41E-01 | 3.96E-03 | 1.15E+01 | 1.15E+00 | 1.29E+01 | L/MJ Electricity | 100% |
| % | 1.87% | 0.03% | 89.18% | 8.93% | 100% | | |

Table 86: Life-Cycle Water Withdrawals for U.S. Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.39E-01 | N/A | 2.72E-01 | N/A | 5.11E-01 | L/MJ Electricity | 82.93% |
| Electricity | 3.16E-03 | N/A | 6.06E-07 | 6.59E-02 | 6.91E-02 | L/MJ Electricity | 11.21% |
| Petroleum Products & NG | 3.32E-03 | 1.78E-03 | 1.02E-06 | N/A | 5.10E-03 | L/MJ Electricity | 0.83% |
| Coal | 3.23E-04 | 1.97E-06 | N/A | N/A | 3.25E-04 | L/MJ Electricity | 0.05% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.14E-03 | N/A | 2.14E-03 | L/MJ Electricity | 0.35% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.38E-04 | N/A | 3.38E-04 | L/MJ Electricity | 0.05% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.42E-04 | N/A | 8.95E-09 | N/A | 1.42E-04 | L/MJ Electricity | 0.02% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.02% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.54% |
| TOTAL | 2.52E-01 | 3.95E-03 | 2.94E-01 | 6.59E-02 | 6.16E-01 | L/MJ Electricity | 100% |
| % | 40.88% | 0.64% | 47.78% | 10.70% | 100% | | |

Table 87: Life-Cycle Water Consumption for ASCC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.39E-01 | N/A | 8.58E+00 | N/A | 8.82E+00 | L/MJ Electricity | 87.61% |
| Electricity | 6.94E-02 | N/A | 1.18E-05 | 1.14E+00 | 1.21E+00 | L/MJ Electricity | 11.99% |
| Petroleum Products & NG | 3.32E-03 | 1.78E-03 | 1.02E-06 | N/A | 5.10E-03 | L/MJ Electricity | 0.05% |
| Coal | 3.23E-04 | 1.97E-06 | N/A | N/A | 3.25E-04 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 5.36E-03 | N/A | 5.36E-03 | L/MJ Electricity | 0.05% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.38E-04 | N/A | 3.38E-04 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.08E-04 | N/A | 5.75E-08 | N/A | 5.09E-04 | L/MJ Electricity | 0.01% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.25% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.03% |
| TOTAL | 3.18E-01 | 3.95E-03 | 8.60E+00 | 1.14E+00 | 1.01E+01 | L/MJ Electricity | 100% |
| % | 3.16% | 0.04% | 85.49% | 11.30% | 100% | | |

Table 88: Life-Cycle Water Withdrawals for ASCC NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.14E-01 | N/A | 3.04E-01 | N/A | 5.18E-01 | L/MJ Electricity | 84.46% |
| Electricity | 6.17E-03 | N/A | N/A | 4.98E-02 | 5.59E-02 | L/MJ Electricity | 9.11% |
| Petroleum Products & NG | 5.46E-03 | 2.65E-03 | 5.76E-10 | N/A | 8.11E-03 | L/MJ Electricity | 1.32% |
| Coal | 6.87E-04 | 5.89E-06 | N/A | N/A | 6.93E-04 | L/MJ Electricity | 0.11% |
| Steel, Copper, & Aluminum Mfg | N/A | 0.00E+00 | 2.26E-03 | N/A | 2.26E-03 | L/MJ Electricity | 0.37% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.97E-05 | N/A | 3.97E-05 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.99E-04 | N/A | N/A | N/A | 2.99E-04 | L/MJ Electricity | 0.05% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.04% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.54% |
| TOTAL | 2.33E-01 | 4.82E-03 | 3.26E-01 | 4.98E-02 | 6.14E-01 | L/MJ Electricity | 100% |
| % | 37.94% | 0.79% | 53.17% | 8.11% | 100% | | |

Table 89: Life-Cycle Water Consumption for FRCC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.14E-01 | N/A | 6.68E+00 | N/A | 6.89E+00 | L/MJ Electricity | 89.16% |
| Electricity | 1.32E-01 | N/A | N/A | 6.62E-01 | 7.94E-01 | L/MJ Electricity | 10.27% |
| Petroleum Products & NG | 5.46E-03 | 2.65E-03 | 5.76E-10 | N/A | 8.11E-03 | L/MJ Electricity | 0.10% |
| Coal | 6.87E-04 | 5.89E-06 | N/A | N/A | 6.93E-04 | L/MJ Electricity | 0.01% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.23E-03 | N/A | 6.23E-03 | L/MJ Electricity | 0.08% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.97E-05 | N/A | 3.97E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.07E-03 | N/A | N/A | N/A | 1.07E-03 | L/MJ Electricity | 0.01% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.32% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.04% |
| TOTAL | 3.59E-01 | 4.82E-03 | 6.70E+00 | 6.62E-01 | 7.73E+00 | L/MJ Electricity | 100% |
| % | 4.65% | 0.06% | 86.73% | 8.56% | 100% | | |

Table 90: Life-Cycle Water Withdrawals for FRCC NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.33E-01 | N/A | 4.24E-01 | N/A | 6.57E-01 | L/MJ Electricity | 84.14% |
| Electricity | 1.20E-02 | N/A | 3.74E-06 | 5.85E-02 | 7.05E-02 | L/MJ Electricity | 9.03% |
| Petroleum Products & NG | 1.44E-02 | 5.46E-03 | 3.84E-08 | N/A | 1.99E-02 | L/MJ Electricity | 2.55% |
| Coal | 2.21E-03 | 2.97E-06 | N/A | N/A | 2.21E-03 | L/MJ Electricity | 0.28% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.13E-03 | N/A | 2.13E-03 | L/MJ Electricity | 0.27% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 4.12E-05 | N/A | 4.12E-05 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 9.97E-04 | N/A | 5.53E-08 | N/A | 9.97E-04 | L/MJ Electricity | 0.13% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 3.17% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.42% |
| TOTAL | 2.68E-01 | 7.63E-03 | 4.46E-01 | 5.85E-02 | 7.81E-01 | L/MJ Electricity | 100% |
| % | 34.35% | 0.98% | 57.18% | 7.49% | 100% | | |

Table 91: Life-Cycle Water Consumption for HICC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.33E-01 | N/A | 8.80E+00 | N/A | 9.03E+00 | L/MJ Electricity | 88.90% |
| Electricity | 2.64E-01 | N/A | 7.30E-05 | 8.04E-01 | 1.07E+00 | L/MJ Electricity | 10.51% |
| Petroleum Products & NG | 1.44E-02 | 5.46E-03 | 3.84E-08 | N/A | 1.99E-02 | L/MJ Electricity | 0.20% |
| Coal | 2.21E-03 | 2.97E-06 | N/A | N/A | 2.21E-03 | L/MJ Electricity | 0.02% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 5.86E-03 | N/A | 5.86E-03 | L/MJ Electricity | 0.06% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 4.12E-05 | N/A | 4.12E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 3.56E-03 | N/A | 3.55E-07 | N/A | 3.56E-03 | L/MJ Electricity | 0.04% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.24% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.03% |
| TOTAL | 5.22E-01 | 7.63E-03 | 8.82E+00 | 8.04E-01 | 1.02E+01 | L/MJ Electricity | 100% |
| % | 5.14% | 0.08% | 86.87% | 7.91% | 100% | | |

Table 92: Life-Cycle Water Withdrawals for HICC NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.70E-01 | N/A | 2.95E-01 | N/A | 4.65E-01 | L/MJ Electricity | 84.56% |
| Electricity | 4.19E-03 | N/A | 1.17E-04 | 4.47E-02 | 4.90E-02 | L/MJ Electricity | 8.90% |
| Petroleum Products & NG | 2.32E-03 | 2.57E-03 | 2.31E-07 | N/A | 4.89E-03 | L/MJ Electricity | 0.89% |
| Coal | 1.32E-04 | 1.97E-05 | N/A | N/A | 1.52E-04 | L/MJ Electricity | 0.03% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.71E-03 | N/A | 2.71E-03 | L/MJ Electricity | 0.49% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.22E-04 | N/A | 1.22E-04 | L/MJ Electricity | 0.02% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.56E-05 | N/A | 1.73E-06 | N/A | 1.74E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.50% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.60% |
| TOTAL | 1.83E-01 | 4.76E-03 | 3.18E-01 | 4.47E-02 | 5.50E-01 | L/MJ Electricity | 100% |
| % | 33.28% | 0.86% | 57.74% | 8.12% | 100% | | |

Table 93: Life-Cycle Water Consumption for MRO NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.70E-01 | N/A | 1.62E+01 | N/A | 1.64E+01 | L/MJ Electricity | 90.61% |
| Electricity | 8.16E-02 | N/A | 2.28E-03 | 1.58E+00 | 1.66E+00 | L/MJ Electricity | 9.16% |
| Petroleum Products & NG | 2.32E-03 | 2.57E-03 | 2.31E-07 | N/A | 4.89E-03 | L/MJ Electricity | 0.03% |
| Coal | 1.32E-04 | 1.97E-05 | N/A | N/A | 1.52E-04 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 7.39E-03 | N/A | 7.39E-03 | L/MJ Electricity | 0.04% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.22E-04 | N/A | 1.22E-04 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.59E-05 | 0.00E+00 | 1.11E-05 | N/A | 6.70E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.14% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.02% |
| TOTAL | 2.61E-01 | 4.76E-03 | 1.63E+01 | 1.58E+00 | 1.81E+01 | L/MJ Electricity | 100% |
| % | 1.44% | 0.03% | 89.84% | 8.70% | 100% | | |

Table 94: Life-Cycle Water Withdrawals for MRO NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.30E-01 | N/A | 2.30E-01 | N/A | 4.59E-01 | L/MJ Electricity | 82.52% |
| Electricity | 9.46E-03 | N/A | 2.65E-06 | 4.41E-02 | 5.36E-02 | L/MJ Electricity | 9.62% |
| Petroleum Products & NG | 8.24E-03 | 3.34E-03 | 5.19E-07 | N/A | 1.16E-02 | L/MJ Electricity | 2.08% |
| Coal | 1.14E-03 | 3.47E-06 | N/A | N/A | 1.15E-03 | L/MJ Electricity | 0.21% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.25E-03 | N/A | 2.25E-03 | L/MJ Electricity | 0.40% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.98E-04 | N/A | 1.98E-04 | L/MJ Electricity | 0.04% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 5.11E-04 | N/A | 3.91E-08 | N/A | 5.11E-04 | L/MJ Electricity | 0.09% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.45% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.59% |
| TOTAL | 2.55E-01 | 5.51E-03 | 2.52E-01 | 4.41E-02 | 5.57E-01 | L/MJ Electricity | 100% |
| % | 45.80% | 0.99% | 45.29% | 7.92% | 100% | | |

Table 95: Life-Cycle Water Consumption for NPCC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.30E-01 | N/A | 1.08E+01 | N/A | 1.10E+01 | L/MJ Electricity | 89.37% |
| Electricity | 2.04E-01 | N/A | 5.17E-05 | 1.06E+00 | 1.26E+00 | L/MJ Electricity | 10.23% |
| Petroleum Products & NG | 8.24E-03 | 3.34E-03 | 5.19E-07 | N/A | 1.16E-02 | L/MJ Electricity | 0.09% |
| Coal | 1.14E-03 | 3.47E-06 | N/A | N/A | 1.15E-03 | L/MJ Electricity | 0.01% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 5.93E-03 | N/A | 5.93E-03 | L/MJ Electricity | 0.05% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 1.98E-04 | N/A | 1.98E-04 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.83E-03 | N/A | 2.51E-07 | N/A | 1.83E-03 | L/MJ Electricity | 0.01% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.20% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.03% |
| TOTAL | 4.51E-01 | 5.51E-03 | 1.08E+01 | 1.06E+00 | 1.23E+01 | L/MJ Electricity | 100% |
| % | 3.66% | 0.04% | 87.72% | 8.58% | 100% | | |

Table 96: Life-Cycle Water Withdrawals for NPCC NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.44E-01 | N/A | 4.22E-01 | N/A | 5.67E-01 | L/MJ Electricity | 85.84% |
| Electricity | 4.61E-03 | N/A | 4.28E-06 | 5.44E-02 | 5.90E-02 | L/MJ Electricity | 8.94% |
| Petroleum Products & NG | 1.81E-03 | 1.96E-03 | 2.88E-08 | N/A | 3.77E-03 | L/MJ Electricity | 0.57% |
| Coal | 7.87E-05 | 1.54E-05 | N/A | N/A | 9.41E-05 | L/MJ Electricity | 0.01% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.50E-03 | N/A | 2.50E-03 | L/MJ Electricity | 0.38% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 6.68E-05 | N/A | 6.68E-05 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.10E-06 | N/A | 6.32E-08 | N/A | 1.17E-06 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 3.75% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.50% |
| TOTAL | 1.57E-01 | 4.14E-03 | 4.45E-01 | 5.44E-02 | 6.60E-01 | L/MJ Electricity | 100% |
| % | 23.76% | 0.63% | 67.37% | 8.24% | 100% | | |

Table 97: Life-Cycle Water Consumption for RFC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.44E-01 | N/A | 1.23E+01 | N/A | 1.25E+01 | L/MJ Electricity | 90.38% |
| Electricity | 9.12E-02 | N/A | 8.35E-05 | 1.20E+00 | 1.29E+00 | L/MJ Electricity | 9.34% |
| Petroleum Products & NG | 1.81E-03 | 1.96E-03 | 2.88E-08 | N/A | 3.77E-03 | L/MJ Electricity | 0.03% |
| Coal | 7.87E-05 | 1.54E-05 | N/A | N/A | 9.41E-05 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.88E-03 | N/A | 6.88E-03 | L/MJ Electricity | 0.05% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 6.68E-05 | N/A | 6.68E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 3.94E-06 | N/A | 4.06E-07 | N/A | 4.35E-06 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.18% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.02% |
| TOTAL | 2.44E-01 | 4.14E-03 | 1.23E+01 | 1.20E+00 | 1.38E+01 | L/MJ Electricity | 100% |
| % | 1.77% | 0.03% | 89.53% | 8.68% | 100% | | |

Table 98: Life-Cycle Water Withdrawals for RFC NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.52E-01 | N/A | 3.61E-01 | N/A | 5.14E-01 | L/MJ Electricity | 85.30% |
| Electricity | 4.52E-03 | N/A | 1.96E-08 | 4.93E-02 | 5.38E-02 | L/MJ Electricity | 8.94% |
| Petroleum Products & NG | 1.98E-03 | 1.92E-03 | 1.45E-07 | N/A | 3.90E-03 | L/MJ Electricity | 0.65% |
| Coal | 1.10E-04 | 1.38E-05 | N/A | N/A | 1.24E-04 | L/MJ Electricity | 0.02% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.44E-03 | N/A | 2.44E-03 | L/MJ Electricity | 0.41% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 9.88E-05 | N/A | 9.88E-05 | L/MJ Electricity | 0.02% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.89E-05 | N/A | 2.90E-10 | N/A | 1.89E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.11% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.55% |
| TOTAL | 1.65E-01 | 4.10E-03 | 3.84E-01 | 4.93E-02 | 6.02E-01 | L/MJ Electricity | 100% |
| % | 27.39% | 0.68% | 63.74% | 8.19% | 100% | | |

Table 99: Life-Cycle Water Consumption for SERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.52E-01 | N/A | 1.47E+01 | N/A | 1.49E+01 | L/MJ Electricity | 90.52% |
| Electricity | 9.03E-02 | N/A | 3.83E-07 | 1.43E+00 | 1.52E+00 | L/MJ Electricity | 9.24% |
| Petroleum Products & NG | 1.98E-03 | 1.92E-03 | 1.45E-07 | N/A | 3.90E-03 | L/MJ Electricity | 0.02% |
| Coal | 1.10E-04 | 1.38E-05 | N/A | N/A | 1.24E-04 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.66E-03 | N/A | 6.66E-03 | L/MJ Electricity | 0.04% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 9.88E-05 | N/A | 9.88E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 6.73E-05 | N/A | 1.86E-09 | N/A | 6.73E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.15% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.02% |
| TOTAL | 2.51E-01 | 4.10E-03 | 1.48E+01 | 1.43E+00 | 1.64E+01 | L/MJ Electricity | 100% |
| % | 1.53% | 0.02% | 89.76% | 8.69% | 100% | | |

Table 100: Life-Cycle Water Withdrawals for SERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.98E-01 | N/A | 4.16E-01 | N/A | 6.14E-01 | L/MJ Electricity | 86.30% |
| Electricity | 3.14E-03 | N/A | 5.56E-05 | 5.90E-02 | 6.22E-02 | L/MJ Electricity | 8.73% |
| Petroleum Products & NG | 2.20E-03 | 2.38E-03 | 1.38E-07 | N/A | 4.58E-03 | L/MJ Electricity | 0.64% |
| Coal | 1.10E-04 | 1.62E-05 | N/A | N/A | 1.27E-04 | L/MJ Electricity | 0.02% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.49E-03 | N/A | 2.49E-03 | L/MJ Electricity | 0.35% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 8.89E-05 | N/A | 8.89E-05 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 1.36E-05 | N/A | 8.21E-07 | N/A | 1.44E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 3.48% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.46% |
| TOTAL | 2.10E-01 | 4.56E-03 | 4.39E-01 | 5.90E-02 | 7.12E-01 | L/MJ Electricity | 100% |
| % | 29.45% | 0.64% | 61.63% | 8.28% | 100% | | |

Table 101: Life-Cycle Water Consumption for SPP Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.98E-01 | N/A | 9.63E+00 | N/A | 9.82E+00 | L/MJ Electricity | 90.38% |
| Electricity | 6.16E-02 | N/A | 1.08E-03 | 9.43E-01 | 1.01E+00 | L/MJ Electricity | 9.25% |
| Petroleum Products & NG | 2.20E-03 | 2.38E-03 | 1.38E-07 | N/A | 4.58E-03 | L/MJ Electricity | 0.04% |
| Coal | 1.10E-04 | 1.62E-05 | N/A | N/A | 1.27E-04 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.82E-03 | N/A | 6.82E-03 | L/MJ Electricity | 0.06% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 8.89E-05 | N/A | 8.89E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 4.86E-05 | N/A | 5.27E-06 | N/A | 5.39E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.23% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.03% |
| TOTAL | 2.68E-01 | 4.56E-03 | 9.65E+00 | 9.43E-01 | 1.09E+01 | L/MJ Electricity | 100% |
| % | 2.47% | 0.04% | 88.81% | 8.68% | 100% | | |

Table 102: Life-Cycle Water Withdrawals for SPP Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.08E-01 | N/A | 4.14E-01 | N/A | 6.22E-01 | L/MJ Electricity | 81.89% |
| Electricity | 3.44E-03 | N/A | 8.56E-05 | 9.96E-02 | 1.03E-01 | L/MJ Electricity | 13.57% |
| Petroleum Products & NG | 1.93E-03 | 1.82E-03 | 5.19E-08 | N/A | 3.75E-03 | L/MJ Electricity | 0.49% |
| Coal | 6.75E-05 | 1.00E-05 | N/A | N/A | 7.75E-05 | L/MJ Electricity | 0.01% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.61E-03 | N/A | 2.61E-03 | L/MJ Electricity | 0.34% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 5.71E-05 | N/A | 5.71E-05 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 8.06E-06 | N/A | 1.26E-06 | N/A | 9.33E-06 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 3.26% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.43% |
| TOTAL | 2.20E-01 | 4.00E-03 | 4.37E-01 | 9.96E-02 | 7.60E-01 | L/MJ Electricity | 100% |
| % | 28.91% | 0.53% | 57.46% | 13.10% | 100% | | |

Table 103: Life-Cycle Water Consumption for TRE NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 2.08E-01 | N/A | 1.47E+01 | N/A | 1.49E+01 | L/MJ Electricity | 85.66% |
| Electricity | 6.99E-02 | N/A | 1.67E-03 | 2.38E+00 | 2.45E+00 | L/MJ Electricity | 14.12% |
| Petroleum Products & NG | 1.93E-03 | 1.82E-03 | 5.19E-08 | N/A | 3.75E-03 | L/MJ Electricity | 0.02% |
| Coal | 6.75E-05 | 1.00E-05 | N/A | N/A | 7.75E-05 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 7.21E-03 | N/A | 7.21E-03 | L/MJ Electricity | 0.04% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 5.71E-05 | N/A | 5.71E-05 | L/MJ Electricity | 0.00% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.88E-05 | N/A | 8.12E-06 | N/A | 3.69E-05 | L/MJ Electricity | 0.00% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.14% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.02% |
| TOTAL | 2.86E-01 | 4.00E-03 | 1.47E+01 | 2.38E+00 | 1.74E+01 | L/MJ Electricity | 100% |
| % | 1.65% | 0.02% | 84.62% | 13.71% | 100% | | |

Table 104: Life-Cycle Water Withdrawals for TRE NERC Region Electricity Generation

| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.40E-01 | N/A | 3.39E-01 | N/A | 4.79E-01 | L/MJ Electricity | 86.16% |
| Electricity | 2.59E-03 | N/A | 9.10E-05 | 4.03E-02 | 4.29E-02 | L/MJ Electricity | 7.72% |
| Petroleum Products & NG | 1.40E-03 | 1.38E-03 | 1.11E-06 | N/A | 2.78E-03 | L/MJ Electricity | 0.50% |
| Coal | 6.00E-05 | 8.64E-06 | N/A | N/A | 6.86E-05 | L/MJ Electricity | 0.01% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 2.55E-03 | N/A | 2.55E-03 | L/MJ Electricity | 0.46% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.82E-04 | N/A | 3.82E-04 | L/MJ Electricity | 0.07% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 7.81E-06 | N/A | 1.68E-04 | N/A | 1.76E-04 | L/MJ Electricity | 0.03% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 4.45% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.59% |
| TOTAL | 1.51E-01 | 3.55E-03 | 3.62E-01 | 4.03E-02 | 5.56E-01 | L/MJ Electricity | 100% |
| % | 27.08% | 0.64% | 65.05% | 7.24% | 100% | | |

Table 105: Life-Cycle Water Consumption for WECC NERC Region Electricity Generation

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| Contributor | Feedstock Extraction/ Production | Feedstock Transportation | Refining | Fuel Transportation, Storage, & Distribution | TOTAL | Units | % |
|---|---|---|---|---|---|---|---|
| Direct | 1.40E-01 | N/A | 4.35E+00 | N/A | 4.49E+00 | L/MJ Electricity | 90.48% |
| Electricity | 5.20E-02 | N/A | 1.63E-03 | 3.77E-01 | 4.30E-01 | L/MJ Electricity | 8.68% |
| Petroleum Products & NG | 1.40E-03 | 1.38E-03 | 1.11E-06 | N/A | 2.78E-03 | L/MJ Electricity | 0.06% |
| Coal | 6.00E-05 | 8.64E-06 | N/A | N/A | 6.86E-05 | L/MJ Electricity | 0.00% |
| Steel, Copper, & Aluminum Mfg | N/A | N/A | 6.50E-03 | N/A | 6.50E-03 | L/MJ Electricity | 0.13% |
| Construction (Concrete Mix + Dust Control) | N/A | N/A | 3.82E-04 | N/A | 3.82E-04 | L/MJ Electricity | 0.01% |
| Chemicals, Plastics/Rubbers, Glass, Sand, & Silicon | 2.79E-05 | N/A | 3.51E-03 | N/A | 3.54E-03 | L/MJ Electricity | 0.07% |
| Supply-Chain Agriculture | 5.44E-03 | 1.58E-03 | 1.77E-02 | N/A | 2.48E-02 | L/MJ Electricity | 0.50% |
| Supply-Chain Services | 5.83E-04 | 5.83E-04 | 2.13E-03 | N/A | 3.30E-03 | L/MJ Electricity | 0.07% |
| TOTAL | 2.00E-01 | 3.55E-03 | 4.38E+00 | 3.77E-01 | 4.96E+00 | L/MJ Electricity | 100% |
| % | 4.03% | 0.07% | 88.29% | 7.60% | 100% | | |

Table 106: Life-Cycle Water Withdrawals for WECC NERC Region Electricity Generation

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# Appendix C: Impact on Ground and Surface Water Availability Calculations

## C.1 Disaggregation of Water Use Inventory by Location and Source

The first step in any impact assessment is spatial disaggregation of the inventory results. As is often the case, there are natural boundaries that make the most sense for a particular emission or resource. Airsheds are useful in analyzing the intake fraction of air pollutant emissions because they can be treated as relatively closed systems, for example. In the case of water resources, watersheds are the resolution of choice (*1*). Watersheds act as precipitation collectors, where the water drains into a common waterway (*2*). This property makes it relatively simple to track water availability in individual watersheds by taking flow measurements in this common waterway.

While resource-side water data is almost always reported by watershed, demand-side data is not. Environmental regulations and reporting of human activities such as agriculture and industry are based on political boundaries. The U.S. Geological Survey used to publish water-use data by 20 separate groups of watersheds known as water-resource regions (*3*). However, the report on 1995 water use was the last one to do so; the 2000 and 2005 reports provide data by state and county only (*4, 5*). Agricultural production is only reported on a county basis by the USDA, and although power plant locations are given in specific coordinates, these coordinates are most often simply the centroid of the county in which the plants are located (*6, 7*). The resulting difference between resource-side data and demand-side data must somehow be reconciled. Either political boundaries, by which demand-side data are reported, must be mapped to watersheds or vice versa. Reference (*1*) chooses to compromise the quality of demand-side data in order to perform their analysis on a watershed basis.

In this dissertation, the opposite approach is taken because one of the main goals of LCA is to provide decision support, and environmental policy is made within political boundaries rather than natural ones. It would be possible for governments to collaborate in order to effectively manage water resources within shared watersheds, but it is simpler to provide LCA results based on the existing paradigm rather than attempt to force the adoption of a new one. In the following sub-sections, the methods for geospatially disaggregating water-intensive industries by county are described. Counties are identified by Federal Information Processing Standard (FIPS) codes, where the first two digits indicate the state and the last three identify the specific county. For example, the state FIPS code for Arizona is 04 and the county FIPS code for Apache County is 001, so the full FIPS code for Apache County, AZ is 04001. For production in other countries, the water use is split up by nation.

This section provides details regarding how various processes and industries were geospatially disaggregated by FIPS code. Where discussion is necessary, the strategy is explained. Where no discussion is necessary, the data sources can be found in Table 114.

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## C.1.1 Fossil and Nuclear Fuel Extraction and Processing

The extraction and processing of fossil and nuclear fuels used in the U.S. is spread over much of the U.S. as well as other countries. Location and extraction methods both play a part in determining the water-intensity of these activities.

### *C.1.1.1 Coal*

To develop a county-level distribution of water requirements for coal mining, the 2007 Coal Production Data from the EIA's Coal Databases is used, which lists each coal mine and coal preparation facility in the United States by location, mine type (surface or underground), and total production (*8*). Because no information exists on whether revegetation will be completed, or to what degree, it is assumed that each surface mine requires an average of 50% of the revegetation estimate by reference (*9*). Information regarding which mines use saline and which use freshwater is also unavailable. Saline water would not be suitable for revegetation, but all other water use was reduced by 43% to account for saline water use. It is more likely that some mines use freshwater exclusively and others use all saline depending on their access to both water sources. Hopefully more information on these practices will be collected in the future.

Finally, assumptions were necessary in determining where coal was processed. Unlike mines, the EIA database does not list production for coal preparation facilities. Some mines have prepping facilities on site while others send their coal offsite to be prepped. The EIA coal mine inventory includes stand-alone mines, mines with attached prepping facilities, and separate prepping facilities. In individual counties, any coal that is not prepped onsite is assumed to be sent to prepping facilities within the county. If no prepping facilities (attached or stand-alone) exist in the county, the coal is assumed to be sent to prepping facilities within the state. If one stand-alone prepping facility exists within the state, all of the coal is sent there. If multiple stand-alone prepping facilities exist, the coal is assumed to be split equally among them (no capacity data for prepping facilities are included in the EIA inventory). If no stand-alone prepping facilities exist in the state, the coal is distributed amongst the attached prepping facilities according to coal production at the mine to which the prepping facility is attached (coal production at the attached mine is used as a proxy for prepping facility size).

There are two specific instances in which the described method breaks down: both Michigan and Minnesota contain prepping facilities but no coal mines according to the EIA database. Hence, these prepping facilities are assumed to process no coal. Although the method used to allocate coal that cannot be prepped in-county to other prepping plants may not be entirely realistic (a detailed network analysis would be preferable), it should be noted that all of the largest coal-producing counties do have local prepping capacity. In fact, only four of the top 50 coal-producing counties do not have at least one prepping facility within the county.

### *C.1.1.2 Uranium*

Unlike other primary fuels such as coal, there are very few uranium extraction sites in the United States. According to the U.S. Nuclear Regulatory Commission, there are only five

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licensed uranium recovery facilities: Crow Butte, Crown Point, Smith Ranch, and Christensen Ranch/Irigaray located in Nebraska, New Mexico, Sweetwater, and Wyoming (*10*). The facilities are listed in Table 107. The Christensen Ranch/Irigaray recovery facility spans two counties and, because it is unclear how much occurs in one county versus the other, the total production has been split equally between them. For the enrichment process, only gaseous diffusion is used in the United States (*11*).

| **Site Name** | **State** | **FIPS** | **Recovery Type** | **% of U.S. Production** | **% of Uranium-Related Water Consumption** |
|---|---|---|---|---|---|
| Crow Butte | NE | 31045 | In-Situ | 30.3% | 11.0% |
| Crown Point | NM | 35031 | In-Situ | 0.0% | 0.0% |
| Smith Ranch | WY | 56009 | In-Situ | 30.3% | 11.0% |
| Sweetwater | WY | 56037 | Conventional Underground | 9.2% | 3.4% |
| Christensen Ranch/Irigaray | WY | 56019 | In-Situ | 15.1% | 5.5% |
| Christensen Ranch/Irigaray | WY | 56005 | In-Situ | 15.1% | 5.5% |

Table 107: U.S. Uranium Recovery Sites (Data Sources: (*9, 10*)

The United States also imports approximately 86% of its uranium, primarily from Australia, Canada, and Russia (*12*). Table 108 shows countries that provide uranium to the United States and the 2008 quantities imported from each country. Data on imports from Brazil, the Czech Republic, Niger, and the United Kingdom were withheld to avoid disclosing an individual company's information, so the total unaccounted-for imports (270 metric tons of $U_3O_8$ equivalent) was divided equally among each of the four countries. In order to calculate the indirect water footprint of uranium production, primary fuel and electricity use information was taken from reference (*13*). For imports, a generic world electricity mix was used. This electricity mix is shown in Table 109.

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| Country | Metric tons $U_3O_8$ Equivalent | % of U.S. Uranium Use |
|---|---|---|
| Australia | 5.79E+03 | 23.91% |
| Brazil | 6.80E+01 | 0.28% |
| Canada | 4.44E+03 | 18.35% |
| China | 0.00E+00 | 0.00% |
| Czech Republic | 6.80E+01 | 0.28% |
| Germany | 0.00E+00 | 0.00% |
| Kazakhstan | 1.73E+03 | 7.16% |
| Kyrgyzstan | 0.00E+00 | 0.00% |
| Namibia | 1.76E+03 | 7.27% |
| Niger | 6.80E+01 | 0.28% |
| Russia | 5.48E+03 | 22.64% |
| South Africa | 3.55E+02 | 1.47% |
| Tajikistan | 0.00E+00 | 0.00% |
| Ukraine | 0.00E+00 | 0.00% |
| United Kingdom | 6.80E+01 | 0.28% |
| Uzbekistan | 8.72E+02 | 3.60% |
| Domestic (U.S.) | 3.50E+03 | 14.47% |

Table 108: U.S. Uranium Suppliers by Country (Source: (*12*))

| Data Category | Liquids | Nuclear | Renewables | Natural Gas | Coal | Weighted Total |
|---|---|---|---|---|---|---|
| Breakdown | 5% | 15% | 19% | 20% | 41% | N/A |
| Fuel Consumption (MJ Fuel/MJ Electricity) | 1.1E+00 | 3.3E+00 | 0.0E+00 | 2.6E+00 | 3.4E+00 | 2.5E+00 |
| Water Embodied in Fuels (L/MJ Electricity) | 1.0E-01 | 8.4E-02 | 0.0E+00 | 2.8E-01 | 1.9E-01 | 1.5E-01 |
| Total Water Consumption (L/MJ Electricity) | 4.8E-01 | 5.8E-01 | 3.5E-01 | 6.6E-01 | 5.9E-01 | 5.5E-01 |
| Total Water Withdrawals (L/MJ of Electricity) | 1.2E+01 | 1.6E+01 | 4.2E-01 | 1.2E+01 | 1.4E+01 | 1.1E+01 |

Table 109: World Electricity Mix (Data Source: (*14*))

### *C.1.1.3 Crude Oil and Natural Gas*

Reference (*15*) provides the top 100 oil and gas fields in the United States, along with their total production in 2008. These data were used to characterize total U.S. oil and gas production, which means that smaller fields are ignored. Furthermore, each oil and gas field is not provided by FIPS code. In the case where a city is provided, the city is mapped to its home county. In cases where cities are not provided, publicly available maps are used to assign the field to a county (or multiple counties). For fields that span across multiple counties, it is assumed to split its production evenly across each county. The crude oil fields are shown in Table 110 and natural gas fields are shown in Table 111.

| PADD | Field Name | State | County Name | County FIPS | 2007 Production (million barrels/year) |
|---|---|---|---|---|---|
| 5 | PRUDHOE BAY | AK | North Slope | 02185 | 96.3 |
| 3 | MISSISSIPPI CANYON BLK 807 (MARS-URSA ) | FG | OFFSHORE | OFFSHORE | 75.2 |

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|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 5 | KUPARUK RIVER | AK | North Slope | 02185 | 43 |
| 5 | MIDWAY-SUNSET | CA | Kern | 06029 | 38 |
| 5 | BELRIDGE SOUTH | CA | Kern | 06029 | 37 |
| 5 | ALPINE | AK | North Slope | 02185 | 33.7 |
| 5 | KERN RIVER | CA | Kern | 06029 | 30.1 |
| 3 | SPRABERRY TREND AREA | TX | Irion | 48235 | 4.683333333 |
| 3 |  |  | Reagan | 48383 | 4.683333333 |
| 3 |  |  | Upton | 48461 | 4.683333333 |
| 3 |  |  | Glasscock | 48173 | 4.683333333 |
| 3 |  |  | Midland | 48329 | 4.683333333 |
| 3 |  |  | Martin | 48317 | 4.683333333 |
| 4 | CEDAR HILLS | MT | Fallon | 30025 | 8.866666667 |
| 2 |  | ND | Bowman | 38011 | 8.866666667 |
| 2 |  | SD | Harding | 46063 | 8.866666667 |
| 3 | MISSISSIPPI CANYON BLK 383 (KEPLER ) | FG | OFFSHORE | OFFSHORE | 25.3 |
| 3 | WASSON | TX | Yoakum | 48501 | 23.6 |
| 5 | CYMRIC | CA | Kern | 06029 | 18.4 |
| 4 | ELM COULEE | MT | Richland | 30083 | 18.4 |
| 3 | MISSISSIPPI CANYON BLK 84 (KING) | FG | OFFSHORE | OFFSHORE | 16.8 |
| 3 | GREEN CANYON BLK 826 (MAD DOG ) | FG | OFFSHORE | OFFSHORE | 16.5 |
| 5 | ELK HILLS | CA | Kern | 06029 | 16.4 |
| 5 | WILMINGTON | CA | Los Angeles | 06037 | 14.9 |
| 5 | NORTHSTAR | AK | OFFSHORE | OFFSHORE | 13.9 |
| 3 | GREEN CANYON BLK 644 (HOLSTEIN ) | FG | OFFSHORE | OFFSHORE | 12.3 |
| 5 | MILNE POINT | AK | North Slope | 02185 | 12.2 |
| 5 | LOST HILLS | CA | Kern | 06029 | 12.2 |
| 3 | MISSISSIPPI CANYON BLK 773 (DEVILS TOWER ) | FG | OFFSHORE | OFFSHORE | 11.6 |
| 3 | SLAUGHTER | TX | Hockley | 48219 | 3.766666667 |
| 3 |  |  | Cochran | 48079 | 3.766666667 |
| 3 |  |  | Terry | 48445 | 3.766666667 |
| 3 | VIOSCA KNOLL BLK 786 (PETRONIUS ) | FG | OFFSHORE | OFFSHORE | 11.2 |
| 4 | WATTENBERG | CO | Weld | 08123 | 11 |
| 3 | GREEN CANYON BLK 158 (BRUTUS ) | FG | OFFSHORE | OFFSHORE | 11 |
| 3 | GREEN CANYON BLK 562 (K 2 ) | FG | OFFSHORE | OFFSHORE | 10.9 |
| 3 | KELLY-SNYDER | TX | Scurry | 48415 | 10.1 |
| 3 | YATES | TX | Pecos | 48371 | 9.9 |
| 5 | POINT MCINTYRE | AK | North Slope | 02185 | 8.8 |
| 3 | MISSISSIPPI CANYON BLK 127 (HORN MT. ) | FG | OFFSHORE | OFFSHORE | 8.4 |
| 3 | LAKE WASHINGTON | LA | Plaquemines | 22075 | 8.3 |
| 3 | LEVELLAND | TX | Hockley | 48219 | 8 |
| 2 | SHO-VEL-TUM | OK | Stephens | 40137 | 3.9 |
| 2 |  |  | Carter | 40019 | 3.9 |
| 3 | SEMINOLE | TX | Gaines | 48165 | 7.5 |
| 3 | GREEN CANYON BLK 680 (CONSTITUTION ) | FG | OFFSHORE | OFFSHORE | 6.6 |
| 3 | GIDDINGS | TX | Lee | 48287 | 6.5 |
| 5 | WEST SAK | AK | North Slope | 02185 | 6.4 |
| 5 | NANUQ | AK | North Slope | 02185 | 6.2 |
| 3 | MISSISSIPPI CANYON BLK 429 (ARIEL ) | FG | OFFSHORE | OFFSHORE | 6.2 |
| 3 | GOLDSMITH | TX | Ector | 48135 | 5.8 |

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|---|---|---|---|---|---|
| 5 | TARN | AK | North Slope | 02185 | 5.8 |
| 3 | MISSISSIPPI CANYON BLK 582 (MEDUSA ) | FG | OFFSHORE | OFFSHORE | 5.7 |
| 5 | HONDO | FP | OFFSHORE | OFFSHORE | 5.6 |
| 5 | COALINGA | CA | Fresno | 06019 | 5.6 |
| 5 | FIORD | AK | North Slope | 02185 | 5.6 |
| 3 | VACUUM | NM | Lea | 35025 | 5.5 |
| 3 | EWING BANK BLK 873 (LOON) | FG | OFFSHORE | OFFSHORE | 5.3 |
| 3 | EAST BREAKS BLK 602 (NANSEN ) | FG | OFFSHORE | OFFSHORE | 5.3 |
| 4 | RANGELY | CO | Rio Blanco | 08103 | 5.2 |
| 3 | COWDEN NORTH | TX | Andrews | 48003 | 5 |
| 3 | MCELROY | TX | Crane | 48103 | 4.7 |
| 5 | BOREALIS | AK | North Slope | 02185 | 4.6 |
| 5 | ENDICOTT | AK | North Slope | 02185 | 4.6 |
| 3 | HOBBS | NM | Lea | 35025 | 2.25 |
| 3 | | TX | Fisher | 48151 | 2.25 |
| 3 | GARDEN BANKS BLK 171 (SALSA ) | FG | OFFSHORE | OFFSHORE | 4.5 |
| 3 | SALT CREEK | TX | Kent | 48263 | 4.5 |
| 5 | PESCADO | FP | OFFSHORE | OFFSHORE | 4.4 |
| 4 | SAN JUAN BASIN GAS AREA | CO | Archuleta | 08007 | 0.44 |
| 4 | | | La Plata | 08067 | 0.44 |
| 4 | | | Montezuma | 08083 | 0.44 |
| 4 | | | Hinsdale | 08053 | 0.44 |
| 4 | | | Mineral | 08079 | 0.44 |
| 3 | | NM | San Juan | 35045 | 0.44 |
| 3 | | | McKinley | 35031 | 0.44 |
| 3 | | | Rio Arriba | 35039 | 0.44 |
| 3 | | | Sandoval | 35043 | 0.44 |
| 3 | | | Valencia | 35061 | 0.44 |
| 3 | | | Bernalillo | 35001 | 0.44 |
| 4 | MONUMENT BUTTE | UT | Duchesne | 49013 | 4.3 |
| 5 | VENTURA | CA | Ventura | 06111 | 4.2 |
| 3 | EAST TEXAS | TX | Gregg | 48183 | 0.84 |
| 3 | | | Rusk | 48401 | 0.84 |
| 3 | | | Upshur | 48459 | 0.84 |
| 3 | | | Smith | 48423 | 0.84 |
| 3 | | | Cherokee | 48073 | 0.84 |
| 3 | ROBERTSON NORTH | TX | Gaines | 48165 | 4.1 |
| 3 | FULLERTON | TX | Andrews | 48003 | 4.1 |
| 3 | MISSISSIPPI CANYON BLK 755 (GOMEZ ) | FG | OFFSHORE | OFFSHORE | 4 |
| 5 | SACATE | FP | OFFSHORE | OFFSHORE | 3.9 |
| 3 | BURR FERRY NORTH | LA | Vernon | 22115 | 1.9 |
| 3 | | | Sabine | 22085 | 1.9 |
| 3 | | TX | | | 0 |
| 5 | LISBURNE | AK | North Slope | 02185 | 3.7 |
| 5 | ORION | AK | North Slope | 02185 | 3.7 |
| 4 | JONAH | WY | Sublette | 56035 | 3.7 |
| 4 | GREATER ANETH | UT | San Juan | 49037 | 3.7 |
| 3 | GREEN CANYON BLK 339 (FRONT RUNNER ) | FG | OFFSHORE | OFFSHORE | 3.6 |
| 3 | GARDEN BANKS BLK 260 (BALDPATE ) | FG | OFFSHORE | OFFSHORE | 3.6 |

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|---|---|---|---|---|---|
| 3 | EUGENE ISLAND SA BLK 330 | FG | OFFSHORE | OFFSHORE | 3.5 |
| 5 | AURORA | AK | North Slope | 02185 | 3.5 |
| 5 | SAN ARDO | CA | Monterey | 06053 | 3.4 |
| 3 | ANTON-IRISH | TX | Hale | 48189 | 3.4 |
| 3 | FUHRMAN-MASCHO | TX | Andrews | 48003 | 3.3 |
| 5 | INGLEWOOD | CA | Los Angeles | 06037 | 3.1 |
| 3 | MEANS | TX | Andrews | 48003 | 3.1 |
| 3 | GRAND ISLE BLK 43 | FG | OFFSHORE | OFFSHORE | 3 |
| 3 | MISSISSIPPI CANYON BLK 109 (AMBERJACK ) | FG | OFFSHORE | OFFSHORE | 3 |
| 4 | SALT CREEK | WY | Natrona | 56025 | 3 |
| 4 | LOST SOLDIER | WY | Sweetwater | 56037 | 2.9 |
| 3 | NEWARK EAST | TX | Denton | 48121 | 0.933333333 |
| 3 |  |  | Tarrant | 48439 | 0.933333333 |
| 3 |  |  | Wise | 48497 | 0.933333333 |
| 5 | POINT PEDERNALES | FP | OFFSHORE | OFFSHORE | 2.8 |
| 3 | MAIN PASS SA BLK 299 | FG | OFFSHORE | OFFSHORE | 2.8 |
| 3 | GREEN CANYON BLK 768 (TICONDEROGA ) | FG | OFFSHORE | OFFSHORE | 2.7 |
| 3 | JAY | AL | Escambia | 01053 | 1.3 |
| 1C |  | FL | Santa Rosa | 12113 | 1.3 |
| 3 | HOWARD-GLASSCOCK | TX | Howard | 48227 | 2.6 |
| 3 | DOLLARHIDE | NM | Lea | 35025 | 1.3 |
| 3 |  | TX | Andrews | 48003 | 1.3 |
| 4 | OREGON BASIN | WY | Park | 56029 | 2.5 |
| 3 | COGDELL | TX | Kent | 48263 | 2.4 |
| 3 | HAWKINS | TX | Wood | 48499 | 2.4 |
| 4 | PINEDALE | WY | Sublette | 56035 | 2.4 |
| 4 | ELK BASIN | MT | Carbon | 30009 | 1.2 |
| 4 |  | WY | Park | 56029 | 1.2 |
| 3 | GRAYBURG JACKSON | NM | Eddy | 35015 | 2.3 |
| 3 | PANHANDLE | TX | Hartley | 48205 | 0.2875 |
| 3 |  |  | Potter | 48375 | 0.2875 |
| 3 |  |  | Moore | 48341 | 0.2875 |
| 3 |  |  | Hutchinson | 48233 | 0.2875 |
| 3 |  |  | Carson | 48065 | 0.2875 |
| 3 |  |  | Gray | 48179 | 0.2875 |
| 3 |  |  | Wheeler | 48483 | 0.2875 |
| 3 |  |  | Collingsworth | 48087 | 0.2875 |
| 3 | JO-MILL | TX | Borden | 48033 | 2.3 |
| 5 | MCARTHUR RIVER | AK | Kenai Peninsula | 02122 | 2.2 |

Table 110: 2007 U.S. Crude Oil Fields (Data Source: (*15*))

| **Field Name** | **State** | **County Name** | **FIPS** | **2007 Production (billion ft$^3$/year)** |
|---|---|---|---|---|
| NATURAL BUTTES/BITTER CREEK | UT | UINTAH | 49047 | 217.1 |
| HUGOTON GAS AREA | KS | SCOTT | 20171 | 59.31666667 |
|  |  | SEWARD | 20175 | 59.31666667 |
|  |  | STEVENS | 20189 | 59.31666667 |
|  |  | MORTON | 20129 | 59.31666667 |
|  | OK | TEXAS | 40139 | 59.31666667 |

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|---|---|---|---|---|
| | TX | GRAY | 48179 | 59.31666667 |
| B-43 (FAYETTEVILLE) | AR | POPE | 05115 | 275.8 |
| GRAND VALLEY | CO | GARFIELD | 08045 | 210.8 |
| ANTRIM | MI | MANISTEE | 26101 | 130.5 |
| CARTHAGE | TX | GREGG | 48183 | 233.3 |
| FOGARTY CREEK | WY | SUBLETTE | 56035 | 168.1 |
| RATON BASIN GAS AREA | CO | LAS ANIMAS | 08071 | 69.5 |
| | NM | COLFAX | 35007 | 69.5 |
| PRB COALBED/ALL NIGHT CREEK UNIT | MT | BIG HORN | 30003 | 267.65 |
| | WY | CAMPBELL | 56005 | 267.65 |
| LAKE RIDGE | WY | SUBLETTE | 56035 | 74.9 |
| LOWER MOBILE BAY AREA | AL | MOBILE | 01097 | 154.5 |
| | FG | N/A | | |
| ELM GROVE | LA | WEBSTER | 22119 | 141 |
| BIG SANDY | KY | JOHNSON | 21115 | 53.5 |
| PARACHUTE | CO | GARFIELD | 08045 | 93 |
| MAMM CREEK | CO | GARFIELD | 08045 | 113.9 |
| SAWYER | TX | CROCKETT | 48105 | 78.6 |
| PINON | TX | PECOS | 48371 | 109.1 |
| MADDEN | WY | FREMONT | 56013 | 102.9 |
| OAKWOOD | VA | TAZEWELL | 51185 | 75.1 |
| FREESTONE | TX | FREESTONE | 48161 | 99.2 |
| RULISON | CO | GARFIELD | 08045 | 114.5 |
| STILES RANCH | OK | ROGER MILLS | 40129 | 44.85 |
| | TX | WHEELER | 48483 | 44.85 |
| OAK HILL | TX | GREGG | 48183 | 105.5 |
| BALD PRAIRIE | TX | LEON | 48289 | 75.5 |
| CARTHAGE NORTH | TX | PANOLA | 48365 | 37.7 |
| WILD ROSE | WY | CARBON | 56007 | 25.6 |
| STRONG CITY DISTRICT | OK | ROGER MILLS | 40129 | 82.8 |
| WAMSUTTER | WY | CARBON | 56007 | 36.3 |
| STANDARD DRAW | WY | SWEETWATER | 56037 | 26.6 |
| BEAR GRASS | TX | FREESTONE | 48161 | 50.8 |
| FARRAR | TX | FREESTONE | 48161 | 72.3 |
| PICEANCE CREEK | CO | RIO BLANCO | 08103 | 18.7 |
| ECHO SPRINGS | WY | CARBON | 56007 | 30.5 |
| PINE HOLLOW SOUTH | OK | PITTSBURG | 40121 | 58.7 |
| BUFFALO WALLOW | TX | HEMPHILL | 48211 | 59.1 |
| TEAGUE | TX | FREESTONE | 48161 | 78.9 |
| CASPIANA | LA | CADDO | 22017 | 53.4 |
| MESA UNIT | WY | SUBLETTE | 56035 | 31.4 |
| VERNON | LA | JACKSON | 22049 | 64.4 |
| RED OAK-NORRIS | OK | LATIMER | 40077 | 53.3 |
| MOCANE-LAVERNE GAS AREA | OK | BEAVER | 40007 | 27.05 |
| | | HARPER | 40059 | 27.05 |
| | KS | N/A | | |
| | TX | N/A | | |
| CEDARDALE NE | OK | HARPER | 40059 | 36.6 |
| HALEY | TX | LOVING | 48301 | 94.7 |

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|---|---|---|---|---|
| DRUNKARDS WASH | UT | CARBON | 49007 | 49.4 |
| WATONGA-CHICKASHA-TREND | OK | BLAINE | 40011 | 42 |
| BUZZARD CREEK | CO | MESA | 08077 | 3.7 |
| GOLDEN TREND | OK | GARVIN | 40049 | 35.1 |
| NORA | VA | RUSSELL | 51167 | 35.6 |
| BELUGA RIVER | AK | TYONEK QUAD | 02020 | 42.9 |
| SULPHUR CREEK | CO | RIO BLANCO | 08103 | 10.5 |
| OVERTON | TX | PARKER | 48367 | 44.1 |
| TRAIL RIDGE | CO | GARFIELD | 08045 | 7.2 |
| BRUFF | WY | LINCOLN | 56023 | 31 |
| BETHANY-LONGSTREET | LA | CADDO | 22017 | 19.45 |
| | | DE SOTO | 22031 | 19.45 |
| | TX | N/A | | |
| MAYFIELD NE | OK | BECKHAM | 40009 | 58.8 |
| RILEY RIDGE | WY | SUBLETTE | 56035 | 0.2 |
| BRACHFIELD SE | TX | RUSK | 48401 | 15.05 |
| | | PANOLA | 48365 | 15.05 |
| TIP TOP | WY | SUBLETTE | 56035 | 14.7 |
| COALGATE NE | OK | COAL | 40029 | 15.8 |
| GARDEN BANKS BLK 506 | FG | OFFSHORE-FEDERAL | N/A | 0.1 |
| MINDEN | TX | RUSK | 48401 | 35.1 |
| VERDEN | OK | CADDO | 22017 | 33 |
| SHREVEPORT | LA | BOSSIER | 22015 | 9.2 |
| MISSISSIPPI CANYON BLK 778 THUNDER HORSE ) | FG | OFFSHORE-FEDERAL | N/A | 9.1 |
| TIERNEY | WY | CARBON | 56007 | 8.9 |
| ELK CITY | OK | ROGER MILLS | 40129 | 41.8 |
| SAVELL | TX | ROBERTSON | 48395 | 63.5 |
| BRUSH CREEK | CO | MESA | 08077 | 10.9 |
| GOMEZ | TX | PECOS | 48371 | 33.8 |
| ARKOMA BASIN (WOODFORD) | OK | CARTER | 40019 | 26.7 |
| KINTA | OK | PITTSBURG | 40121 | 20.25 |
| | | HASKELL | 40061 | 20.25 |
| DEW | TX | FREESTONE | 48161 | 25.9 |
| VEGA | CO | MESA | 08077 | 10.5 |
| DOWDY RANCH | TX | FREESTONE | 48161 | 31.7 |
| BEGERT | TX | HEMPHILL | 48211 | 5.9 |
| JOHN AMORUSO | TX | ROBERTSON | 48395 | 114 |
| WAYNOKA NE | OK | WOODS | 40151 | 23.6 |
| CEMENT | OK | CADDO | 22017 | 36.8 |
| BLUE CREEK COAL DEGAS | AL | TUSCALOOSA | 01125 | 22.4 |
| SLIGO | LA | WEBSTER | 22119 | 35.3 |
| FRENCHIE DRAW | WY | FREMONT | 56013 | 14 |
| WILBURTON | OK | PITTSBURG | 40121 | 29.2 |
| EUGENE IS BLK 24 | FG | OFFSHORE-STATE | N/A | 17.7 |
| WOODARDVILLE | LA | BIENVILLE | 22013 | 23.5 |
| MENDOTA NW | TX | HEMPHILL | 48211 | 39.1 |

Table 111: 2007 U.S. Natural Gas Fields (Data Source: (*15*))

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### *C.1.1.4 Oil Sands*

Both Venezuela and Canada have large oil sands reserves, but Canada supplies the vast majority of SCO from oil sands to the United States, totaling to more than 7% of crude oil consumption, so only Canadian oil sands are considered here.  Most oil sands extraction takes place in the Athabasca region of northern Alberta, which falls into the WECC NERC region, so all electricity consumption is assigned the WECC mix (*7*).  In terms of direct water use, international water consumption and withdrawals are disaggregated only by country, so 100% of direct water use for oil sands extraction is assigned to Canada.

## C.1.2 Agricultural Production

### *C.1.2.1 Corn Grain and Stover*

Corn grain production in the United States is tracked at the county level by the USDA National Agricultural Statistics Service (*6*), so these data are used alongside the county-to-NERC region mapping to determine the average electricity mix consumed for corn farming.  Direct water use is not uniform throughout the country, however, so state-level irrigation data are used to weight direct water use by irrigation application.  Unfortunately, because the USDA Farm and Ranch Irrigation Survey (*6*) only reports irrigation inputs by state, total irrigation requirements per unit of corn output are assumed to be constant within individual states.

## C.1.3 Power Generation

Different power plants have dramatically different environmental footprints.  Coal can be more than twice as carbon intensive as natural gas-fired power plants (*16*), and open-loop coal plants withdraw nearly 50 times more water than coal plants with closed-loop cooling systems. Hence, when determining the environmental footprint of electricity consumed by a particular facility, it is important to account for the types of power plants that are supplying this energy. This task is made difficult by the fact that customers do not purchase power from the plants directly, but rather whatever mix is fed onto the grid, which changes on an hourly, seasonal, and longer-term basis depending on fuel prices and generation capacity.  "Balancing areas", containing anywhere between dozens and hundreds of power plants are controlled by balancing authorities that match generation and demand by purchasing more electricity within the balancing area or importing power from other areas via "tie lines" that connect balancing areas (*17*).  While some utilities offer "green" power, for which customers pay a premium that is theoretically used to purchase a larger quantity of wind, solar, etc., no one who purchases power from the grid has direct control over where or how that electricity is generated.

When measuring the impacts of any kind of interaction with the electrical grid, whether a user is drawing power or supplying power, it is important to establish appropriate system boundaries such that all of the entities that interact with the user are included.  If the boundaries are too small, relevant players will be left out and if the boundaries are too large, the region will incorporate power plants or demands that are not relevant to the user being studied (*16*).  North American Electric Reliability Corporation (NERC) regions are often used in

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electrical grid analyses because, while there is some trade of power across NERC boundaries, the vast majority of power produced in each region is consumed within the region. While NERC supplies a map of these regions, definitive boundaries do not exist. Rather, NERC regions are made up of collections of electric utilities. Two facilities could be in very close proximity to one another, but if they are served by two different utilities, it is possible that they belong to different NERC regions. A location may also appear to clearly be in one region based on the NERC map (although still relatively close to the region's border), but in reality be contained in the neighboring region. This makes mapping any sort of political boundaries such as counties to NERC regions a difficult task. Unfortunately, datasets for power-consuming or producing facilities other than power plants themselves generally do not identify which NERC region they reside in or which utility supplies or buys their power; the location information given (typically city or county) must be used to estimate the NERC region.

Matching FIPS codes to NERC regions is, by definition, imperfect because one county may contain multiple NERC regions. Even in a single zip code, the U.S. EPA Power Profiler demonstrates that a user can be located in one of multiple NERC regions depending on which utility supplies its power (*18*). However, the model created for this research is structured such that each county must be connected to only one NERC region. This matching is done in the following manner:

1. U.S. EPA eGRID data provides a list of all power generators in the U.S., along with the county and NERC region in which they reside. In cases where only one power plant exists in a particular county or the county contains multiple power plants that are all identified as being in the same NERC region, the county is listed as being in that particular region. In the relatively uncommon instance where multiple power plants exist in one county and are listed as being in different NERC regions, the NERC region is assigned such that it matches that of the larger plant.

2. For counties that contain no power generators, the EPA Power Profiler is used, plugging in a sample zip code from that county and assigning the NERC region with which the zip code is identified. For counties that are shown as being in two or more NERC regions, one is chosen at random.

Although the method for assigning counties to NERC regions is subject to uncertainty, it allows for a more accurate picture of the impacts of electricity consumption than if a generic U.S. mix were universally applied. In the future, counties that fall into multiple NERC regions could be disaggregated based on the fraction of electricity consumption that occurs in each region. However, the data to perform this analysis are not readily available.

### C.1.4 Corn Grain Ethanol Production

| FIPS Code | Site | Total Operable Capacity (barrels/day) |
|---|---|---|
| 04021 | Maricopa | 55 |
| 06107 | Pixley | 55 |
| 06099 | Keyes | 50 |

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| | | |
|---|---|---|
| 06065 | Corona | 5 |
| 06039 | Madera | 40 |
| 06077 | Stockton | 60 |
| 06107 | Goshen | 31.5 |
| 08069 | Windsor | 40 |
| 08005 | Aurora | 3 |
| 08075 | Sterling | 42 |
| 08125 | Yuma | 40 |
| 13283 | Soperton | 20 |
| 13125 | Mitchell Co. | 100 |
| 13205 | Baconton | 0.4 |
| 19013 | St. Ansgar | 100 |
| 19029 | Atlantic | 110 |
| 19179 | Eddyville | 35 |
| 19197 | Goldfield | 55 |
| 19109 | Lakota | 97 |
| 19033 | Mason City | 115 |
| 19139 | Muscatine | 20 |
| 19145 | Shenandoah | 55 |
| 19059 | Superior | 55 |
| 19019 | Fairbank | 120 |
| 19083 | Iowa Falls | 105 |
| 19077 | Menlo | 110 |
| 19023 | Shell Rock | 110 |
| 19037 | New Hampton | 100 |
| 19073 | Grand Junction | 100 |
| 19169 | Nevada | 50 |
| 19035 | Marcus | 92 |
| 19113 | Cedar Rapids | 45 |
| 19083 | Steamboat Rock | 20 |
| 19093 | Arthur | 110 |
| 19149 | Merrill | 50 |
| 19143 | Ashton | 56 |
| 19027 | Coon Rapids | 54 |
| 19003 | Corning | 65 |
| 19147 | Emmetsburg | 55 |
| 19187 | Gowrie | 69 |
| 19195 | Hanlontown | 56 |
| 19079 | Jewell | 69 |
| 19093 | Galva | 30 |
| 19167 | Sioux Center | 60 |
| 19155 | Council Bluffs | 110 |
| 19187 | Ft. Dodge | 105 |
| 19011 | Blairstown | 5 |
| 16027 | Caldwell | 4 |
| 16031 | Burley | 50 |
| 17177 | Lena | 40 |
| 17055 | Benton | 5 |
| 17073 | Galva | 100 |

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|---|---|---|
| 17163 | Sauget | 54 |
| 17141 | Rochelle | 100 |
| 17033 | Palestine | 48 |
| 17155 | Hennepin | 100 |
| 17179 | Pekin | 78 |
| 17053 | Gibson City | 100 |
| 17073 | Annawan | 100 |
| 17057 | Canton | 37 |
| 18135 | Union City | 100 |
| 18053 | Marion | 40 |
| 18179 | Bluffton | 101 |
| 18073 | Rensselaer | 40 |
| 18141 | South Bend | 102 |
| 18141 | Alexandria | 68 |
| 18169 | North Manchester | 68 |
| 18075 | Portland | 68 |
| 18017 | Clymers | 110 |
| 20175 | Liberal | 110 |
| 20055 | Garden City | 55 |
| 20181 | Goodland | 20 |
| 20003 | Garnett | 35 |
| 20203 | Leoti | 1.5 |
| 20159 | Lyons | 55 |
| 20147 | Phillipsburg | 40 |
| 20055 | Garden City | 12 |
| 20109 | Campus | 45 |
| 20167 | Russell | 48 |
| 21047 | Hopkinsville | 33 |
| 21111 | Louisville | 5.4 |
| 22053 | Jennings | 1.5 |
| 26091 | Riga | 57 |
| 26147 | Marysville | 50 |
| 26157 | Caro | 53 |
| 26025 | Albion | 55 |
| 27133 | Luverne | 21 |
| 27039 | Claremont | 42 |
| 27067 | Atwater | 50 |
| 27097 | Little Falls | 21.5 |
| 27151 | Benson | 45 |
| 27043 | Winnebago | 44 |
| 27149 | Morris | 21.5 |
| 27173 | Granite Falls | 52 |
| 27143 | Winthrop | 100 |
| 27063 | Heron Lake | 50 |
| 27127 | Lamberton | 50 |
| 27145 | Melrose | 2.6 |
| 27129 | Buffalo Lake | 18 |
| 27111 | Fergus Falls | 57.5 |
| 27033 | Bingham Lake | 35 |

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|---|---|---|
| 27047 | Albert Lea | 42 |
| 27013 | Lake Crystal | 56 |
| 27045 | Preston | 46 |
| 29087 | Craig | 20 |
| 29021 | St. Joseph | 40 |
| 29195 | Malta Bend | 50 |
| 29007 | Laddonia | 55 |
| 29121 | Macon | 46 |
| 29033 | Carrollton | 55 |
| 28149 | Vicksburg | 54 |
| 37093 | Raeford | 60 |
| 38055 | Underwood | 50 |
| 38089 | Richardton | 50 |
| 38017 | Casselton | 110 |
| 31059 | Fairmont | 100 |
| 31079 | Wood River | 115 |
| 31177 | Blair | 85 |
| 31001 | Hastings | 62 |
| 31047 | Lexington | 40 |
| 31067 | Adams | 50 |
| 31139 | Plainview | 75 |
| 31099 | Minden | 40 |
| 31119 | Norfolk | 45 |
| 31065 | Cambridge | 44 |
| 31135 | Madrid | 44 |
| 31111 | Sutherland | 25 |
| 31089 | Atkinson | 44 |
| 31043 | Jackson | 50 |
| 31087 | Trenton | 40 |
| 36075 | Volney | 114 |
| 36063 | Shelby | 50 |
| 39003 | Lima | 54 |
| 39147 | Fostoria | 68 |
| 39137 | Leipsic | 68 |
| 39101 | Marion | 65 |
| 39037 | Greenville | 110 |
| 41009 | Clatskanie | 108 |
| 41049 | Boardman | 40 |
| 42033 | Clearfield | 110 |
| 46013 | Aberdeen | 50 |
| 46005 | Huron | 65 |
| 46079 | Wentworth | 50 |
| 46029 | Watertown | 100 |
| 46109 | Rosholt | 20 |
| 46051 | Big Stone City | 79 |
| 46125 | Chancellor | 110 |
| 46083 | Hudson | 56 |
| 46035 | Mitchell | 68 |
| 46009 | Scotland | 11 |

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|---|---|---|
| 46013 | Groton | 53 |
| 46115 | Redfield | 50 |
| 46011 | Aurora | 0 |
| 47131 | Obion | 100 |
| 47105 | Loudon | 105 |
| 48219 | Levelland | 40 |
| 48117 | Hereford | 115 |
| 48117 | Hereford | 100 |
| 48189 | Plainview | 100 |
| 53015 | Longview | 55 |
| 55017 | Stanley | 41 |
| 55045 | Monroe | 48 |
| 55057 | Necedah | 50 |
| 55021 | Cambria | 40 |
| 55055 | Jefferson Junction | 130 |
| 55105 | Milton | 52 |
| 55021 | Friesland | 49 |
| 55139 | Oshkosh | 48 |
| 55033 | Boyceville | 40 |
| 56045 | Upton | 1.5 |
| 56015 | Torrington | 5 |

Table 112: U.S. Corn Grain-to-Ethanol Biorefineries (Data Source: (*19*))

## C.1.5 Crude Oil Refining

| FIPS Code | Owner | Operating Capacity (barrels/day) |
|---|---|---|
| 10003 | PREMCOR REFINING GROUP INC | 182200 |
| 13051 | CITGO ASPHALT REFINING CO | 28000 |
| 34039 | CONOCOPHILLIPS COMPANY | 238000 |
| 34015 | CITGO ASPHALT REFINING CO | 32000 |
| 34015 | VALERO REFINING CO NEW JERSEY | 160000 |
| 34023 | CHEVRON USA INC | 80000 |
| 34023 | SUNOCO INC | 145000 |
| 42083 | AMERICAN REFINING GROUP INC | 10000 |
| 42045 | SUNOCO INC | 178000 |
| 42101 | SUNOCO INC (R&M) | 335000 |
| 42045 | CONOCOPHILLIPS COMPANY | 185000 |
| 42123 | UNITED REFINING CO | 65000 |
| 51199 | WESTERN REFINING YORKTOWN INC | 63650 |
| 54029 | ERGON WEST VIRGINIA INC | 20000 |
| 17197 | EXXONMOBIL REFINING & SUPPLY CO | 238600 |
| 17031 | PDV Midwest Refining LLC | 167000 |
| 17033 | MARATHON PETROLEUM CO LLC | 204000 |
| 17119 | WRB REFINING LLC | 306000 |
| 18129 | COUNTRYMARK COOPERATIVE INC | 23000 |
| 18089 | BP PRODUCTS NORTH AMERICA INC | 410000 |
| 20125 | COFFEYVILLE RESOURCES RFG & MKTG LLC | 115700 |
| 20015 | FRONTIER EL DORADO REFINING CO | 107500 |
| 20113 | NCRA | 82700 |

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|---|---|---|
| 21019 | MARATHON PETROLEUM CO LLC | 226000 |
| 21199 | SOMERSET REFINERY INC | 5500 |
| 26163 | MARATHON PETROLEUM CO LLC | 102000 |
| 27123 | Flint Hills Resources LP | 288150 |
| 27123 | MARATHON PETROLEUM CO LLC | 74000 |
| 38059 | Tesoro West Coast | 58000 |
| 39151 | MARATHON PETROLEUM CO LLC | 78000 |
| 39003 | LIMA REFINING COMPANY | 146200 |
| 39095 | BP PRODUCTS NORTH AMERICA INC | 131000 |
| 39095 | SUNOCO INC | 160000 |
| 40019 | VALERO REFINING CO OKLAHOMA | 87400 |
| 40071 | CONOCOPHILLIPS COMPANY | 194000 |
| 40039 | VENTURA REFINING & TRANSMISSION LLC | 12000 |
| 40143 | SINCLAIR OIL CORP | 70300 |
| 40143 | SUNOCO INC | 85000 |
| 40049 | WYNNEWOOD REFINING CO | 71700 |
| 47157 | PREMCOR REFINING GROUP INC | 180000 |
| 55031 | MURPHY OIL USA INC | 34300 |
| 1053 | GOODWAY REFINING LLC | 4100 |
| 1097 | SHELL CHEMICAL LP | 86000 |
| 1125 | HUNT REFINING CO | 34500 |
| 5139 | LION OIL CO | 70000 |
| 5139 | CROSS OIL REFINING & MARKETING INC | 7500 |
| 22033 | EXXONMOBIL REFINING & SUPPLY CO | 503000 |
| 22075 | CONOCOPHILLIPS COMPANY | 247000 |
| 22087 | Chalmette Refining LLC | 192760 |
| 22093 | Motiva Enterprises LLC | 235000 |
| 22119 | CALUMET LUBRICANTS CO LP | 13020 |
| 22095 | MARATHON PETROLEUM CO LLC | 256000 |
| 22097 | VALERO REFINING CO LOUISIANA | 80000 |
| 22019 | CALCASIEU REFINING CO | 78000 |
| 22019 | CITGO PETROLEUM CORP | 429500 |
| 22087 | MURPHY OIL USA INC | 120000 |
| 22089 | Motiva Enterprises LLC | 236400 |
| 22089 | VALERO REFINING NEW ORLEANS LLC | 185003 |
| 22121 | PLACID REFINING CO | 56000 |
| 22015 | CALUMET LUBRICANTS CO LP | 8300 |
| 22089 | SHELL CHEMICAL LP | 55000 |
| 22017 | CALUMET SHREVEPORT LLC | 42000 |
| 22019 | CONOCOPHILLIPS COMPANY | 239400 |
| 28059 | CHEVRON USA INC | 330000 |
| 28067 | HUNT SOUTHLAND REFINING CO | 11000 |
| 28149 | ERGON REFINING INC | 23000 |
| 35015 | NAVAJO REFINING CO | 84000 |
| 35045 | WESTERN REFINING SOUTHWEST INC | 16800 |
| 35031 | WESTERN REFINING SOUTHWEST INC | 20800 |
| 48201 | EXXONMOBIL REFINING & SUPPLY CO | 567000 |
| 48245 | EXXONMOBIL REFINING & SUPPLY CO | 348500 |
| 48227 | ALON USA ENERGY INC | 67000 |

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|---|---|---|
| 48233 | WRB REFINING LLC | 146000 |
| 48355 | CITGO REFINING & CHEMICAL INC | 156000 |
| 48355 | Flint Hills Resources LP | 288126 |
| 48355 | VALERO REFINING CO TEXAS LP | 142000 |
| 48201 | DEER PARK REFINING LTD PARTNERSHIP | 329800 |
| 48141 | WESTERN REFINING COMPANY LP | 122000 |
| 48201 | HOUSTON REFINING LP | 270600 |
| 48201 | VALERO REFINING CO TEXAS LP | 83000 |
| 48207 | PASADENA REFINING SYSTEMS INC | 100000 |
| 48245 | Motiva Enterprises LLC | 285000 |
| 48245 | PREMCOR REFINING GROUP INC | 289000 |
| 48245 | TOTAL PETROCHEMICALS INC | 232000 |
| 48029 | AGE REFINING INC | 13500 |
| 48341 | VALERO ENERGY CORPORATION | 171000 |
| 48039 | CONOCOPHILLIPS COMPANY | 247000 |
| 48167 | BP PRODUCTS NORTH AMERICA INC | 467720 |
| 48167 | MARATHON PETROLEUM CO LLC | 76000 |
| 48167 | VALERO REFINING CO TEXAS LP | 199500 |
| 48297 | VALERO ENERGY CORPORATION | 93000 |
| 48423 | DELEK REFINING LTD | 58000 |
| 8001 | SUNCOR ENERGY (USA) INC | 32000 |
| 8001 | SUNCOR ENERGY (USA) INC | 62000 |
| 30111 | CONOCOPHILLIPS COMPANY | 58000 |
| 30111 | EXXONMOBIL REFINING & SUPPLY CO | 60000 |
| 30013 | MONTANA REFINING CO | 9500 |
| 30111 | Cenex Harvest States Coop | 59600 |
| 49011 | BIG WEST OIL CO | 29400 |
| 49035 | CHEVRON USA INC | 45000 |
| 49035 | Tesoro West Coast | 58000 |
| 49011 | HOLLY CORP REFINING & MARKETING | 25050 |
| 49011 | Silver Eagle Refining | 10250 |
| 56021 | FRONTIER REFINING INC | 47000 |
| 56041 | Silver Eagle Refining | 3000 |
| 56025 | LITTLE AMERICA REFINING CO | 24500 |
| 56045 | WYOMING REFINING CO | 14000 |
| 56007 | SINCLAIR OIL CORP | 66000 |
| 2122 | TESORO ALASKA PETROLEUM CO | 72000 |
| 2090 | FLINT HILLS RESOURCES ALASKA LLC | 210000 |
| 2090 | PETRO STAR INC | 17500 |
| 2185 | BP EXPLORATION ALASKA INC | 12780 |
| 2185 | CONOCOPHILLIPS ALASKA INC | 15000 |
| 2261 | PETRO STAR INC | 48000 |
| 6079 | CONOCOPHILLIPS COMPANY | 44200 |
| 6029 | BIG WEST OF CALIFORNIA | 66000 |
| 6029 | KERN OIL & REFINING CO | 26000 |
| 6029 | SAN JOAQUIN REFINING CO INC | 15000 |
| 6095 | VALERO REFINING CO CALIFORNIA | 144000 |
| 6037 | CHEVRON USA INC | 260000 |
| 6037 | EDGINGTON OIL CO INC | 35000 |

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|---|---|---|
| 6037 | BP West Coast Products LLC | 265000 |
| 6013 | Shell Oil Products US | 155600 |
| 6013 | TESORO REFINING & MARKETING CO | 166000 |
| 6111 | TENBY INC | 2800 |
| 6037 | PARAMOUNT PETROLEUM CORPORATION | 53000 |
| 6013 | CHEVRON USA INC | 242901 |
| 6013 | CONOCOPHILLIPS COMPANY | 76000 |
| 6083 | Greka Energy | 9500 |
| 6037 | LUNDAY THAGARD CO | 8500 |
| 6037 | EXXONMOBIL REFINING & SUPPLY CO | 149500 |
| 6037 | CONOCOPHILLIPS COMPANY | 139000 |
| 6037 | TESORO REFINING & MARKETING CO | 97000 |
| 6037 | ULTRAMAR INC | 80887 |
| 6037 | VALERO REFINING CO CALIFORNIA | 6300 |
| 15003 | TESORO HAWAII CORP | 93500 |
| 15003 | CHEVRON USA INC | 54000 |
| 32033 | FORELAND REFINING CORP | 2000 |
| 53057 | Shell Oil Products US | 145000 |
| 53057 | Tesoro West Coast | 120000 |
| 53073 | BP West Coast Products LLC | 225000 |
| 53073 | CONOCOPHILLIPS COMPANY | 100000 |
| 53053 | US OIL & REFINING CO | 37850 |

Table 113: U.S. Crude Oil Refineries (Data Sources: (*19, 20*))

### C.1.6 Supply-Chain Service and Agriculture

Supply-chain service and agriculture water use as quantified by EIO-LCA includes all service sectors and all agriculture. For service sectors, county-level population data is used to allocate service-related water use, based on the expectation that the amount of economic activity in service sectors is roughly correlated with population in any given location. For agriculture, water use is allocated using data from the USGS report that provides annual water withdrawals for irrigation by county (*5*).

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## C.2 Summary of Data Sources and Results

| Process/Industry | Data Source(s) |
|---|---|
| Coal Mining | (*8*) |
| Uranium Mining | (*10-12*) |
| Oil Extraction | (*15*) |
| Oil Sands Extraction | None occurring in the United States |
| Natural Gas Extraction & Processing | (*15*) |
| Steel Production | (*21-24*) |
| Chemicals Manufacturing | (*25*) |
| Corn Grain Agriculture | (*6*) |
| Corn Stover Agriculture | Assumed to be the same as corn grain |
| Miscanthus Agriculture | Assumed to be the same as corn grain |
| Petroleum Refining | (*19, 20*) |
| Corn Grain Biorefining | (*19*) |
| Corn Stover Biorefining | Assumed to be the same as corn grain biorefining |
| Miscanthus Biorefining | Assumed to be the same as corn grain biorefining |
| Electric Power Generation | (*7*) |
| Glass, Sand & Clay | (*25*) |
| Plastics & Rubbers | (*25*) |
| Supply-Chain Agriculture | (*5*) |
| Supply-Chain Services | (*5*) |

Table 114: Data Sources for Geospatial Disaggregation of Industries in the United States

Because county-level data are too large to print in this appendix, the input data and county-level results are available by on www.energy-water-footprint.com or by request (corinne.scown@gmail.com).

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# Appendix D: Embodied Energy and Greenhouse Gas Emissions Calculations

| End Use | Fuel for Water Pumping | Motor Efficiency | GW Energy Use (MJ/L) | SW Energy Use (MJ/L) |
|---|---|---|---|---|
| Domestic (Private) | Electricity | 90% | 9.0E-04 | N/A |
| Public Supply | Electricity | 90% | 7.9E-04 | 2.6E-04 |
| Commercial | Electricity | 90% | 9.0E-04 | 2.8E-04 |
| Petroleum Refineries | Electricity | 90% | 9.6E-04 | 2.8E-04 |
| Natural Gas Processing Plants | Electricity | 90% | 9.6E-04 | 2.8E-04 |
| Other Industrial | Electricity | 90% | 9.6E-04 | 2.8E-04 |
| Coal Mining | Electricity | 90% | 9.6E-04 | 2.8E-04 |
| Oil & Gas Extraction | Natural Gas | 26% | 3.3E-03 | 9.7E-04 |
| Other Mining/Extraction | Electricity | 90% | 9.6E-04 | 2.8E-04 |
| Power Generation | Electricity | 90% | 1.0E-03 | 2.8E-04 |
| Agriculture/Livestock | Combination | Combination | Shown in Table 116 | Shown in Table 116 |

Table 115: Energy for Self-Supplied Water Pumping by Sector

| | Surface Water (MJ/L) | | | | Groundwater (MJ/L) | | | |
|---|---|---|---|---|---|---|---|---|
| State | Electricity | NG | Propane/ Butane/LPG | Diesel | Electricity | NG | Propane/ Butane/ LPG | Diesel |
| AL | 2.1E-05 | N/A | N/A | 2.4E-05 | 4.9E-05 | N/A | N/A | 5.5E-05 |
| AK | 1.6E-05 | N/A | N/A | 2.7E-05 | 3.7E-05 | N/A | N/A | 6.2E-05 |
| AZ | 2.3E-05 | 1.5E-05 | 1.2E-07 | 6.4E-06 | 5.5E-05 | 3.5E-05 | 2.9E-07 | 1.5E-05 |
| AR | 1.2E-05 | 2.0E-06 | 8.7E-07 | 3.0E-05 | 2.7E-05 | 4.7E-06 | 2.0E-06 | 7.1E-05 |
| CA | 2.3E-05 | 5.6E-06 | 6.9E-07 | 1.6E-05 | 5.4E-05 | 1.3E-05 | 1.6E-06 | 3.7E-05 |
| CO | 3.5E-05 | 6.4E-06 | 2.8E-07 | 3.3E-06 | 8.2E-05 | 1.5E-05 | 6.6E-07 | 7.6E-06 |
| CT | 8.4E-06 | N/A | 1.2E-05 | 2.5E-05 | 2.0E-05 | N/A | 2.7E-05 | 5.8E-05 |
| DE | 8.0E-06 | N/A | N/A | 3.7E-05 | 1.9E-05 | N/A | N/A | 8.7E-05 |
| FL | 9.2E-06 | N/A | 1.1E-07 | 3.6E-05 | 2.2E-05 | N/A | 2.6E-07 | 8.4E-05 |
| GA | 1.9E-05 | N/A | 3.9E-07 | 2.6E-05 | 4.4E-05 | N/A | 9.0E-07 | 6.1E-05 |
| HI | 2.4E-05 | N/A | N/A | 2.0E-05 | 5.7E-05 | N/A | N/A | 4.7E-05 |
| ID | 4.3E-05 | 2.7E-08 | 9.5E-08 | 1.6E-06 | 1.0E-04 | 6.4E-08 | 2.2E-07 | 3.8E-06 |
| IL | 1.5E-05 | N/A | 2.1E-06 | 2.8E-05 | 3.5E-05 | N/A | 4.9E-06 | 6.5E-05 |
| IN | 2.0E-05 | 5.1E-07 | 9.5E-07 | 2.4E-05 | 4.6E-05 | 1.2E-06 | 2.2E-06 | 5.5E-05 |
| IA | 2.4E-05 | N/A | 2.8E-06 | 1.8E-05 | 5.7E-05 | N/A | 6.5E-06 | 4.2E-05 |
| KS | 2.7E-06 | 3.4E-05 | 5.0E-07 | 7.7E-06 | 6.4E-06 | 8.0E-05 | 1.2E-06 | 1.8E-05 |
| KY | 8.3E-06 | N/A | N/A | 3.0E-05 | 2.0E-05 | N/A | N/A | 6.9E-05 |
| LA | 4.4E-06 | 1.8E-06 | 5.6E-07 | 3.8E-05 | 1.0E-05 | 4.3E-06 | 1.3E-06 | 8.9E-05 |
| ME | 4.2E-06 | N/A | 4.9E-06 | 3.3E-05 | 9.8E-06 | N/A | 1.1E-05 | 7.7E-05 |
| MD | 3.8E-06 | N/A | 3.8E-07 | 3.8E-05 | 8.9E-06 | N/A | 8.8E-07 | 8.9E-05 |
| MA | 8.0E-06 | N/A | 2.6E-05 | 9.2E-06 | 1.9E-05 | N/A | 6.1E-05 | 2.1E-05 |
| MI | 2.3E-05 | 7.4E-07 | 3.5E-07 | 2.1E-05 | 5.3E-05 | 1.7E-06 | 8.1E-07 | 4.8E-05 |
| MN | 3.0E-05 | N/A | 1.7E-07 | 1.5E-05 | 7.0E-05 | N/A | 4.1E-07 | 3.5E-05 |
| MS | 1.3E-05 | N/A | N/A | 3.2E-05 | 2.9E-05 | N/A | N/A | 7.6E-05 |
| MO | 1.1E-05 | 5.4E-07 | 7.1E-06 | 2.5E-05 | 2.5E-05 | 1.3E-06 | 1.7E-05 | 6.0E-05 |
| MT | 3.8E-05 | 9.4E-07 | 4.1E-07 | 6.0E-06 | 8.8E-05 | 2.2E-06 | 9.7E-07 | 1.4E-05 |
| NE | 1.2E-05 | 1.4E-05 | 2.7E-06 | 1.6E-05 | 2.7E-05 | 3.3E-05 | 6.3E-06 | 3.9E-05 |
| NV | 4.0E-05 | N/A | N/A | 5.1E-06 | 9.4E-05 | N/A | N/A | 1.2E-05 |
| NH | 4.5E-05 | N/A | N/A | N/A | 1.1E-04 | N/A | N/A | N/A |

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|---|---|---|---|---|---|---|---|---|
| NJ | 4.8E-06 | N/A | 3.0E-08 | 3.7E-05 | 1.1E-05 | N/A | 7.0E-08 | 8.7E-05 |
| NM | 3.2E-05 | 1.0E-05 | N/A | 3.0E-06 | 7.4E-05 | 2.4E-05 | N/A | 6.9E-06 |
| NY | 5.4E-06 | N/A | N/A | 3.6E-05 | 1.3E-05 | N/A | N/A | 8.5E-05 |
| NC | 8.9E-06 | N/A | 3.0E-07 | 3.3E-05 | 2.1E-05 | N/A | 7.0E-07 | 7.7E-05 |
| ND | 3.4E-05 | 1.2E-06 | 3.0E-07 | 9.4E-06 | 8.0E-05 | 2.9E-06 | 7.0E-07 | 2.2E-05 |
| OH | 1.6E-05 | 1.5E-05 | N/A | 1.2E-05 | 3.9E-05 | 3.5E-05 | N/A | 2.7E-05 |
| OK | 8.8E-06 | 2.9E-05 | 7.3E-07 | 6.2E-06 | 2.1E-05 | 6.8E-05 | 1.7E-06 | 1.4E-05 |
| OR | 4.2E-05 | N/A | N/A | 2.9E-06 | 9.9E-05 | N/A | N/A | 6.7E-06 |
| PA | 1.1E-05 | N/A | 8.1E-08 | 2.5E-05 | 2.7E-05 | N/A | 1.9E-07 | 5.8E-05 |
| RI | 1.8E-05 | N/A | 2.7E-05 | N/A | 4.3E-05 | N/A | 6.3E-05 | N/A |
| SC | 3.2E-05 | 2.1E-06 | 1.7E-06 | 8.5E-06 | 7.6E-05 | 4.9E-06 | 4.1E-06 | 2.0E-05 |
| SD | 2.9E-05 | 5.5E-07 | 5.5E-07 | 1.5E-05 | 6.9E-05 | 1.3E-06 | 1.3E-06 | 3.4E-05 |
| TN | 1.6E-05 | N/A | 1.2E-06 | 2.5E-05 | 3.7E-05 | N/A | 2.8E-06 | 5.9E-05 |
| TX | 1.0E-05 | 3.1E-05 | 7.8E-08 | 3.6E-06 | 2.3E-05 | 7.4E-05 | 1.8E-07 | 8.3E-06 |
| UT | 3.5E-05 | 1.9E-07 | 1.0E-07 | 9.5E-06 | 8.2E-05 | 4.4E-07 | 2.5E-07 | 2.2E-05 |
| VT | 1.1E-05 | N/A | N/A | 2.2E-05 | 2.6E-05 | N/A | N/A | 5.1E-05 |
| VA | 1.4E-05 | N/A | 3.8E-07 | 2.6E-05 | 3.3E-05 | N/A | 8.9E-07 | 6.0E-05 |
| WA | 4.4E-05 | N/A | N/A | 7.9E-07 | 1.0E-04 | N/A | N/A | 1.8E-06 |
| WV | 3.9E-05 | N/A | N/A | 6.0E-06 | 9.1E-05 | N/A | N/A | 1.4E-05 |
| WI | 2.4E-05 | N/A | 1.7E-07 | 2.0E-05 | 5.7E-05 | N/A | 4.1E-07 | 4.7E-05 |
| WY | 3.6E-05 | 1.6E-06 | 8.0E-07 | 6.7E-06 | 8.4E-05 | 3.8E-06 | 1.9E-06 | 1.6E-05 |

Table 116: Fuel Use for Agricultural Water Pumping (Calculated from (*1*))

| GHG | NG | Distillate Fuel Oil | Gasoline | LPG |
|---|---|---|---|---|
| $CO_2e$ (g/MJ) | 5.7E+01 | 7.0E+01 | 6.1E+01 | 6.9E+01 |
| $CO_2$ (g/MJ) | 4.9E+01 | 7.0E+01 | 5.9E+01 | 6.8E+01 |
| $CH_4$ (g/MJ) | 3.5E-01 | 3.7E-03 | 2.9E-02 | 1.0E-03 |
| $N_2O$ (g/MJ) | 1.4E-03 | 1.9E-03 | 1.9E-03 | 4.6E-03 |

Table 117 Combustion Emission Factors Water Pumping (Source: (*2*))

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| MWD Member Agency | County |
|---|---|
| Anaheim | Orange |
| Beverly Hills | Los Angeles |
| Burbank | Los Angeles |
| Calleguas | Ventura |
| Central Basin | Los Angeles |
| Compton | Los Angeles |
| Eastern | Riverside |
| Foothill | Los Angeles |
| Fullerton | Orange |
| Glendale | Los Angeles |
| Inland Empire | San Bernadino |
| Las Virgenes | Los Angeles |
| Long Beach | Los Angeles |
| Los Angeles | Los Angeles |
| MWDOC | Orange |
| Pasadena | Los Angeles |
| San Diego | San Diego |
| San Fernando | Los Angeles |
| San Marino | Los Angeles |
| Santa Ana | Orange |
| Santa Monica | Los Angeles |
| Three Valleys | Los Angeles |
| Torrance | Los Angeles |
| Upper San Gabriel | Los Angeles |
| West Basin | Los Angeles |
| Western | Riverside |

Table 118: MWD Member Agencies Mapped to CA Counties (Based on Reference (*3*))

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| Member Agency | Total Local Production ($m^3$) | Total Local Use ($m^3$) | MWD Direct Deliveries ($m^3$) | MWD Indirect Deliveries ($m^3$) | MWD Total Deliveries ($m^3$) | Total Water Use ($m^3$) | MWD Direct Deliveries as % of Total Use |
|---|---|---|---|---|---|---|---|
| Anaheim | 5.85E+07 | 5.85E+07 | 2.51E+07 | N/A | 2.51E+07 | 8.35E+07 | 30% |
| Beverly Hills | 1.05E+06 | 1.05E+06 | 1.46E+07 | N/A | 1.46E+07 | 1.56E+07 | 93% |
| Burbank | 1.21E+07 | 1.21E+07 | 1.74E+07 | N/A | 1.74E+07 | 2.95E+07 | 59% |
| Calleguas | 4.49E+07 | 5.71E+07 | 1.38E+08 | N/A | 1.38E+08 | 1.96E+08 | 71% |
| Central Basin | 2.30E+08 | 2.57E+08 | 6.51E+07 | N/A | 6.51E+07 | 3.22E+08 | 20% |
| Compton | 7.66E+06 | 7.66E+06 | 2.67E+06 | N/A | 2.67E+06 | 1.03E+07 | 26% |
| Eastern | 1.50E+08 | 1.50E+08 | 1.20E+08 | 8.58E+06 | 1.29E+08 | 2.79E+08 | 43% |
| Foothill | 1.14E+07 | 1.14E+07 | 1.27E+07 | N/A | 1.27E+07 | 2.41E+07 | 53% |
| Fullerton | 2.42E+07 | 2.42E+07 | 1.20E+07 | N/A | 1.20E+07 | 3.61E+07 | 33% |
| Glendale | 1.28E+07 | 1.28E+07 | 2.58E+07 | N/A | 2.58E+07 | 3.86E+07 | 67% |
| Inland Empire | 2.41E+08 | 2.41E+08 | 5.44E+07 | N/A | 5.44E+07 | 2.96E+08 | 18% |
| Las Virgenes | 4.84E+06 | 5.01E+06 | 2.93E+07 | N/A | 2.93E+07 | 3.43E+07 | 85% |
| Long Beach | 3.82E+07 | 3.82E+07 | 2.73E+07 | 7.67E+06 | 3.49E+07 | 7.32E+07 | 37% |
| Los Angeles | 2.65E+08 | 2.65E+08 | 5.35E+08 | N/A | 5.35E+08 | 8.00E+08 | 67% |
| MWDOC | 3.56E+08 | 3.70E+08 | 2.65E+08 | 2.74E+07 | 2.92E+08 | 6.63E+08 | 40% |
| Pasadena | 1.41E+07 | 1.46E+07 | 2.80E+07 | N/A | 2.80E+07 | 4.25E+07 | 66% |
| San Diego | 1.11E+08 | 1.11E+08 | 6.95E+08 | N/A | 6.95E+08 | 8.06E+08 | 86% |
| San Fernando | 3.39E+06 | 3.39E+06 | N/A | N/A | 0.00E+00 | 3.39E+06 | 0% |
| San Marino | 5.23E+06 | 5.23E+06 | 1.25E+06 | N/A | 1.25E+06 | 6.47E+06 | 19% |
| Santa Ana | 3.13E+07 | 3.13E+07 | 7.23E+06 | N/A | 7.23E+06 | 3.85E+07 | 19% |
| Santa Monica | 2.44E+06 | 2.44E+06 | 1.49E+07 | N/A | 1.49E+07 | 1.73E+07 | 86% |
| Three Valleys | 6.49E+07 | 6.49E+07 | 8.02E+07 | N/A | 8.02E+07 | 1.45E+08 | 55% |
| Torrance | 3.43E+06 | 7.25E+06 | 2.39E+07 | N/A | 2.39E+07 | 3.11E+07 | 77% |
| Upper San Gabriel | 2.52E+08 | 2.07E+08 | 1.05E+07 | N/A | 1.05E+07 | 2.17E+08 | 5% |
| West Basin | 6.99E+07 | 7.04E+07 | 1.41E+08 | 1.21E+07 | 1.53E+08 | 2.23E+08 | 63% |
| Western | 2.24E+08 | 2.20E+08 | 1.20E+08 | N/A | 1.20E+08 | 3.41E+08 | 35% |

Table 119: FY 2008-2009 Water Supply for MWD Member Agencies (Data Source: (*3*))

**Notes**: Total Local Use is equal to Total Local Production, adjusted inter-agency transfers and water produced for groundwater recharge projects; Indirect Deliveries include full service seawater barrier and groundwater spreading deliveries

| County | Total Local Production ($m^3$) | Total Local Use ($m^3$) | MWD Direct Deliveries ($m^3$) | MWD Indirect Deliveries ($m^3$) | MWD Total Deliveries ($m^3$) | Total Water Use ($m^3$) | MWD Direct Deliveries as % of Total Use |
|---|---|---|---|---|---|---|---|
| Orange | 4.70E+08 | 4.84E+08 | 3.09E+08 | 2.74E+07 | 3.37E+08 | 8.21E+08 | 38% |
| Los Angeles | 9.98E+08 | 9.85E+08 | 1.03E+09 | 1.97E+07 | 1.05E+09 | 2.03E+09 | 51% |
| Ventura | 4.49E+07 | 5.71E+07 | 1.38E+08 | N/A | 1.38E+08 | 1.96E+08 | 71% |
| Riverside | 3.75E+08 | 3.71E+08 | 2.41E+08 | 8.58E+06 | 2.49E+08 | 6.20E+08 | 39% |
| San Diego | 1.11E+08 | 1.11E+08 | 6.95E+08 | N/A | 6.95E+08 | 8.06E+08 | 86% |
| San Bernadino | 2.41E+08 | 2.41E+08 | 5.44E+07 | N/A | 5.44E+07 | 2.96E+08 | 18% |
| TOTAL | 2.24E+09 | 2.25E+09 | 2.47E+09 | 5.57E+07 | 2.52E+09 | 4.77E+09 | 52% |

Table 120: County Water Supplies by Source

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| County Name | Assumed Fraction from CRA | CRA Energy Intensity (kWh/AF Water) | Assumed Fraction from SWP | SWP Energy Intensity (kWh/AF Water) | MJ Electricity/L Imported Water | Source |
|---|---|---|---|---|---|---|
| Los Angeles | 47% | 2.0E+03 | 53% | 2.6E+03 | 6.7E-03 | (*4*) |
| Ventura | 47% | 2.0E+03 | 53% | 2.6E+03 | 6.7E-03 | (*4*) |
| Orange | 47% | 2.0E+03 | 53% | 3.2E+03 | 7.6E-03 | (*4*) |
| Riverside | 47% | 2.0E+03 | 53% | 3.2E+03 | 7.6E-03 | (*4*) |
| San Bernadino | 47% | 2.0E+03 | 53% | 3.2E+03 | 7.6E-03 | (*4*) |
| San Diego | 47% | 2.0E+03 | 53% | 3.2E+03 | 7.6E-03 | (*4*) |

Table 121: Energy Intensity of California Public Water Imports

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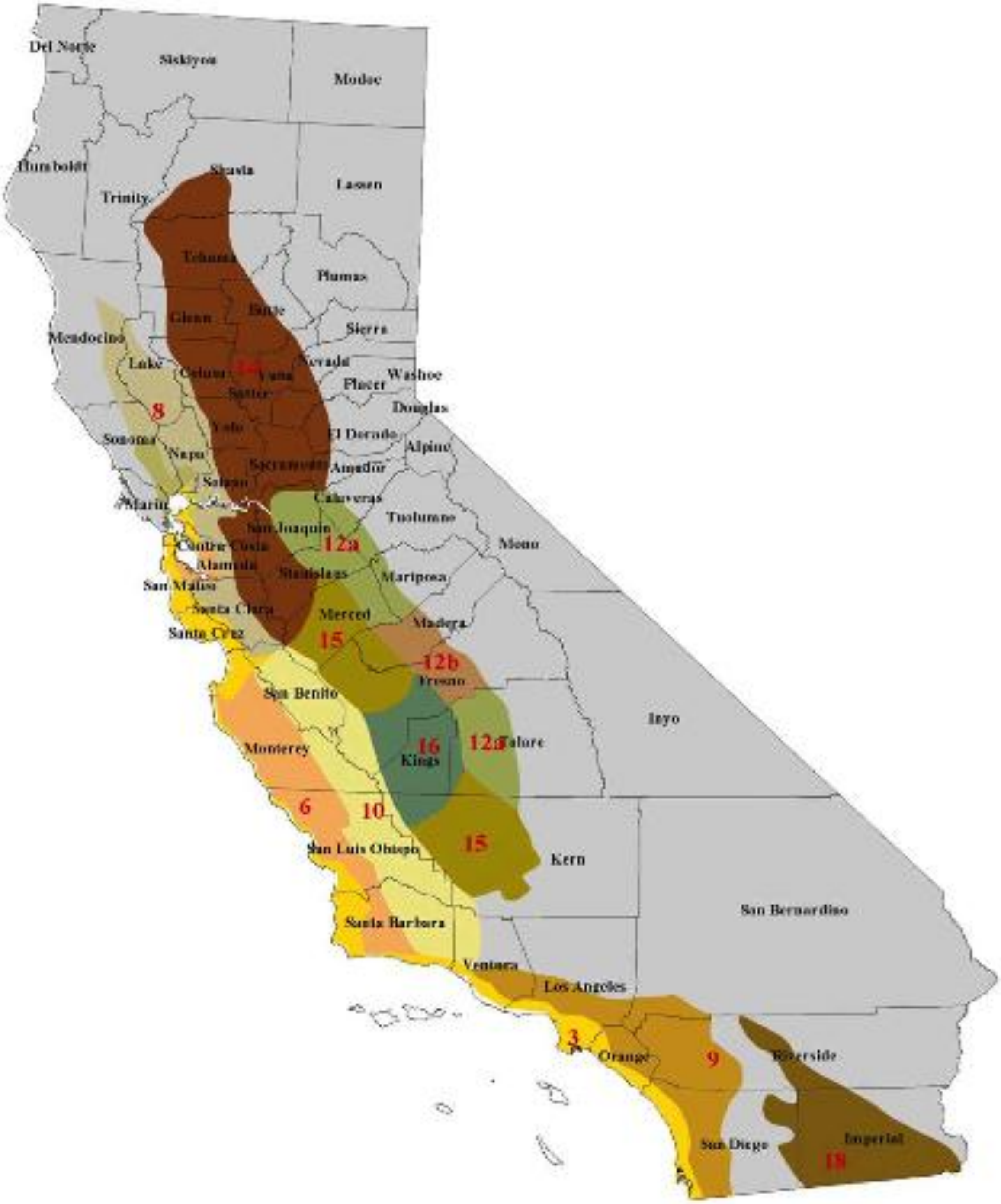

Figure 69: Modified Evapotranspiration Zones Used for Energy Analysis (Source: (*5*))

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| Irrigation Region | Surface Water Imported or Pumped by Irrigation District | Groundwater Pumped by Irrigation District | On-Farm Groundwater Pumping |
|---|---|---|---|
| 1 | N/A | N/A | 100.0% |
| 3 | N/A | N/A | 100.0% |
| 4 | N/A | N/A | 100.0% |
| 6 | N/A | N/A | 100.0% |
| 8 | 67.1% | 0.4% | 32.6% |
| 9 | N/A | N/A | 100.0% |
| 10 | N/A | N/A | 100.0% |
| 12a | 73.3% | 3.1% | 23.6% |
| 12b | 61.5% | 2.6% | 35.8% |
| 14 | 95.0% | 0.2% | 4.8% |
| 15 | 48.8% | 5.9% | 45.3% |
| 16 | 50.7% | 0.8% | 48.4% |
| 18 | 98.5% | N/A | 1.5% |

Table 122: Breakdown of Water Sources for CA Irrigation Regions (Source: (*5*))

| Irrigation Region | Surface Water Imported or Pumped by Irrigation District (kWh/$m^3$) | Groundwater Pumped by Irrigation District (kWh/$m^3$) | Groundwater Pumped On-Farm (kWh/$m^3$) | Energy Intensity: On-Farm Booster Pumping (kWh/$m^3$) | % of Farm Water Pumped w/ Diesel |
|---|---|---|---|---|---|
| 1 | N/A | N/A | 0.359 | 0.136 | 10% |
| 3 | N/A | N/A | 0.359 | 0.143 | 10% |
| 4 | N/A | N/A | 0.359 | 0.106 | 10% |
| 6 | N/A | N/A | 0.339 | 0.125 | 5% |
| 8 | 0.027 | 0.163 | 0.210 | 0.100 | 10% |
| 9 | N/A | N/A | 0.235 | 0.081 | 20% |
| 10 | N/A | N/A | 0.331 | 0.071 | 20% |
| 12a | 0.007 | 0.169 | 0.236 | 0.059 | 20% |
| 12b | 0.007 | 0.169 | 0.232 | 0.053 | 20% |
| 14 | 0.056 | 0.117 | 0.207 | 0.045 | 35% |
| 15 | 0.346 | 0.320 | 0.347 | 0.065 | 30% |
| 16 | 0.042 | 0.166 | 0.271 | 0.059 | 30% |
| 18 | N/A | N/A | 0.188 | 0.080 | 10% |

Table 123: Energy Intensity of Water by Irrigation Region (Based on Data from (*5*))

| FIPS | California County | Irrigation Region | Electricity for Irrigation Region (MJ/L) | Diesel for Irrigation Region (MJ/L) | MJ Electricity/L Irrigation Water | MJ Diesel/L Irrigation Water |
|---|---|---|---|---|---|---|
| 06103 | Tehama | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 06007 | Butte | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06021 | Glenn | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06115 | Yuba | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06057 | Nevada | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06061 | Placer | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06017 | El Dorado | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06067 | Sacramento | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06011 | Colusa | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06113 | Yolo | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06095 | Solano | 14 | 3.9E-04 | 6.4E-04 | 5.3E-04 | 4.3E-04 |
| | | 8 | 6.7E-04 | 2.3E-04 | | |
| 06033 | Lake | 8 | 6.7E-04 | 2.3E-04 | 6.7E-04 | 2.3E-04 |
| 06045 | Mendocino | 8 | 6.7E-04 | 2.3E-04 | 6.7E-04 | 2.3E-04 |
| 06055 | Napa | 8 | 6.7E-04 | 2.3E-04 | 5.6E-04 | 2.8E-04 |
| | | 12a | 4.5E-04 | 3.4E-04 | | |
| 06097 | Sonoma | 8 | 6.7E-04 | 2.3E-04 | 5.6E-04 | 2.8E-04 |
| | | 12a | 4.5E-04 | 3.4E-04 | | |
| 06041 | Marin | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06013 | Contra Costa | 8 | 6.7E-04 | 2.3E-04 | 5.3E-04 | 4.3E-04 |
| | | 14 | 3.9E-04 | 6.4E-04 | | |
| 06009 | Calaveras | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06109 | Tuolumne | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06043 | Mariposa | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06077 | San Joaquin | 12a | 4.5E-04 | 3.4E-04 | 4.2E-04 | 4.9E-04 |
| | | 14 | 3.9E-04 | 6.4E-04 | | |
| 06099 | Stanislaus | 12a | 4.5E-04 | 3.4E-04 | 4.2E-04 | 4.9E-04 |
| | | 14 | 3.9E-04 | 6.4E-04 | | |
| 06047 | Merced | 12a | 4.5E-04 | 3.4E-04 | 9.6E-04 | 1.1E-03 |
| | | 15 | 1.5E-03 | 1.9E-03 | | |
| 06107 | Tulare | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06029 | Kern | 15 | 1.5E-03 | 1.9E-03 | 1.5E-03 | 1.9E-03 |
| 06031 | Kings | 16 | 7.7E-04 | 9.9E-04 | 7.7E-04 | 9.9E-04 |
| 06025 | Imperial | 18 | 3.0E-04 | 1.0E-04 | 3.0E-04 | 1.0E-04 |
| 06073 | San Diego | 9 | 1.1E-03 | 8.6E-04 | 1.5E-03 | 7.3E-04 |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06065 | Riverside | 18 | 3.0E-04 | 1.0E-04 | 7.2E-04 | 4.8E-04 |
| | | 9 | 1.1E-03 | 8.6E-04 | | |
| 06059 | Orange | 9 | 1.1E-03 | 8.6E-04 | 1.5E-03 | 7.3E-04 |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06037 | Los Angeles | 9 | 1.1E-03 | 8.6E-04 | 1.5E-03 | 7.3E-04 |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06111 | Ventura | 10 | 1.4E-03 | 1.1E-03 | 1.5E-03 | 8.5E-04 |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| | | 9 | 1.1E-03 | 8.6E-04 | | |
| 06083 | Santa Barbara | 10 | 1.4E-03 | 1.1E-03 | 1.6E-03 | 6.6E-04 |
| | | 6 | 1.7E-03 | 2.7E-04 | | |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06079 | San Luis Obispo | 6 | 1.7E-03 | 2.7E-04 | 1.6E-03 | 6.6E-04 |
| | | 10 | 1.4E-03 | 1.1E-03 | | |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06053 | Monterey | 6 | 1.7E-03 | 2.7E-04 | | |
| | | 10 | 1.4E-03 | 1.1E-03 | 1.6E-03 | 6.6E-04 |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06069 | San Benito | 10 | 1.4E-03 | 1.1E-03 | 1.4E-03 | 1.1E-03 |
| 06019 | Fresno | 12b | 5.2E-04 | 3.9E-04 | | |
| | | 16 | 7.7E-04 | 9.9E-04 | 9.2E-04 | 1.1E-03 |
| | | 15 | 1.5E-03 | 1.9E-03 | | |
| 06039 | Madera | 12b | 5.2E-04 | 3.9E-04 | 1.0E-03 | 1.2E-03 |
| | | 15 | 1.5E-03 | 1.9E-03 | | |
| 06001 | Alameda | 6 | 1.7E-03 | 2.7E-04 | | |
| | | 8 | 6.7E-04 | 2.3E-04 | 1.1E-03 | 4.4E-04 |
| | | 14 | 3.9E-04 | 6.4E-04 | | |
| | | 3 | 1.8E-03 | 6.1E-04 | | |
| 06089 | Shasta | 14 | 3.9E-04 | 6.4E-04 | 3.9E-04 | 6.4E-04 |
| 06041 | Marin | 12a | 4.5E-04 | 3.4E-04 | 4.5E-04 | 3.4E-04 |
| 06081 | San Mateo | 3 | 1.8E-03 | 6.1E-04 | 1.8E-03 | 6.1E-04 |
| 06087 | Santa Cruz | 3 | 1.8E-03 | 6.1E-04 | 1.8E-03 | 6.1E-04 |
| 06085 | Santa Clara | 8 | 6.7E-04 | 2.3E-04 | 5.3E-04 | 4.3E-04 |
| | | 14 | 3.9E-04 | 6.4E-04 | | |

Table 124: Energy-Intensity of California Agricultural Water by County (Sources: (*1, 5*))

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| Member Agency | Percent of MWD Preferential Supply Used in FY 98-99 |
|---|---|
| Anaheim | 93.03% |
| Beverly Hills | 63.24% |
| Burbank | 68.55% |
| Calleguas | 154.48% |
| Central Basin | 35.33% |
| Compton | 80.51% |
| Eastern | 103.91% |
| Foothill | 60.90% |
| Fullerton | 50.20% |
| Glendale | 102.17% |
| Inland Empire | 97.30% |
| Las Virgenes | 144.44% |
| Long Beach | 77.11% |
| Los Angeles | 14.66% |
| MWDOC | 83.68% |
| Pasadena | 66.53% |
| San Diego | 150.38% |
| San Fernando | N/A |
| San Marino | 20.52% |
| Santa Ana | 81.12% |
| Santa Monica | 57.54% |
| Three Valleys | 127.55% |
| Torrance | 86.77% |
| Upper San Gabriel | 7.63% |
| West Basin | 84.23% |
| Western | 99.48% |
| TOTAL | 73.47% |

Table 125: Fraction of MWD Preferential Supply Used by Member Agencies (Source: (*6*))

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# Appendix E: Uncertainty and Sensitivity Calculations

| **Process** | **W: Low** | **C: Low** | **W: Avg.** | **C: Avg.** | **W: High** | **C: High** | **Units** | **Source(s)** |
|---|---|---|---|---|---|---|---|---|
| PADD I Crude Oil Extraction | 0 | 0 | 0 | 0 | 0.0857 | 0.0857 | L/MJ Crude Oil | (*1*) |
| PADD II Crude Oil Extraction | 0 | 0 | 0.0546 | 0.0546 | 0.184 | 0.184 | L/MJ Crude Oil | (*1*) |
| PADD III Crude Oil Extraction | 0 | 0 | 0.0598 | 0.0598 | 0.190 | 0.190 | L/MJ Crude Oil | (*1*) |
| PADD IV Crude Oil Extraction | 0 | 0 | 0 | 0 | 0 | 0 | L/MJ Crude Oil | (*1*) |
| PADD V Crude Oil Extraction | 0 | 0 | 0.140 | 0.140 | 0.270 | 0.270 | L/MJ Crude Oil | (*1*) |
| Saudi Arabia Crude Oil Extraction | 0 | 0 | 0.0779 | 0.0779 | 0.0779 | 0.0779 | L/MJ Crude Oil | (*1*) |
| Oil Sands Extraction | 0.034 | 0.034 | 0.0789 | 0.0789 | 0.132 | 0.132 | L/MJ SCO | (*1*) |
| Miscanthus Green Water Consumption Relative to Previous Crop | 0 | 0 | 0 | 0 | 6.13 | 6.13 | L/MJ EtOH | (*2*) |
| Corn Grain Irrigation | 0 | 0 | 5.86 | 5.86 | 84.8 | 84.8 | L/MJ EtOH | (*3*) |
| Petroleum Refining | 0.104 | 0.102 | 0.141 | 0.135 | 0.176 | 0.166 | L Water/MJ Gasoline | (*1, 4*) |
| Miscanthus Biorefining | 0.0848 | 0.0848 | 0.259 | 0.259 | 1.48 | 0.416 | L Water/MJ EtOH | (*1, 5-7*) |
| Corn Stover Biorefining | .0848 | .0848 | 0.259 | 0.259 | 1.48 | 0.416 | L Water/MJ EtOH | (*1, 5, 6, 8*) |
| Corn Grain Biorefining | 0.127 | 0.127 | 0.154 | 0.154 | 1.06 | 0.297 | L Water/MJ EtOH | (*1, 6, 9*) |
| U.S. Electricity Generation | 4.96 | 0.55 | 12.9 | 0.609 | 18.1 | 0.781 | L Water/MJ Electricity | Varied by NERC Region |
| Ammonia Manufacturing | 141 | 7.00 | 141 | 11.0 | 141 | 15.0 | L Water/kg Ammonia | (*6*) |
| Sulfuric Acid Manufacturing | 66.0 | 3.00 | 66.0 | 5.00 | 66.0 | 7.00 | L Water/kg Sulfuric Acid | (*6*) |
| Phosphoric Acid Manufacturing | 282 | 20.0 | 282 | 30.0 | 282 | 40.0 | L Water/kg $P_2O_5$ | (*6*) |
| Chlorine Manufacturing | 75.0 | 6.00 | 75.0 | 9.00 | 75.0 | 12.0 | L Water/kg Chlorine | (*6*) |
| Polyethylene Manufacturing | 83.0 | 4.00 | 83.0 | 6.50 | 83.0 | 9.00 | L Water/kg Polyethylene | (*6*) |

Table 126: Inputs Varied for Sensitivity Analysis

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| Pathway | C/ W | Scenario | Feedstock Extraction/ Production | Feedstock Transportation | Refining/Fuel Production | Fuel Transportation, Storage & Distribution | TOTAL |
|---|---|---|---|---|---|---|---|
| Crude Oil to Gasoline | C | Low | 5.22E-02 | 8.60E-03 | 5.02E-01 | 4.24E-03 | 5.67E-01 |
| | | Avg | 4.24E-01 | 1.48E-02 | 6.34E-01 | 8.71E-03 | 1.08E+00 |
| | | High | 6.27E-01 | 1.89E-02 | 7.58E-01 | 1.16E-02 | 1.42E+00 |
| | W | Low | 7.19E-02 | 2.60E-02 | 8.52E-01 | 1.17E-02 | 9.62E-01 |
| | | Avg | 4.45E-01 | 3.23E-02 | 9.75E-01 | 1.62E-02 | 1.47E+00 |
| | | High | 6.49E-01 | 3.63E-02 | 1.14E+00 | 1.91E-02 | 1.85E+00 |
| Oil Sands to Gasoline | C | Low | 3.20E-01 | 6.72E-03 | 5.66E-01 | 4.24E-03 | 8.97E-01 |
| | | Avg | 5.03E-01 | 8.42E-03 | 6.34E-01 | 8.71E-03 | 1.15E+00 |
| | | High | 7.82E-01 | 9.53E-03 | 6.81E-01 | 1.16E-02 | 1.48E+00 |
| | W | Low | 4.37E-01 | 4.27E-02 | 8.74E-01 | 1.17E-02 | 1.37E+00 |
| | | Avg | 6.69E-01 | 4.44E-02 | 9.42E-01 | 1.62E-02 | 1.67E+00 |
| | | High | 9.00E-01 | 4.56E-02 | 9.89E-01 | 1.91E-02 | 1.95E+00 |
| Corn Stover to Ethanol | C | Low | 1.02E-01 | 4.93E-03 | 4.96E-01 | 8.17E-03 | 6.12E-01 |
| | | Avg | 1.30E-01 | 7.59E-03 | 1.23E+00 | 1.65E-02 | 1.38E+00 |
| | | High | 1.55E-01 | 9.31E-03 | 2.06E+00 | 2.18E-02 | 2.24E+00 |
| | W | Low | 7.72E-01 | 4.93E-03 | -2.55E+00 | 2.55E-02 | -1.75E+00 |
| | | Avg | 7.83E-01 | 7.59E-03 | -1.85E+00 | 3.38E-02 | -1.03E+00 |
| | | High | 7.90E-01 | 9.31E-03 | 7.76E+00 | 3.92E-02 | 8.60E+00 |
| Miscanthus to Ethanol | C | Low | 3.11E-02 | 6.44E-03 | 5.25E-01 | 8.17E-03 | 5.71E-01 |
| | | Avg | 4.21E-02 | 9.99E-03 | 1.25E+00 | 1.65E-02 | 1.32E+00 |
| | | High | 2.46E+01 | 1.23E-02 | 2.08E+00 | 2.18E-02 | 2.67E+01 |
| | W | Low | 6.23E-02 | 6.44E-03 | -2.36E+00 | 2.55E-02 | -2.27E+00 |
| | | Avg | 7.29E-02 | 9.99E-03 | -1.66E+00 | 3.38E-02 | -1.55E+00 |
| | | High | 2.46E+01 | 1.23E-02 | 7.82E+00 | 3.92E-02 | 3.25E+01 |
| Corn Grain to Ethanol | C | Low | 1.41E-01 | 1.30E-02 | 9.59E-01 | 8.17E-03 | 1.12E+00 |
| | | Avg | 2.36E+01 | 2.56E-02 | 1.07E+00 | 1.65E-02 | 2.47E+01 |
| | | High | 3.39E+02 | 3.38E-02 | 1.64E+00 | 2.18E-02 | 3.41E+02 |
| | W | Low | 1.31E+00 | 1.30E-02 | 3.67E+00 | 2.55E-02 | 5.02E+00 |
| | | Avg | 2.47E+01 | 2.56E-02 | 3.78E+00 | 3.38E-02 | 2.86E+01 |
| | | High | 3.40E+02 | 3.38E-02 | 7.40E+00 | 3.92E-02 | 3.48E+02 |
| Electricity: U.S. | C | Low | 1.93E-01 | 3.65E-03 | 3.39E-01 | 4.75E-02 | 5.83E-01 |
| | | Avg | 1.78E-01 | 4.22E-03 | 4.13E-01 | 5.48E-02 | 6.50E-01 |
| | | High | 3.39E-01 | 1.01E-02 | 4.76E-01 | 6.69E-02 | 8.91E-01 |
| | W | Low | 2.12E-01 | 3.16E-03 | 4.67E+00 | 4.02E-01 | 5.28E+00 |
| | | Avg | 2.57E-01 | 4.22E-03 | 1.23E+01 | 1.23E+00 | 1.38E+01 |
| | | High | 2.79E-01 | 5.99E-03 | 1.73E+01 | 1.68E+00 | 1.93E+01 |

Table 127: Sensitivity Analysis Results by Life-Cycle Phase

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| **Pathway** | **C / W** | **Scn.** | **Direct** | **Electricity** | **Primary Fuel** | **Chem.** | **Const. & Materials** | **Supply-Chain Ag.** | **Supply-Chain Services** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|---|
| Crude Oil to Gasoline | C | Low | 4.07E-01 | 1.83E-02 | 4.56E-02 | 2.02E-03 | 4.49E-04 | 8.19E-02 | 1.21E-02 | 5.67E-01 |
| | | Avg | 9.08E-01 | 1.83E-02 | 5.85E-02 | 2.33E-03 | 4.49E-04 | 8.19E-02 | 1.21E-02 | 1.08E+00 |
| | | High | 1.23E+00 | 1.83E-02 | 6.68E-02 | 2.80E-03 | 4.49E-04 | 8.19E-02 | 1.21E-02 | 1.42E+00 |
| | W | Low | 4.15E-01 | 3.99E-01 | 4.56E-02 | 7.22E-03 | 1.01E-03 | 8.19E-02 | 1.21E-02 | 9.62E-01 |
| | | Avg | 9.08E-01 | 3.99E-01 | 5.85E-02 | 8.32E-03 | 1.01E-03 | 8.19E-02 | 1.21E-02 | 1.47E+00 |
| | | High | 1.28E+00 | 3.99E-01 | 6.68E-02 | 1.00E-02 | 1.01E-03 | 8.19E-02 | 1.21E-02 | 1.85E+00 |
| Oil Sands to Gasoline | C | Low | 6.33E-01 | 3.21E-02 | 1.37E-01 | 5.45E-06 | 4.41E-04 | 8.19E-02 | 1.21E-02 | 8.97E-01 |
| | | Avg | 9.18E-01 | 3.79E-02 | 1.04E-01 | 5.45E-06 | 4.41E-04 | 8.19E-02 | 1.21E-02 | 1.15E+00 |
| | | High | 1.21E+00 | 3.22E-02 | 1.48E-01 | 5.45E-06 | 4.41E-04 | 8.19E-02 | 1.21E-02 | 1.48E+00 |
| | W | Low | 6.33E-01 | 5.01E-01 | 1.37E-01 | 1.95E-05 | 9.92E-04 | 8.19E-02 | 1.21E-02 | 1.37E+00 |
| | | Avg | 9.18E-01 | 5.55E-01 | 1.04E-01 | 1.95E-05 | 9.92E-04 | 8.19E-02 | 1.21E-02 | 1.67E+00 |
| | | High | 1.21E+00 | 5.01E-01 | 1.48E-01 | 1.95E-05 | 9.92E-04 | 8.19E-02 | 1.21E-02 | 1.95E+00 |
| Corn Stover to Ethanol | C | Low | 3.39E-01 | -1.70E-01 | 1.81E-02 | 2.01E-01 | 1.69E-02 | 1.90E-01 | 1.57E-02 | 6.12E-01 |
| | | Avg | 1.03E+00 | -1.70E-01 | 3.96E-02 | 2.53E-01 | 1.69E-02 | 1.90E-01 | 1.57E-02 | 1.38E+00 |
| | | High | 1.66E+00 | 8.13E-04 | 5.35E-02 | 3.04E-01 | 1.69E-02 | 1.90E-01 | 1.57E-02 | 2.24E+00 |
| | W | Low | 3.39E-01 | -4.69E+00 | 1.81E-02 | 2.34E+00 | 4.51E-02 | 1.90E-01 | 1.57E-02 | -1.75E+00 |
| | | Avg | 1.03E+00 | -4.69E+00 | 3.96E-02 | 2.34E+00 | 4.51E-02 | 1.90E-01 | 1.57E-02 | -1.03E+00 |
| | | High | 5.93E+00 | 1.82E-02 | 5.35E-02 | 2.34E+00 | 4.51E-02 | 1.90E-01 | 1.57E-02 | 8.60E+00 |
| Miscan. to Ethanol | C | Low | 3.39E-01 | -1.65E-01 | 1.88E-02 | 1.64E-01 | 8.67E-03 | 1.90E-01 | 1.57E-02 | 5.71E-01 |
| | | Avg | 1.03E+00 | -1.66E-01 | 4.12E-02 | 1.98E-01 | 8.67E-03 | 1.90E-01 | 1.57E-02 | 1.32E+00 |
| | | High | 2.62E+01 | 8.13E-04 | 5.57E-02 | 2.31E-01 | 8.67E-03 | 1.90E-01 | 1.57E-02 | 2.67E+01 |
| | W | Low | 3.39E-01 | -4.57E+00 | 1.88E-02 | 1.72E+00 | 2.23E-02 | 1.90E-01 | 1.57E-02 | -2.27E+00 |
| | | Avg | 1.03E+00 | -4.57E+00 | 4.12E-02 | 1.72E+00 | 2.23E-02 | 1.90E-01 | 1.57E-02 | -1.55E+00 |
| | | High | 3.04E+01 | 1.82E-02 | 5.57E-02 | 1.72E+00 | 2.23E-02 | 1.90E-01 | 1.57E-02 | 3.25E+01 |
| Corn Grain to Ethanol | C | Low | 5.09E-01 | 1.03E-01 | 1.79E-01 | 1.04E-01 | 2.11E-02 | 1.90E-01 | 1.57E-02 | 1.12E+00 |
| | | Avg | 2.39E+01 | 1.03E-01 | 2.11E-01 | 1.32E-01 | 2.11E-02 | 1.90E-01 | 1.57E-02 | 2.46E+01 |
| | | High | 3.40E+02 | 1.03E-01 | 2.32E-01 | 1.60E-01 | 2.11E-02 | 1.90E-01 | 1.57E-02 | 3.41E+02 |
| | W | Low | 5.09E-01 | 2.80E+00 | 1.79E-01 | 1.27E+00 | 5.66E-02 | 1.90E-01 | 1.57E-02 | 5.02E+00 |
| | | Avg | 2.39E+01 | 2.81E+00 | 2.11E-01 | 1.27E+00 | 5.66E-02 | 1.90E-01 | 1.57E-02 | 2.85E+01 |
| | | High | 3.43E+02 | 2.81E+00 | 2.32E-01 | 1.27E+00 | 5.66E-02 | 1.90E-01 | 1.57E-02 | 3.48E+02 |
| Electricity: U.S. | C | Low | 4.95E-01 | 5.21E-02 | 2.76E-03 | 1.45E-05 | 3.02E-03 | 2.64E-02 | 3.52E-03 | 5.83E-01 |
| | | Avg | 5.54E-01 | 5.90E-02 | 3.95E-03 | 1.46E-05 | 2.83E-03 | 2.64E-02 | 3.52E-03 | 6.50E-01 |
| | | High | 7.52E-01 | 7.97E-02 | 2.62E-02 | 1.28E-03 | 2.32E-03 | 2.64E-02 | 3.52E-03 | 8.91E-01 |
| | W | Low | 4.78E+00 | 4.59E-01 | 1.68E-03 | 2.58E-05 | 1.11E-02 | 2.64E-02 | 3.52E-03 | 5.28E+00 |
| | | Avg | 1.24E+01 | 1.31E+00 | 3.95E-03 | 5.22E-05 | 7.94E-03 | 2.64E-02 | 3.52E-03 | 1.38E+01 |
| | | High | 1.75E+01 | 1.77E+00 | 7.07E-03 | 7.16E-05 | 8.02E-03 | 2.64E-02 | 3.52E-03 | 1.93E+01 |

Table 128: Sensitivity Analysis Results by Contributor

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| **Pathway** | | **This Dissertation** | | | **(*10*)** | | **(*1*)** | | **(*11*)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Low | Avg | High | Low | High | Low | High | Low | Avg | High |
| Crude Oil to Gasoline | C | 0.57 | 1.08 | 1.42 | 0.16 | 0.33 | 0.58 | 1.12 | N/A | N/A | N/A |
| | W | 0.96 | 1.49 | 1.85 | 1.48 | 1.48 | N/A | N/A | N/A | N/A | N/A |
| Oil Sands to Gasoline | C | 0.90 | 1.15 | 1.48 | 0.47 | 1.08 | 0.44 | 1.05 | N/A | N/A | N/A |
| | W | 1.37 | 1.67 | 1.95 | 1.79 | 2.23 | N/A | N/A | N/A | N/A | N/A |
| Corn Stover to Ethanol | C | 0.61 | 1.38 | 2.24 | 0.63 | 127.19 | N/A | N/A | N/A | N/A | N/A |
| | W | -1.75 | -1.03 | 8.60 | 1.12 | 174.21 | N/A | N/A | N/A | N/A | N/A |
| Miscanthus to Ethanol | C | 0.57 | 1.32 | 26.68 | N/A | N/A | 0.32 | 1.66 | 0.49 | 1.10 | 71.65 |
| | W | -2.27 | -1.55 | 32.47 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Corn Grain to Ethanol | C | 1.12 | 24.69 | 340.68 | 0.38 | 171.44 | 1.69 | 54.88 | 4.74 | 23.37 | 71.65 |
| | W | 5.02 | 28.57 | 347.58 | 0.88 | 306.97 | N/A | N/A | N/A | N/A | N/A |
| Electricity: U.S. Mix | C | 0.58 | 0.65 | 0.89 | 0.56 | 0.56 | N/A | N/A | N/A | N/A | N/A |
| | W | 5.28 | 13.75 | 19.31 | 18.34 | 18.34 | N/A | N/A | N/A | N/A | N/A |

Table 129: Data for External Validation of Water Use Inventory

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