Pacific Northwest NATIONAL LABORATORY

PNNL-36021

Water & Energy Interdependencies Across Economic Sectors of the United States

May 2024

Kendall Mongird
Juliet Homer
Jennie Rice
Konstantinos Oikonomou

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

PNNL-36021

Water & Energy Interdependencies Across Economic Sectors of the United States

May 2024

Kendall Mongird
Juliet Homer
Jennie Rice
Konstantinos Oikonomou

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

The motivation of the Integrated Water Power Resilience Project is to identify and develop opportunities for improving resilience in the water and power sectors through coordinated planning, investment, and operations and thereby provide benefits to power and water utilities, consumers, and the environment. Water and power systems are interdependent, subject to many of the same natural and manmade hazards, and are critical for the well-being of communities and society. Because of the interconnectedness of water and power systems, there are substantial economic, social, and environmental benefits to co-managing the market sectors for resilience instead of managing them separately. To support this initiative and future research in this area, a county level water and energy flow dataset was developed to build, calculate, and visualize interconnections in water and energy between various sectors. This report presents county and regional water and energy visualizations across nine economic sectors of the United States: agriculture, commercial, electricity generation, industrial, mining, public water supply, residential, transportation, and wastewater treatment.

Acknowledgments

This research was funded by the Department of Energy, Water Power Technologies Office (WPTO). We would like to thank Amanda Lounsbury and Colin Sasthav from WPTO for their support and guidance in this effort. We would also like to thank Chris Chini and Alisha Fernandez for their review of this report.

Acronyms and Abbreviations

BTU	British thermal units
BBTU	Billion British thermal units
MG	Million gallons
MGD	Million gallons per day
PNNL	Pacific Northwest National Laboratory

Contents

Figures

Tables

1.0 Introduction

The motivation of the Integrated Water Power Resilience Project is to identify and develop opportunities for improving resilience in the water and power sectors through coordinated planning, investment, and operations and thereby provide benefits to power and water utilities, consumers, and the environment. Water and power systems are interdependent, subject to many of the same natural and manmade hazards, and they are critical for the well-being of communities and society. Because of the interconnectedness of water and power systems, there are substantial economic, social, and environmental benefits in co-managing the market sectors for resilience, instead of managing them separately. To support this initiative and future research in this area, county level water and energy flow data was developed to build, calculate, and visualize interconnections in water and energy between various sectors. The methodology behind the dataset is featured in Mongird et al. (2023), which developed water-energy Sankey diagrams for the three electric interconnections in the United States. Methodology for the data shown in the visualizations in this report can be found in that publication.

Nine different economic sectors are covered in this report. They are:

1. Agriculture Sector
2. Commercial Sector
3. Electricity Generation Sector
4. Industrial Sector
5. Mining Sector
6. Public Water Supply Sector
7. Residential Sector
8. Transportation Sector
9. Wastewater Treatment Sector

The purpose of this report is to provide high-level water and energy diagrams of each of the nine economic sectors included in the analysis to show county level and regional aggregate results. We believe that these diagrams offer valuable insight into water and energy dependencies across sectors, regions, and applications.

The following list of assumptions applies to the data used in this analysis:

- Data values presented are for the year 2015, the most recent year available for comprehensive county level water use data in the United States at the time the data was collected. When data was unavailable for 2015, the closest year available was applied, or methods were developed to estimate data for 2015 based on factors from surrounding years. A table documenting water and energy inflows and outflows tracked for each sector is provided in Appendix A.

- Many calculation methodologies and intensity parameters are informed by the literature. Descriptions of these methodologies and their associated references are provided in Mongird et al. (2023).
- Water values are provided in million gallons per day (MGD). Energy values are provided in billion British thermal units (BBTU) per day.
- To get values at the county level across multiple datasets in a consistent manner, a set of counties was established as the base county list for 2015. This list contains all U.S. counties (not including U.S. territories) included in Dieter et al. (2018).

For each of the economic sectors, as appropriate, we provide county level maps of water inflows (withdrawals and/or processed water), energy inflows (electricity and/or direct fuels), and when applicable, water or energy intensity (e.g., water required per unit of energy generated). In addition to county level maps, we provide boxplots of the distribution of counties by region, and bar charts with values by sector and region.

Additional plots that aggregate and compare across sectors can be found in Section 3.0. This includes supplemental analyses such as water use by county across all sectors, energy use by county across all sectors, water and energy use across water sectors, and direct and indirect water use by energy resource (e.g., biomass, nuclear).

The United States is divided into four separate regions in this analysis: West, Midwest, South, and Northeast. Which counties fall in each region follows the guidelines of the U.S. Census Bureau (U.S. Census Bureau American Community Survey Office 2019). Figure 1.1 shows regional boundaries for the United States.

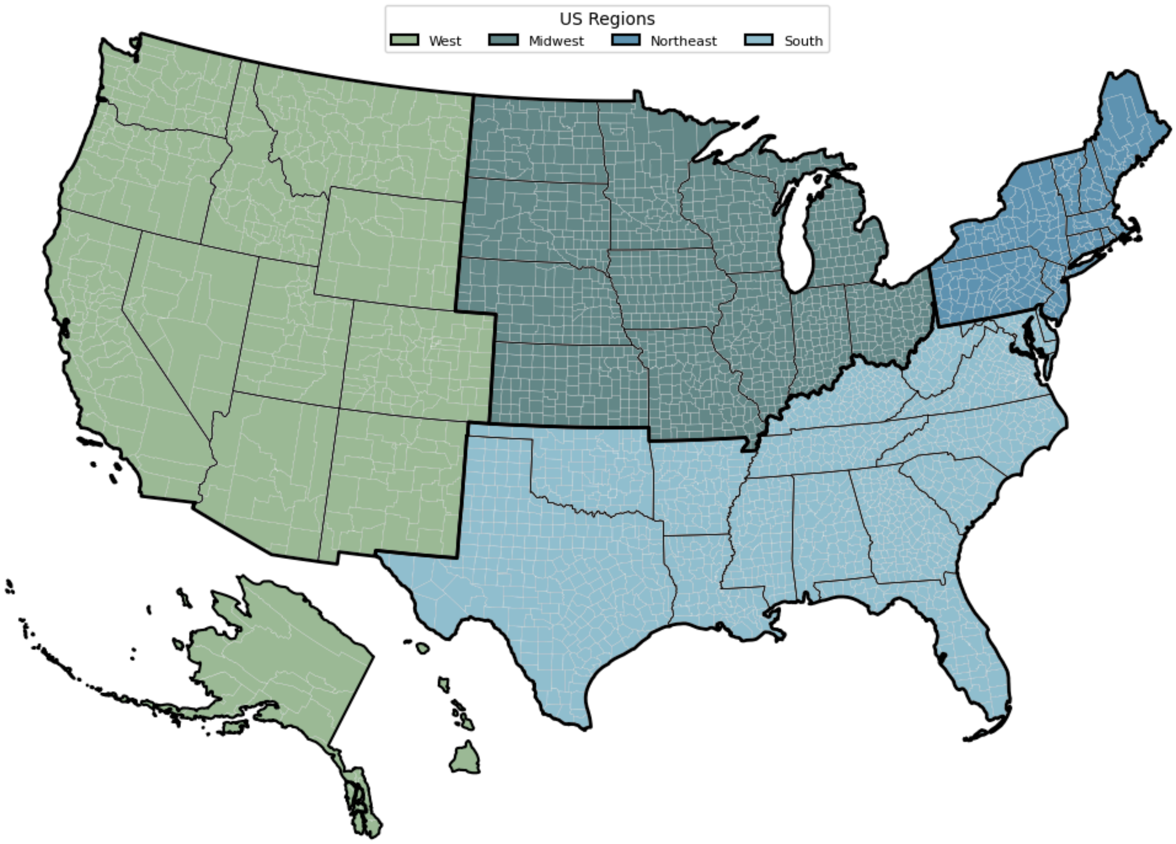

Figure 1.1 Map of the United States Divided by Region

States in the West region include Alaska, Hawaii, California, Oregon, Washington, Idaho, Utah, Nevada, New Mexico, Arizona, Colorado, Wyoming, and Montana. States in the Midwest region include North Dakota South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Michigan, Illinois, Indiana, and Ohio. States in the Northeast region include Pennsylvania, New York, New Jersey, Connecticut, Massachusetts, Rhode Island, Vermont, New Hampshire, and Maine. States in the South region include Texas, Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Kentucky, Georgia, Florida, South Carolina, North Carolina, Virginia, West Virginia, Maryland, and Delaware.

The database used to generate the visualizations in this report is extensive. There are many more diagrams available than could be included in this high-level report. For the latest information on this effort, please visit the Pacific Northwest National Laboratory (PNNL) Integrated Water Power Resilience Project website at https://www.pnnl.gov/projects/integrated-water-power-resilience-project.

2.0 Economic Sectors

In the subsections below, we present the county and regional diagrams for each of the nine economic sectors in this analysis.

2.1 Mining Sector

2.1.1 Water in the Mining Sector

Water withdrawals used in the mining sector include those used in the extraction of solids (e.g., coal), liquids (e.g., crude oil), and gases (e.g., natural gas). In addition to materials used for energy purposes, this sector also includes extraction of other materials such as sand and gravel. Water use for petroleum mining includes water use in conventional petroleum (i.e., petroleum that can be extracted without using novel technologies such as hydraulic fracking) and unconventional petroleum. Water use for natural gas mining includes water used for unconventional natural gas extraction. Last, water use in coal mining includes water used primarily for dust control (Mongird et al. 2023).

Figure 2.1 shows the average daily water use in the mining sector by county. The figure demonstrates how most mining in the United States is concentrated in the eastern portions of the West region, mainly in the Rocky Mountain subregion; in the states of Texas and Oklahoma in the South region; and in Ohio, Pennsylvania, and West Virginia, which represent the intersection of multiple regions.

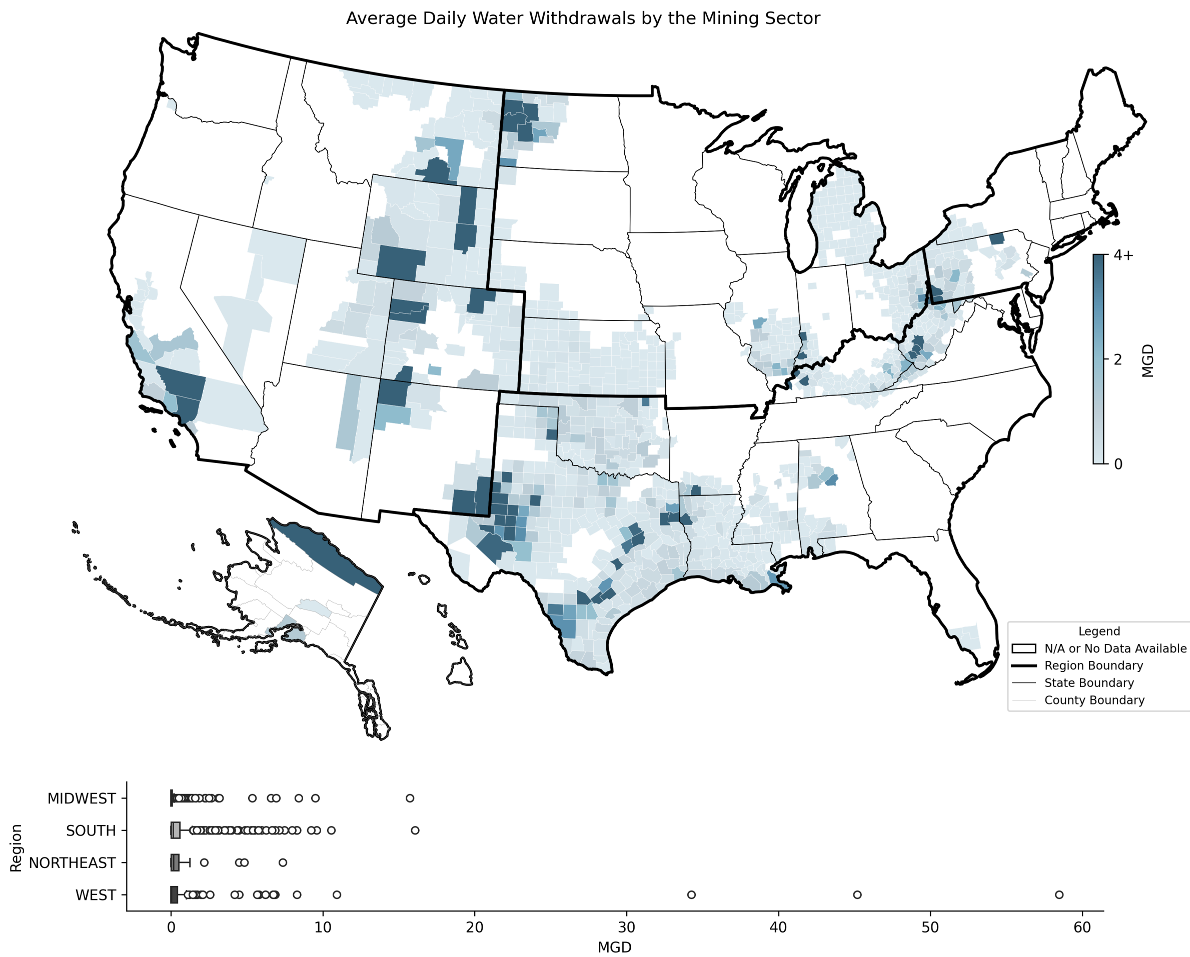

Figure 2.1 Map of Daily Average Water Withdrawals (MGD) of the Mining Sector by County

The top three states for water use in the mining sector are Texas (239 MGD), Wyoming (74 MGD), and North Dakota (52 MGD). Campbell County, Wyoming (58 MGD), North Slope County, Alaska (45 MGD), and Kern County, California (34 MGD) withdraw the most water for mining daily on a county level.

Figure 2.2 shows average daily water demand in the mining sector by subsector, water type, and region. Across all regions, the largest flow is from fresh surface water to petroleum mining (264 MGD), followed by fresh groundwater to petroleum mining (114 MGD). The dominance of petroleum in water withdrawals in this sector demonstrates how electrification and other decarbonization efforts that move the economy away from petroleum can have water usage implications. The South region and West region use the most water on a daily basis, with most water coming from fresh surface water sources; however, saline groundwater is also used for other types of mining (for non-energy-related materials).

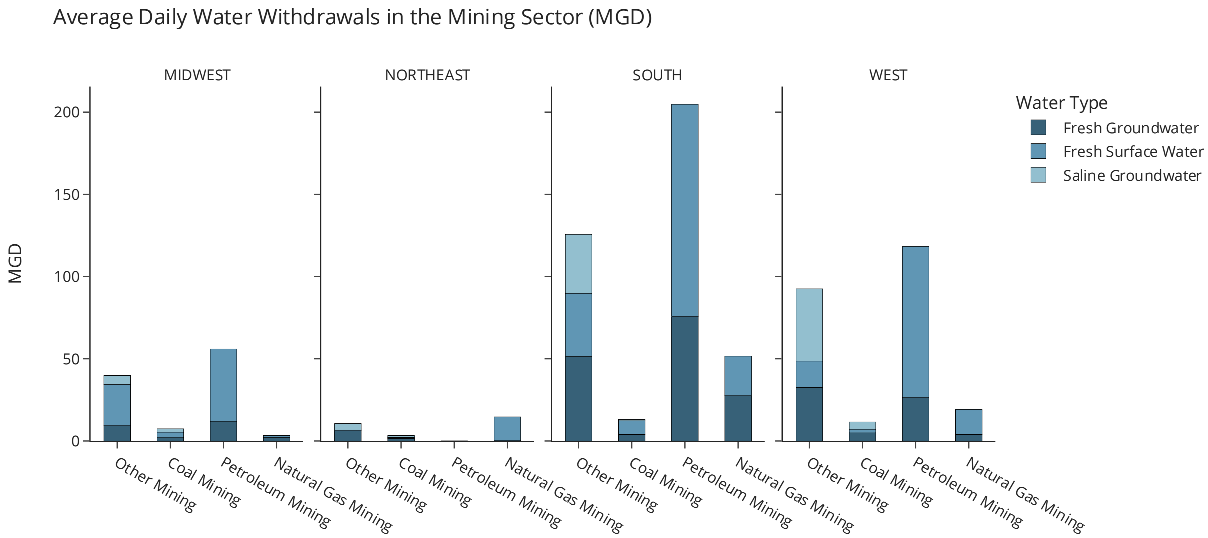

Figure 2.2 Average Daily Water Withdrawals by the Mining Sector by Region, Subsector, and Water Type

2.1.2 Mining Sector Energy Production

There is limited data available on the energy demand of the mining sector, and determining estimates was outside the scope of the initial analysis. Energy production from the mining sector, however, is included. This section, therefore, is framed differently from other sectors in this report and provides energy based on production rather than consumption.

Energy production from the mining sector includes coal produced from coal mining, natural gas produced from unconventional natural gas mining, and petroleum products from unconventional and conventional petroleum mining. Figure 2.3 shows a map of average daily production (BBTU) of coal, natural gas, and petroleum by county.

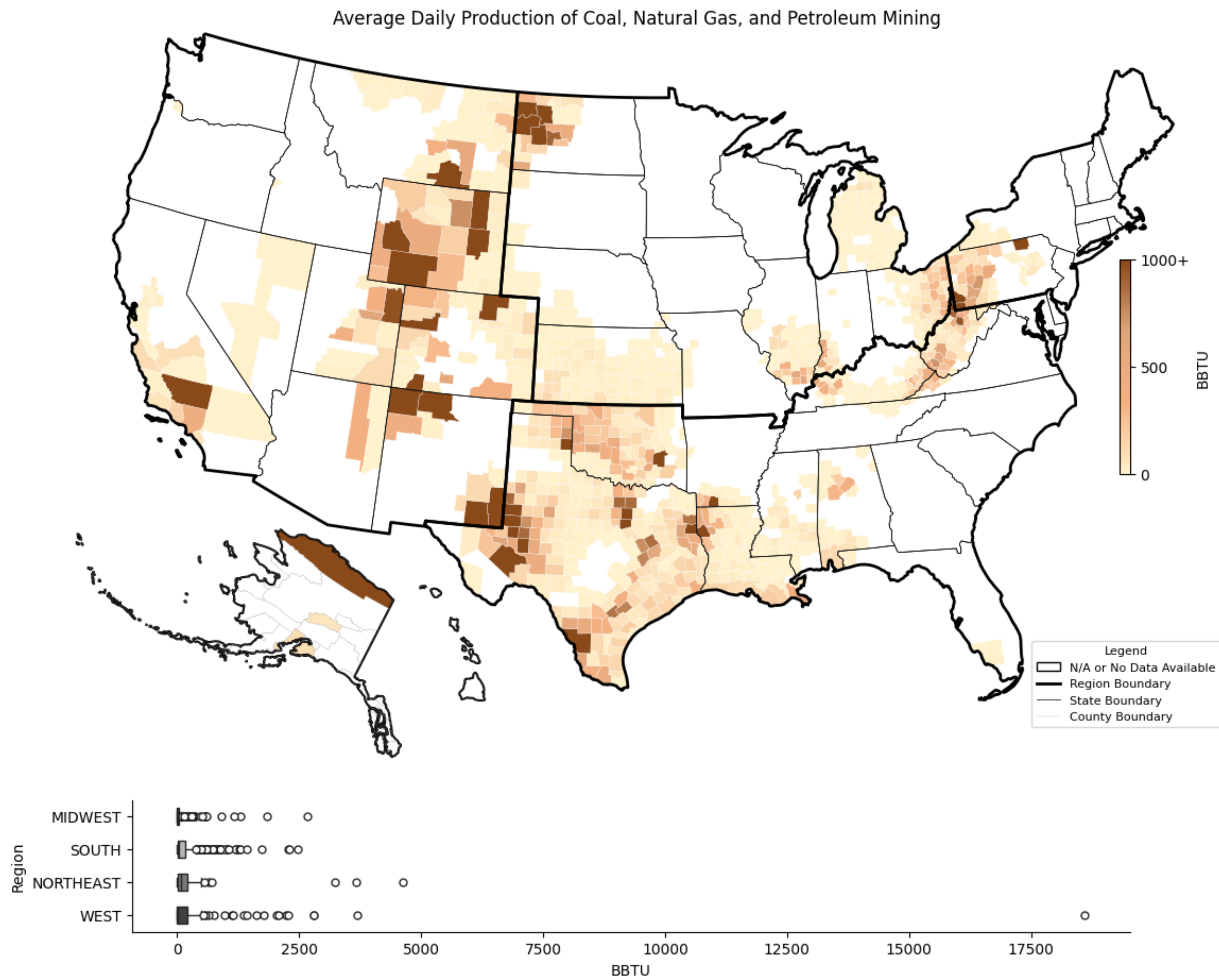

Figure 2.3 Map of Daily Average Coal, Natural Gas, and Petroleum Production (BBTU) by the Mining Sector by County

Regionally, energy production from the mining sector appears consistent. Mining production differences are more apparent on a subregional basis. The top three states for the aggregate production of coal, natural gas, and petroleum are Texas (47,423 BBTU), Wyoming (27,512 BBTU), and Pennsylvania (16,708 BBTU). On a county level, Campbell County, Wyoming (18,597 BBTU); Bradford County, Pennsylvania (4,631 BBTU); and North Slope County, Alaska (3,690 BBTU) produce the highest quantity of energy materials from their mining sectors.

Figure 2.4 shows average daily energy production in the mining sector by subsector (coal mining, natural gas mining, and petroleum mining). Across all regions, the largest energy producing mining subsector is natural gas (85,690 BBTU), followed by coal (49,292 BBTU), and petroleum (45,121 BBTU). The South region has the most production across all regions and subsectors, mostly consisting of natural gas.

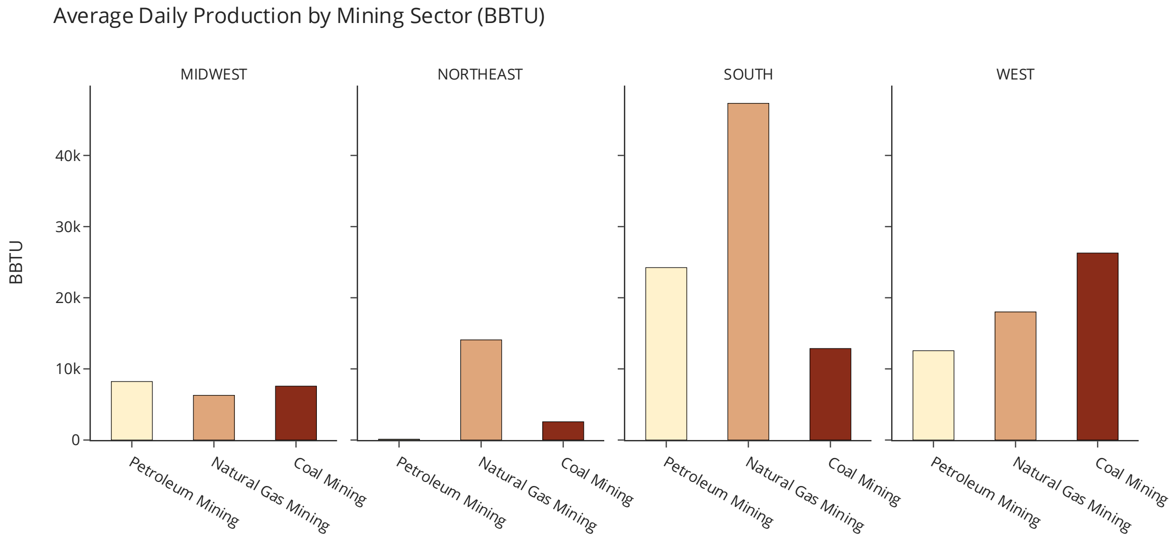

Figure 2.4 Average Daily Energy Production (BBTU) in the Mining Sector by Region and Subsector

2.1.3 Water Intensity of Energy Production in the Mining Sector

Water intensity of the mining sector demonstrates the average amount of water (MG) required per unit of fuel produced (BBTU). Fuel production includes coal production, natural gas production, and petroleum production. Water use includes water used for coal mining, water used in petroleum mining, and water used in natural gas mining. Figure 2.5 shows a map of the daily average water intensity of energy production in the mining sector.

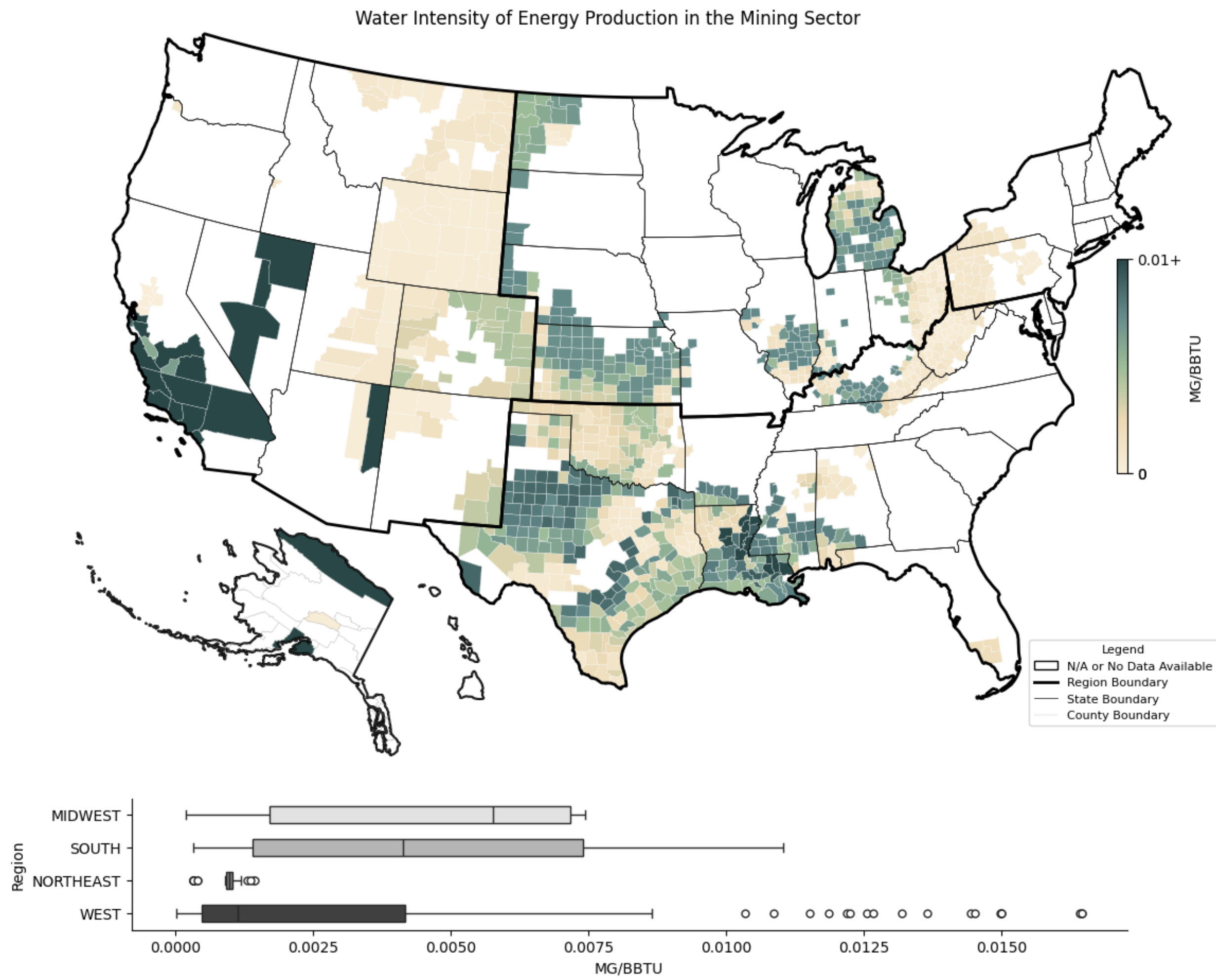

Figure 2.5 Map of Daily Average Water Intensity (MG per BBTU Fuel Produced) of Coal, Natural Gas, and Petroleum Mining by County

Regionally, the Midwest has the highest median water intensity in its mining sector, followed by the South, and then the West. On a state level, Nevada, California, and Alaska stand out in their high intensity, but we can see in Figure 2.5 that mining is highly localized to sub-state regions. On a county level, Elko County, Eureka County, and Nye County, Nevada, all have the highest water intensity for energy production in the mining sector. All three of these counties have a water intensity of 0.02 MG/BBTU. Overall, energy production in the mining sector is a low intensity water user compared to other energy sectors such as electricity generation, as discussed in Section 2.2.

Figure 2.6 shows the average daily water intensity of energy production in the mining sector by subsector. Across the entire United States, petroleum has the highest average water intensity (0.0083 MG/BBTU), followed by natural gas (0.0010 MG/BBTU) and coal (0.0007 MG/BBTU). Regionally we see similar water intensities in coal and natural gas mining. For petroleum mining, however, the Northeast region requires substantially less water per unit of energy output.

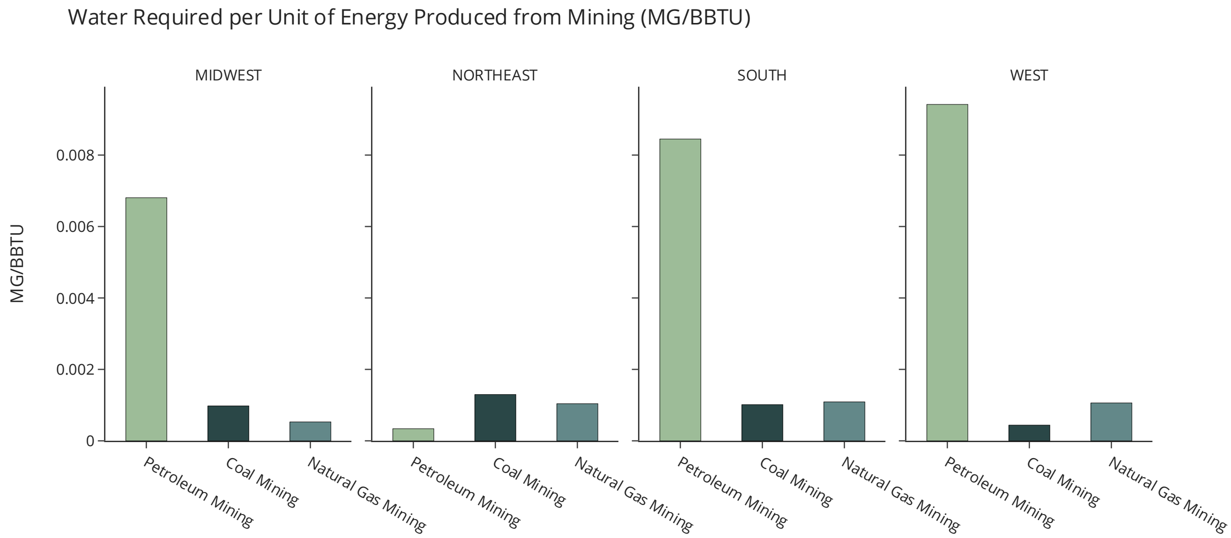

Figure 2.6 Daily Average Water Intensity (MG Required per BBTU Produced) of Energy Production in the Mining Sector by Region and Subsector

2.2 Electricity Generation Sector

The electricity generation sector consists of biomass, coal, natural gas, nuclear, wind, solar, petroleum, geothermal, hydroelectric, and other (e.g., fuel cell) energy generation resources (U.S. EIA 2022). Two forms of direct water use for electricity generation are included in this analysis: water for thermoelectric cooling of nuclear, coal, biomass, natural gas, petroleum, and other generation and water use in hydropower generation. Each of these are documented separately due to differences in quantity and process.

2.2.1 Water in the Electricity Generation Sector

2.2.1.1 Thermoelectric Generation Water Withdrawals

Figure 2.7 shows a county level map of average daily water use (including direct withdrawals and reclaimed wastewater) for thermoelectric cooling across all types of thermoelectric generation: biomass, natural gas, coal, nuclear, petroleum, and other thermoelectric sources.

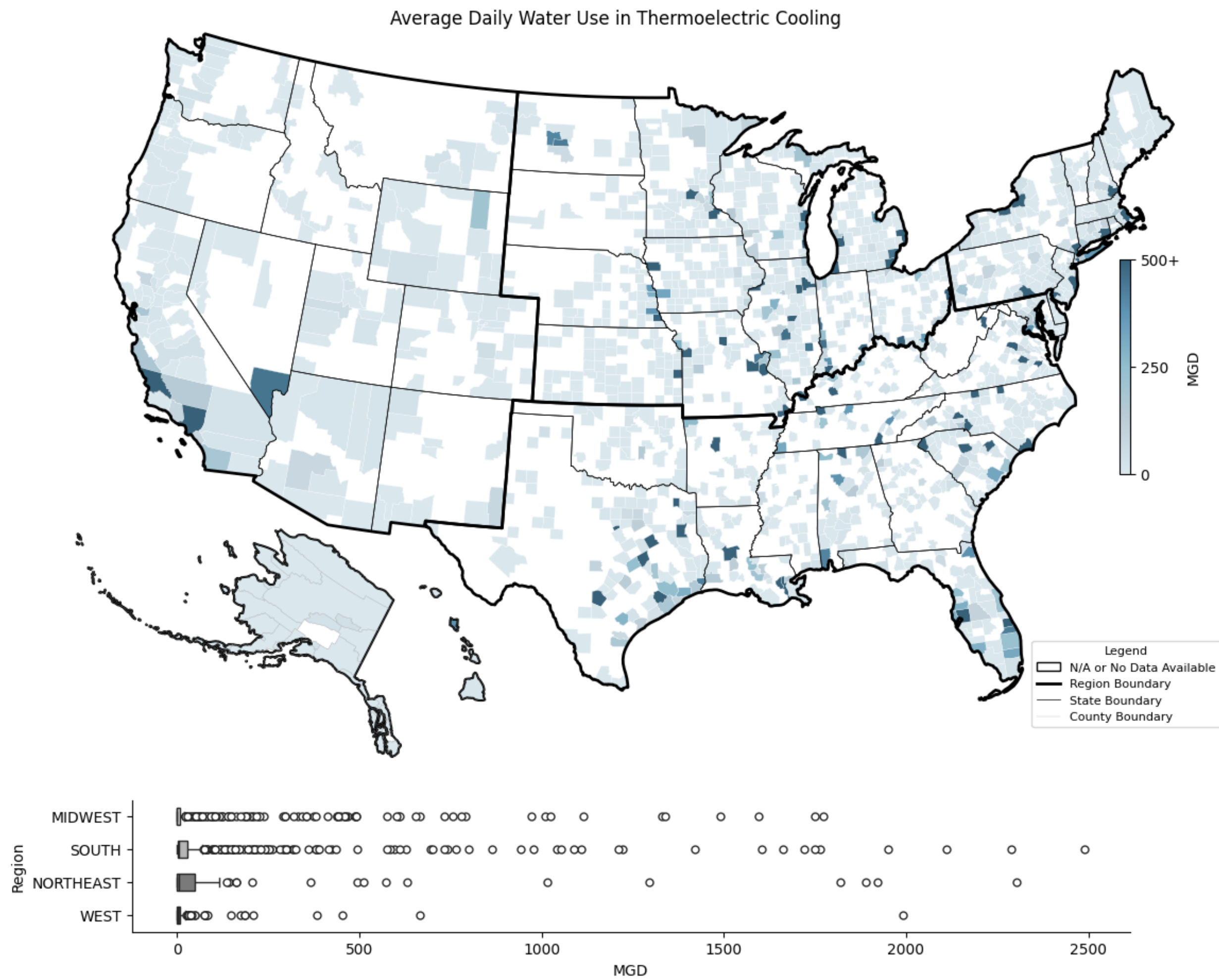

Figure 2.7 Map of Daily Average Water Demand (MGD) for Thermoelectric Cooling by County

The states that draw the most water for cooling on a daily basis are Texas (10,986 MGD), Illinois (7,916 MGD), and Michigan (6,612 MGD). Individual power facilities are the primary drivers of large thermoelectric cooling water withdrawals in each county. Limestone County, Alabama (2,490 MGD); York County, Pennsylvania (2,304 MGD); and Oconee County, South Carolina (2,290 MGD) have the largest aggregate water withdrawals for this purpose. Each of these counties have large thermoelectric power plants. For example, Limestone County, Alabama, is home to the Browns Ferry Nuclear Power Plant, which—with a generating capacity of 3.8 gigawatts (GW)—is Tennessee Valley Authority's largest nuclear power plant (Tennessee Valley Authority 2024).

Figure 2.8 shows the average daily water demand of thermoelectric cooling by generation type and water type for each region. Across all regions in 2015, coal generation used the highest amount of water for cooling followed closely by nuclear generation. Fresh surface water is the most common type of water used for thermoelectric cooling. This is followed by saline surface water, which makes up more than 25 percent of nuclear and natural gas cooling in the United States.

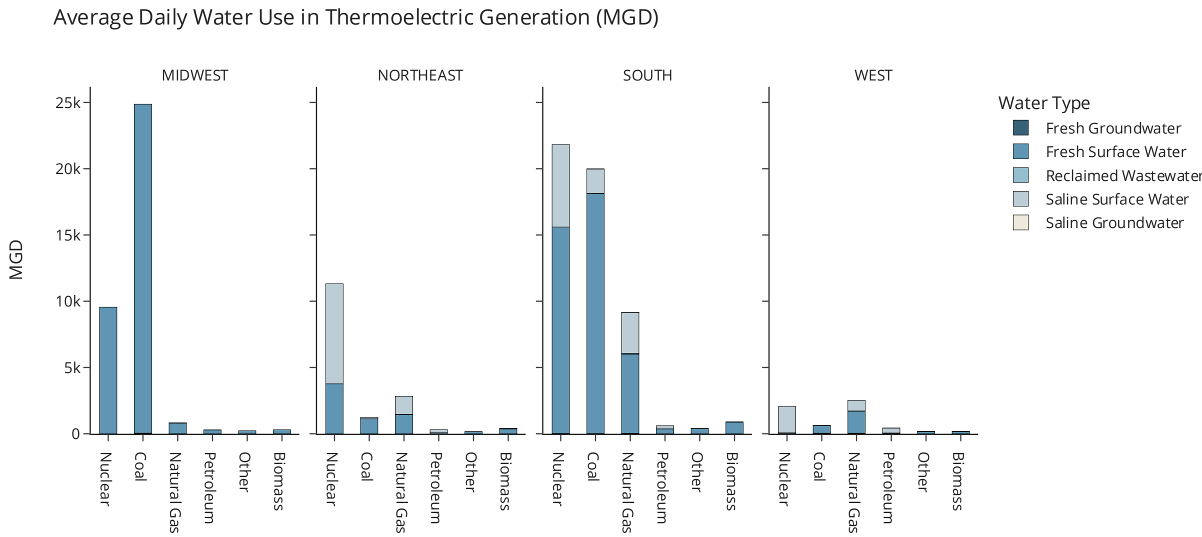

Figure 2.8 Daily Average Water Use (MGD) in Thermoelectric Cooling by Generation Technology and Water Type

Regionally, the South and Midwest withdraw the most amount of water for thermoelectric cooling, mostly for coal and nuclear, though the South also uses a substantial amount of water for natural gas cooling. The West region, by comparison, uses very little water for thermoelectric cooling due to once-through cooling phaseout policies.

Note that, given the base year of 2015 used in this analysis, a portion of the facilities included have since retired, with a large amount of those retired plants being coal-fired generation. If this trend continues, we will see a shift in the water use for cooling toward natural gas and other technologies.

2.2.1.2 Hydroelectric Generation Water Use

The water used for hydropower generation is not withdrawn from a water source but represents use directly within a river channel. All water use for hydroelectric generation is assumed to be fresh surface water. Figure 2.9 shows a map of the daily average water use of hydroelectric generation by county.

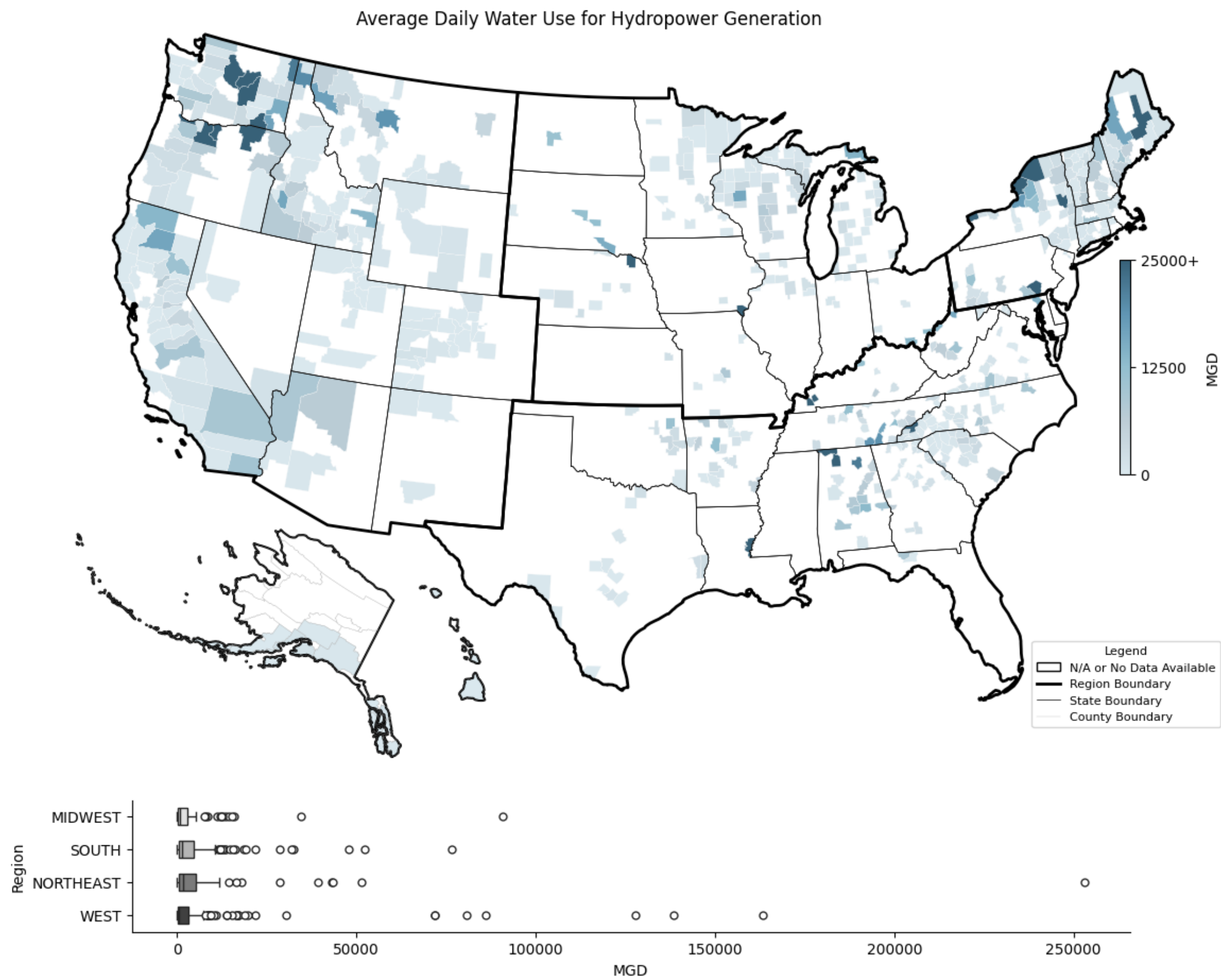

Figure 2.9 Map of Daily Average Water Use (MGD) in Hydroelectric Generation by County

The Pacific Northwest subregion of the West and upstate New York in the Northeast have some of the highest hydropower water use values in the country. On a state-basis, Washington (563,116 MGD), New York (451,795 MGD), and Oregon (354,164 MGD) are the top three.

2.2.2 Electricity Generation

Figure 2.10 shows a map of the daily average electricity generation (in BBTU) across all generation resource types in each county. Values shown represent all technologies (renewable and non-renewable).

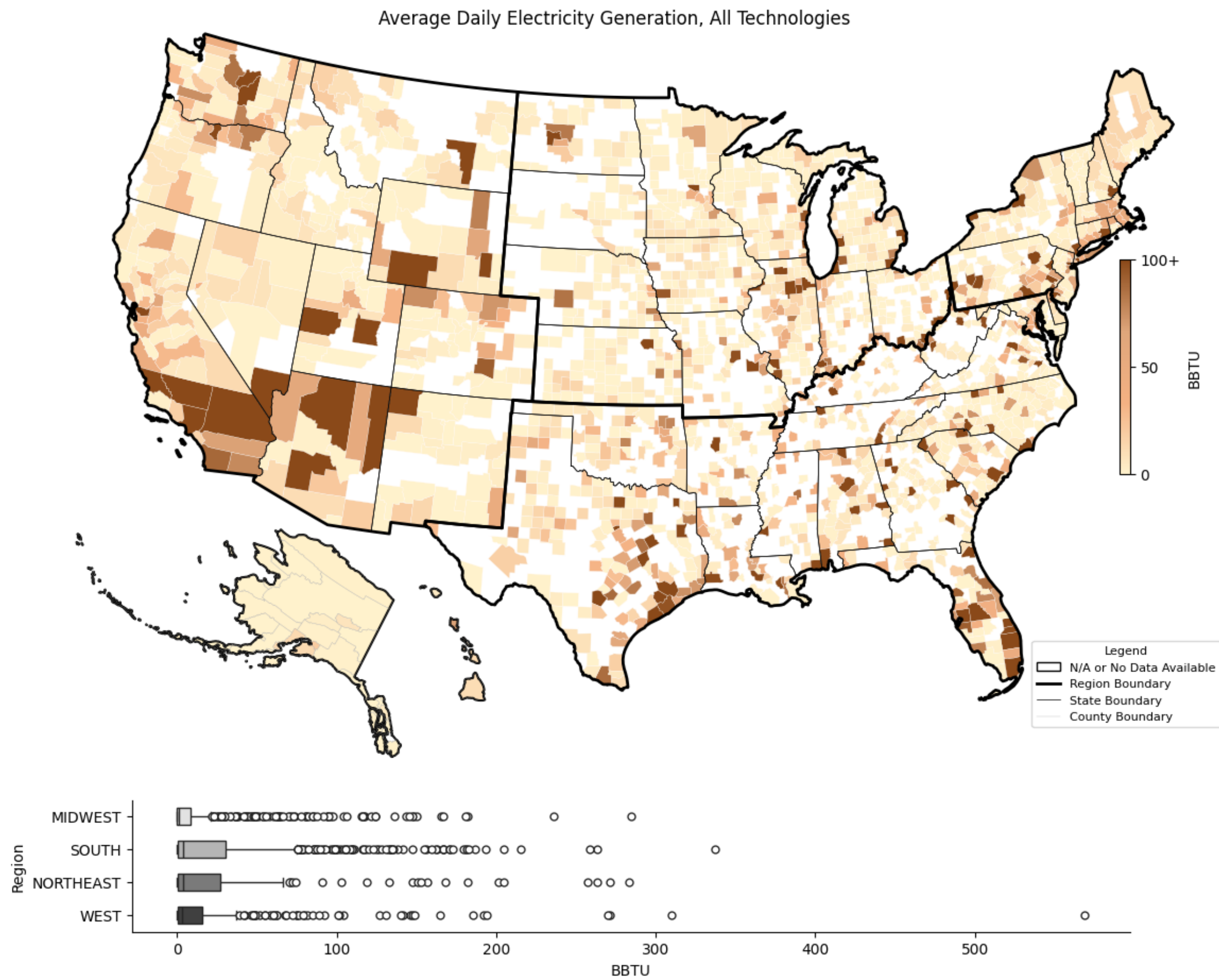

Figure 2.10 Map of Daily Average Electricity Generation (BBTU) by County

When looking at state level aggregates, Texas (4,175 BBTU), Florida (2,193 BBTU), and Pennsylvania (2,006 BBTU) generate the most electricity across the United States. On an average daily basis, Maricopa County, Arizona (568 BBTU); Harris County, Texas (337 BBTU); and Kern County, California (309 BBTU) are the leading electricity generating counties. County level quantities are tied to the production of large individual facilities. For example, Maricopa County, Arizona is home to the Palo Verde Generating Station, which is the largest nuclear generation facility in the United States with a generating capacity of 4 GW. Note that electricity generated in each county is not necessarily consumed only by that county but may be transferred across transmission lines to other counties.

Figure 2.11 shows the average daily electricity generation in the United States by generating technology type. The largest supplier of electricity in 2015 on an average daily basis was coal-fired generation (12,610 BBTU), followed closely by natural gas-fired generation (12,343 BBTU).

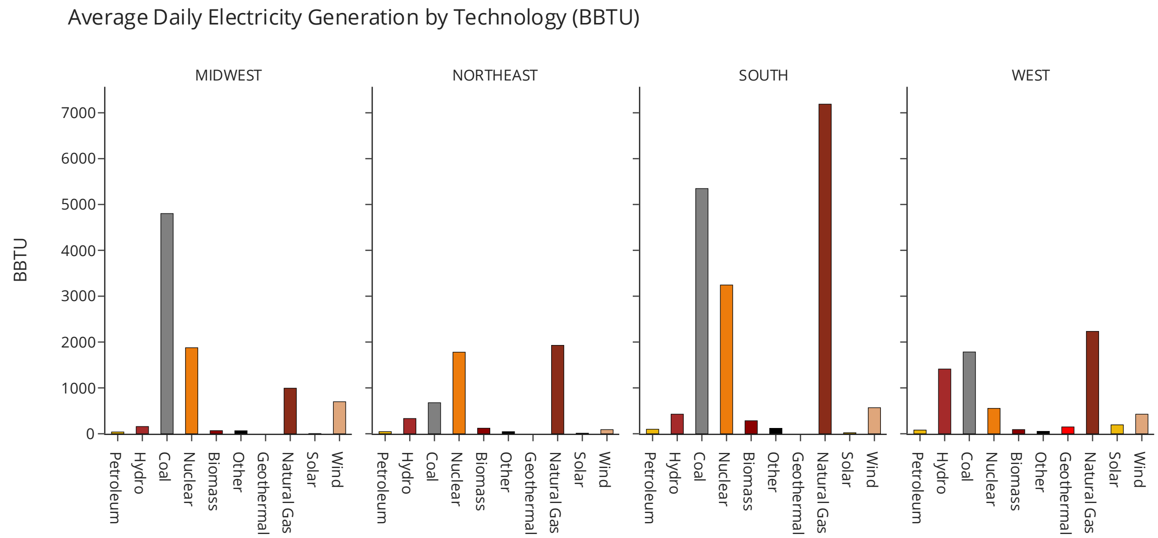

Figure 2.11 Average Daily Electricity Generation (BBTU) by Generator Type

The South region generates the most electricity daily, mostly consisting of natural gas-fired generation and coal-fired generation, with a large amount of nuclear, as well. This is followed by the Midwest region, which is predominantly coal-fired electricity. The Northeast region and West region produce less electricity daily and have different resource profiles. The West region is mostly split between hydro, coal, and natural gas, whereas the Northeast region relies on natural gas and nuclear in relatively equal parts.

The South region and Midwest region results reveal a significant reliance on natural gas and coal for electricity generation. This dependency implies that disruptions in the supply of coal or natural gas caused by extreme weather events (such as frozen coal piles, piping issues, or flooded power stations) have the potential to impact electricity generation. Given the dependencies of downstream sectors, extreme events can be particularly disruptive to these regions.

2.2.3 Water Intensity of Electricity Generation

2.2.3.1 Thermoelectric Generation Water Intensity

Figure 2.12 shows the water intensity by county of thermoelectric generation. Water intensity here is measured as the total amount of water use for thermoelectric cooling (MGD) in each county, divided by the total electricity generation output from thermoelectric generation resources (BBTU).

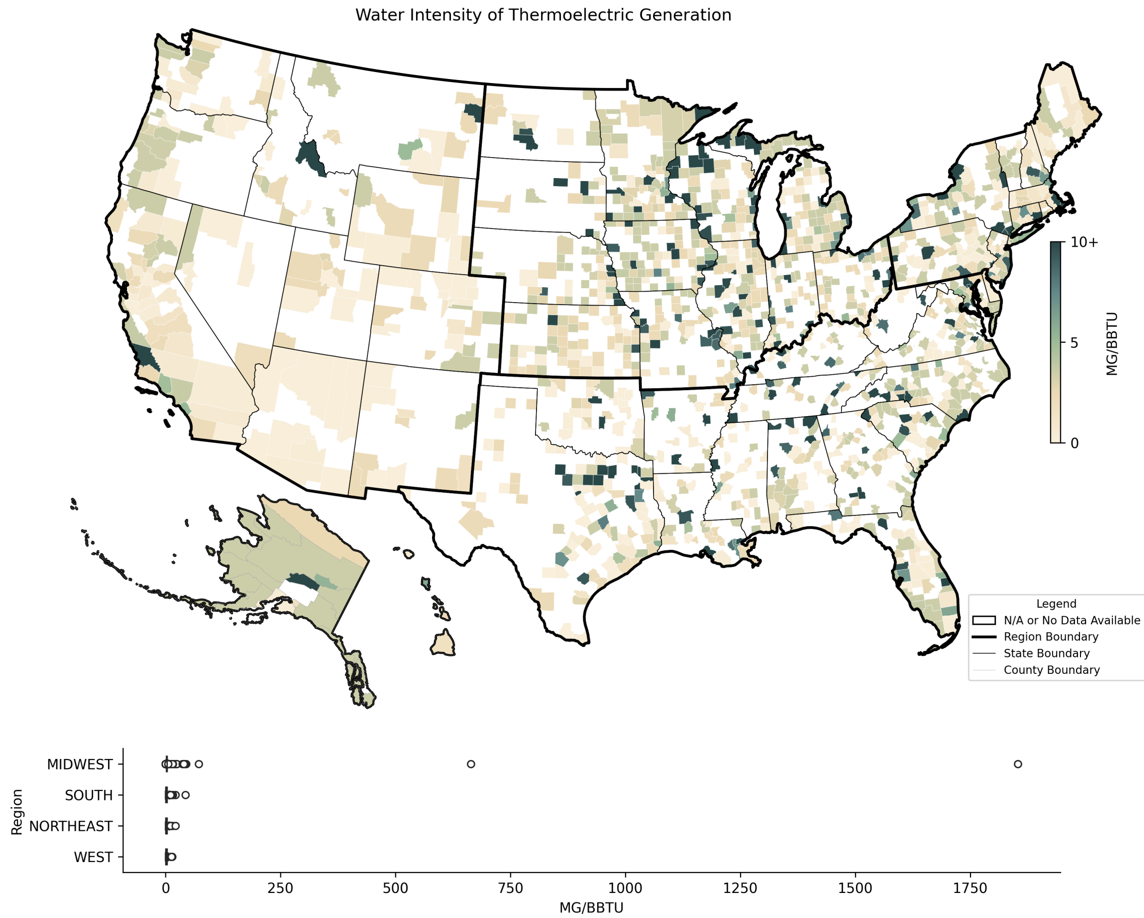

Figure 2.12 Map of Daily Average Water Intensity (MG of Cooling Water per BBTU of Generation Output) of Thermoelectric Technologies by County

Regionally, the water intensity of thermoelectric generation is consistent, with the Midwest being slightly higher when comparing median values. Note that, due to the nature of the data sources from which these estimates were derived, individual counties with extreme outlier intensity estimates are likely due to inconsistencies or underreported generation values in the source data.

Figure 2.13 shows the daily average water intensity of thermoelectric generation by generation type. Across all regions, petroleum has the highest water intensity for cooling (6.21 MG/BBTU), followed closely by nuclear (6.00 MG/BBTU). Nuclear plants in the West region and Midwest region tend to use less water per unit generation than nuclear plants in the Northeast and South regions.

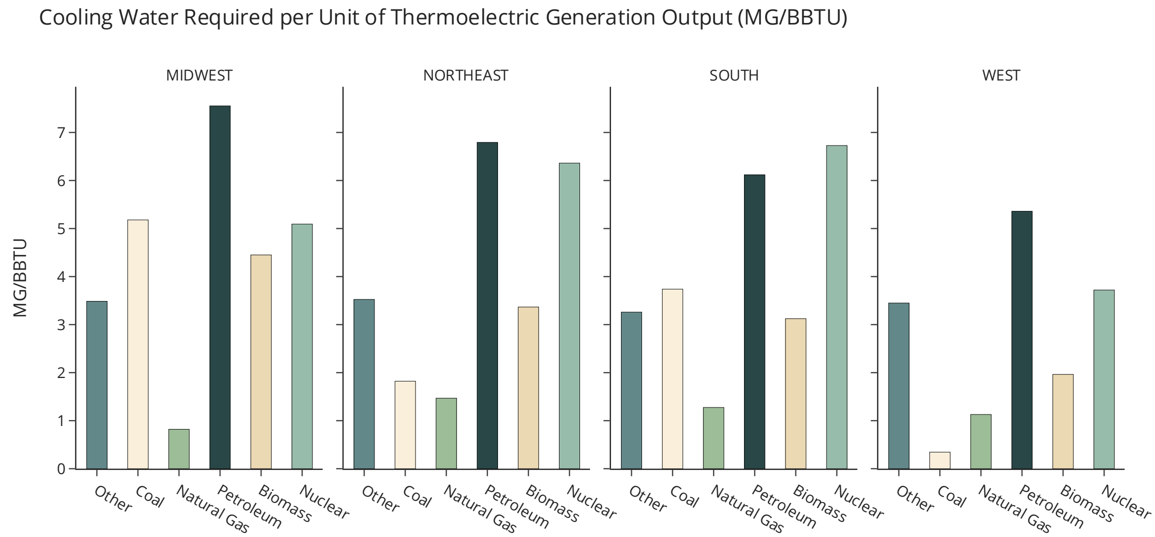

Figure 2.13 Daily Average Water Intensity (MG Input per BBTU Generated) for Thermoelectric Cooling by Generation Technology

2.2.3.2 Hydropower Generation Water Intensity

Figure 2.14 shows a map of the daily average water intensity of hydropower generation by county.

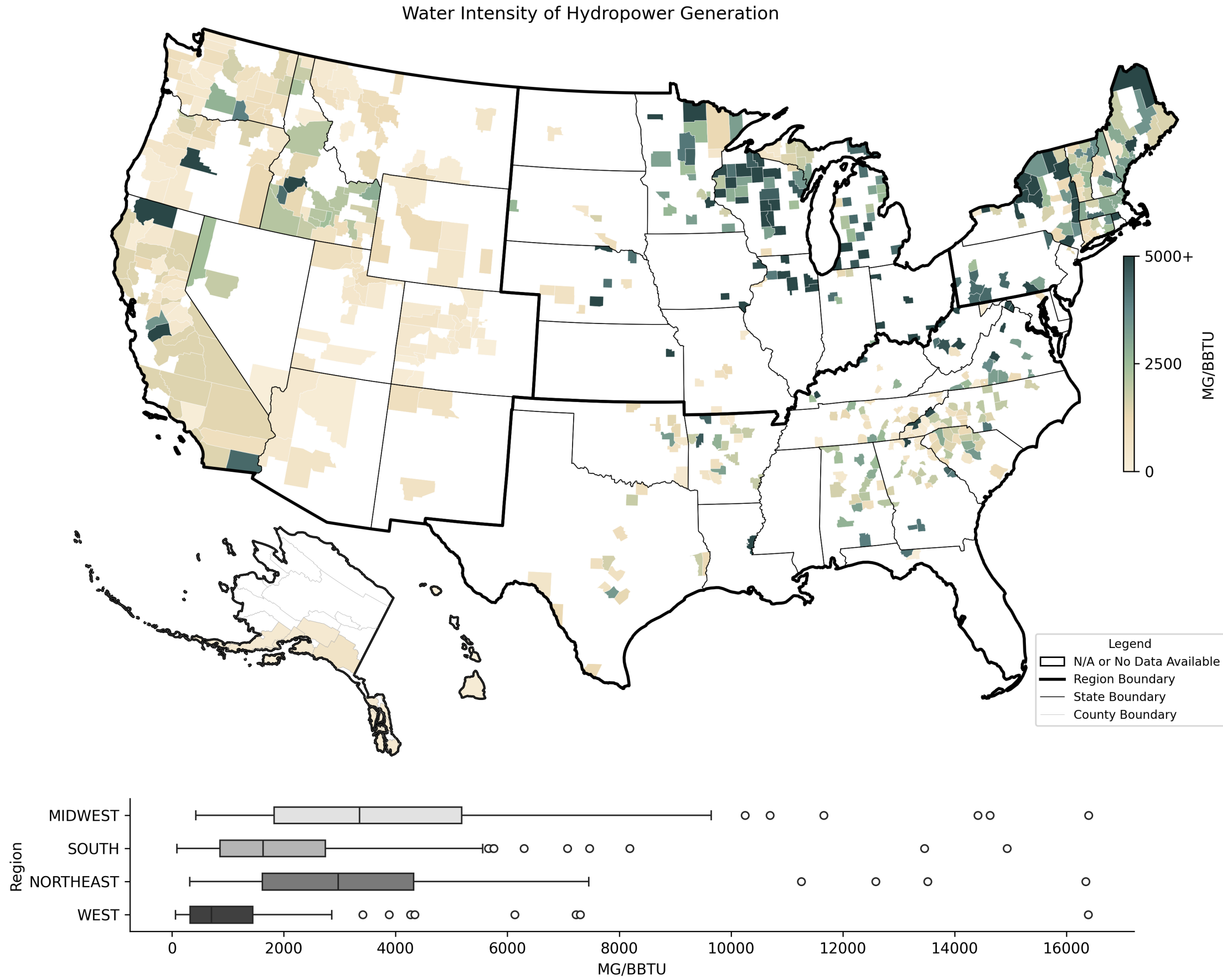

Figure 2.14 Map of Daily Average Water Intensity (MG of Water Use per BBTU of Generation Output) of Hydropower Generation by County

The Northeast region and Midwest region of the United States have higher water intensity per unit of hydropower generation compared to the West region. This is potentially due to older equipment (U.S. EIA 2017) and lower head (height differential of cascading water) (Hall et al. 2004) on average, leading to lower gravitational potential energy per unit of water. At a county level, Buffalo County, Nebraska (16,394 MG/BBTU); Boise County, Idaho (16,387 MG/BBTU); and Essex County, New York (16,347 MG/BBTU) have the highest water intensity for hydropower generation.

2.3 Agriculture Sector

2.3.1 Water in the Agriculture Sector

Water use in agriculture consists of water withdrawals and reclaimed wastewater for crop irrigation, golf irrigation, livestock, and aquaculture (Dieter et al. 2018). Figure 2.15 shows the county level daily average water use in the agriculture sector.

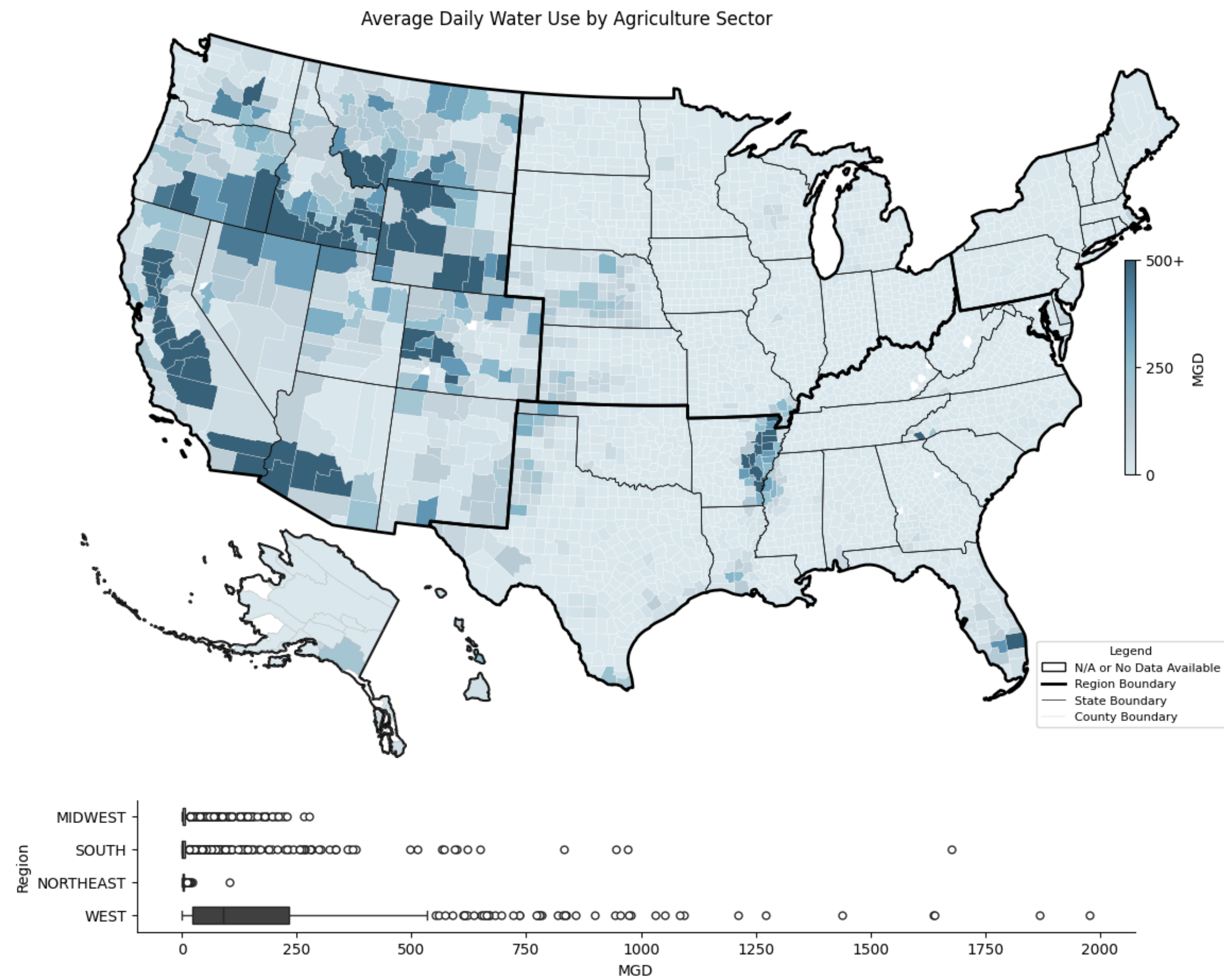

Figure 2.15. Map of Water Use (MGD) in the Agriculture Sector by County

Figure 2.15 demonstrates the West region's heavy reliance on water for agriculture compared to the other U.S. regions. The Mississippi delta area in eastern Arkansas, where crops include cotton, corn, soybeans, grain sorghum, rice, and wheat production, is one of the few other subregions with comparatively high water use.

The top three states by aggregate water use values are California (19,965 MGD), Idaho (17,309 MGD), and Arkansas (11,853 MGD). On a county level, Twin Falls County, Idaho (1,977 MGD); Imperial County, California (1,867 MGD); and Arkansas County, Arkansas (1,676 MGD) withdraw the most water on an average daily basis for agriculture.

Figure 2.16 shows the breakdown in subsector water withdrawals by agriculture application and water type. The largest flows are in the West region and include fresh surface water to crop irrigation (53,262 MGD) and fresh groundwater to crop irrigation (26,962 MGD). Advancements in agriculture water efficiency, pioneering water transfers, and coordinated water supply could address drought risks.

The South and Midwest regions are the next largest water users for crop irrigation, though their use predominantly consists of groundwater rather than surface water (Dieter et al. 2018). There are many water resource management challenges in agriculture, the large use of groundwater in these regions may point toward opportunities to increase use of reclaimed water and improve groundwater recharge practices.

Though not covered in this analysis, it is worth acknowledging that crop irrigation in the Midwest and Northeast regions is heavily reliant on rainfall. If rainfall patterns were to change, this could also present challenges to existing agriculture challenges in these regions.

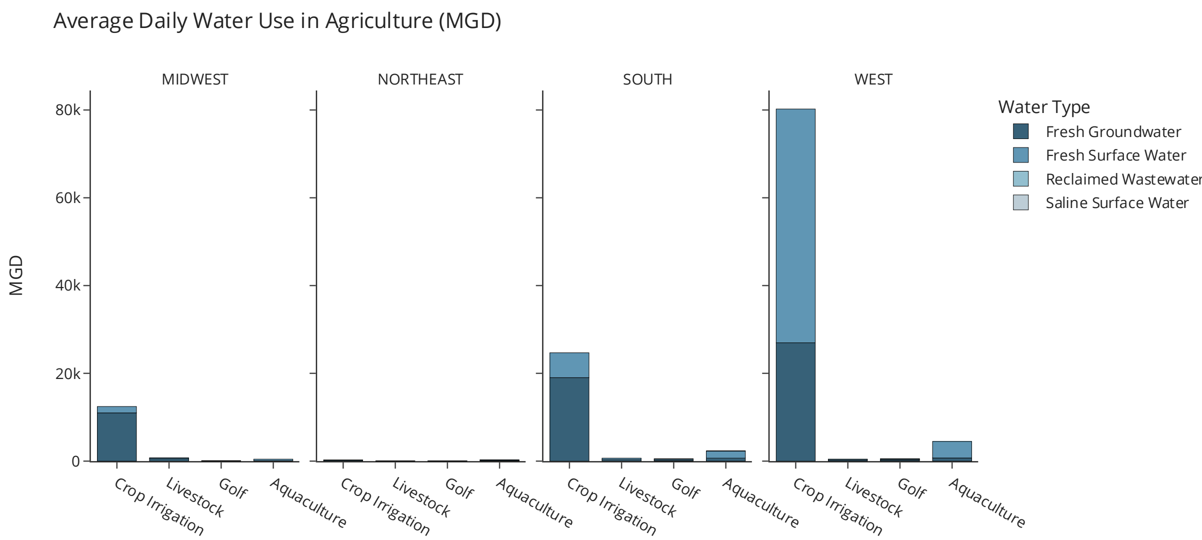

Figure 2.16 Average Daily Water Use (MGD) in the Agriculture Sector by Subsector, Region, and Water Type

2.3.2 Energy in Agriculture

Energy demand in agriculture consists of pumping surface and groundwater for crop irrigation, golf irrigation, livestock, and aquaculture as well as pumping for interbasin transfers. Figure 2.17 shows the county level energy demand for the agriculture sector. Note that energy demand consists of both electricity demand and direct fuel (natural gas and petroleum) demand. Electricity is the most common source of energy demand in agriculture, at 4.5 times the amount of the other sources combined.

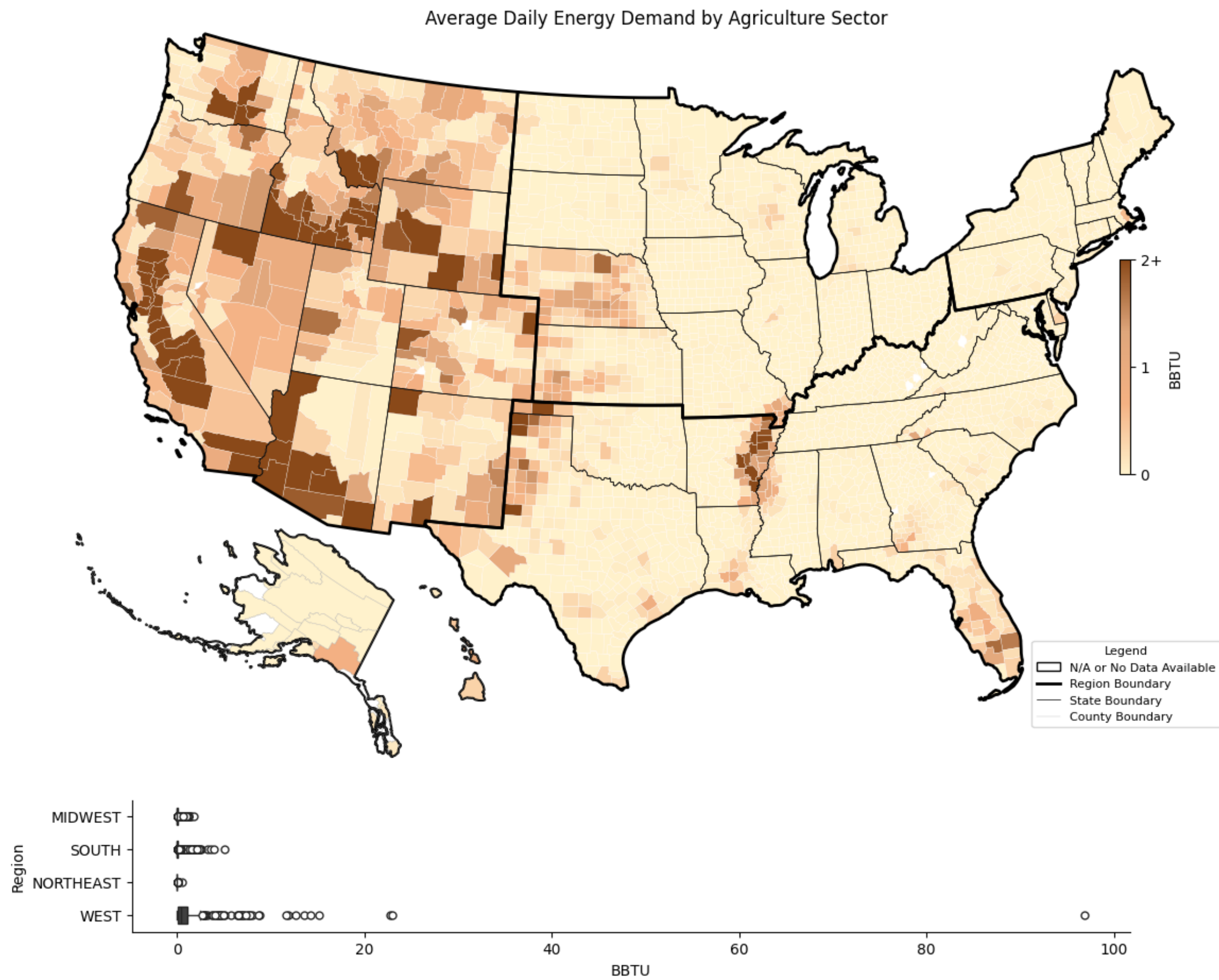

Figure 2.17 Map of Average Daily Energy Demand (BBTU) in the Agriculture Sector by County

The states with the largest energy use in agriculture on an average daily basis are California (271 BBTU), Idaho (95 BBTU), and Arizona (70 BTTU). At the county level, Kern County, California (96 BBTU); Merced County, California (23 BBTU); and Yuma County, Arizona (22 BBTU) have the largest energy demand for agriculture. Kern County's substantial energy demand, which stands out as a large outlier in the West region, stems from large amounts of interbasin transfers, which are particularly energy-intensive (Tidwell et al. 2009). Water source as well as water quantity drive the total energy demand of this sector. Counties that rely on groundwater or interbasin transfers will require more energy on a per unit basis compared to those that predominantly use surface water.

Figure 2.18 shows the breakdown in energy demand by agriculture subsector and application type. Across all U.S. regions, the largest energy demand on an average daily basis is pumping for crop irrigation (263 BBTU), followed by interbasin transfers for crop irrigation (178 BBTU). Pump efficiency improvement programs could be instituted to increase efficiency of agricultural pumping.

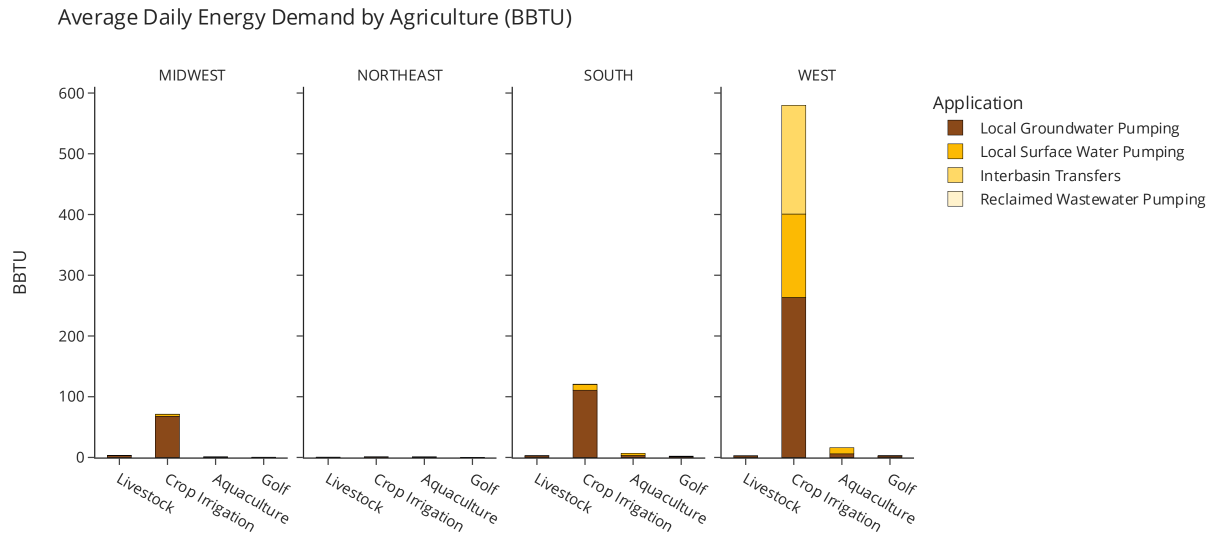

Figure 2.18 Average Daily Energy Demand (BBTU) in the Agriculture Sector by Subsector and Application

Agriculture accounts for the highest energy demand among all water-based sectors in the West region of the United States, with a substantial portion attributed to interbasin transfers (approximately 30 percent). As water shortages escalate in this region, the potential necessity to transport water from more distant regions could increase the energy required for delivery, coupled with compensatory water withdrawals to offset conveyance losses from leaks or evaporation during transfer. The critical need for collaborative and integrated planning for water and energy in agricultural services in the West region becomes increasingly evident under the backdrop of growing drought conditions. Policymaking efforts that define planning and integration requirements can wield substantial influence in addressing these challenges.

2.3.3 Energy Intensity of Water for Agriculture

Figure 2.19 shows the energy intensity of water for agriculture at county scale across the four U.S. regions. The values plotted indicate the energy (BBTU) required per unit of water (MG) withdrawn or transferred. Energy used in this calculation includes all energy sources used in agriculture (electricity, petroleum, and natural gas) per county and water includes water across all source and water types (fresh/saline, surface/groundwater, and wastewater reuse) used in all agriculture applications.

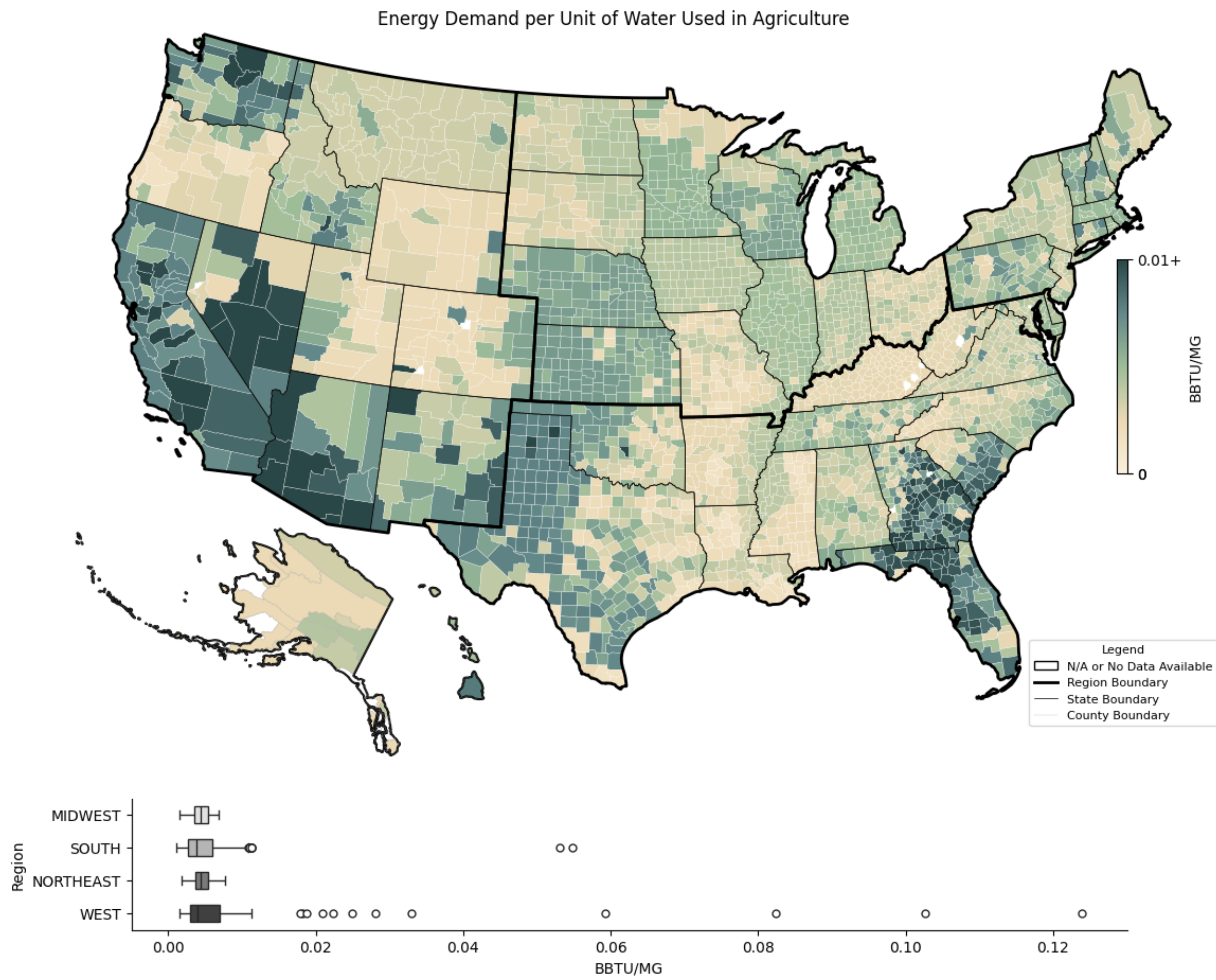

Figure 2.19 Map of Energy Intensity of Water Use (BBTU/MG) in the Agriculture Sector by County

While the median energy intensity of agriculture is roughly equivalent in each region, the West region and South region have high outliers. In the West region, the states of Washington, California, and Arizona are consistently higher, and in the South region, the states of Georgia and Florida are consistently higher. Dolores County, Colorado (0.12 BBTU/MG); Mohave County, Arizona (0.10 BBTU/MG); and Contra Costa County, California (0.08 BBTU/MG) have the highest energy intensity in agriculture over all counties.

Figure 2.20 shows the energy intensity of the agriculture sector by application, subsector, and region. Crop irrigation has the highest energy intensity across all regions (0.007 BBTU/MG), followed by livestock (0.005 BBTU/MG). On a region-by-region basis, the West region has the highest energy intensity in all agriculture subsectors except for aquaculture. The West region's high energy intensity is mostly from large quantities of interbasin transfers. Energy intensity in this sector is predominantly driven by large amounts of interbasin transfers or large portions of water being sourced from groundwater sources. The farther away (either from another basin where pumping is required or deeper underground) water is, the more energy is required.

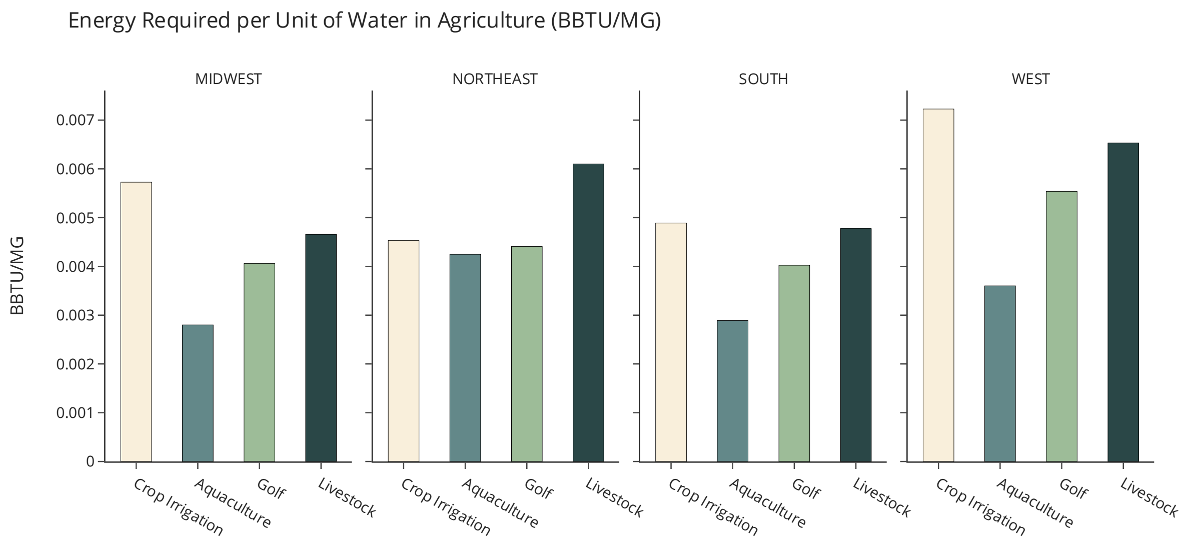

Figure 2.20 Energy Intensity of Water in the Agriculture Sector (BBTU/MG) by Subsector and Region

2.4 Public Water Supply Sector

2.4.1 Water in the Public Water Supply Sector

Public water supply withdrawals are considered to be "water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections" (Dieter et al. 2018). Figure 2.21 shows the daily average water withdrawn by the public water supply sector by county.

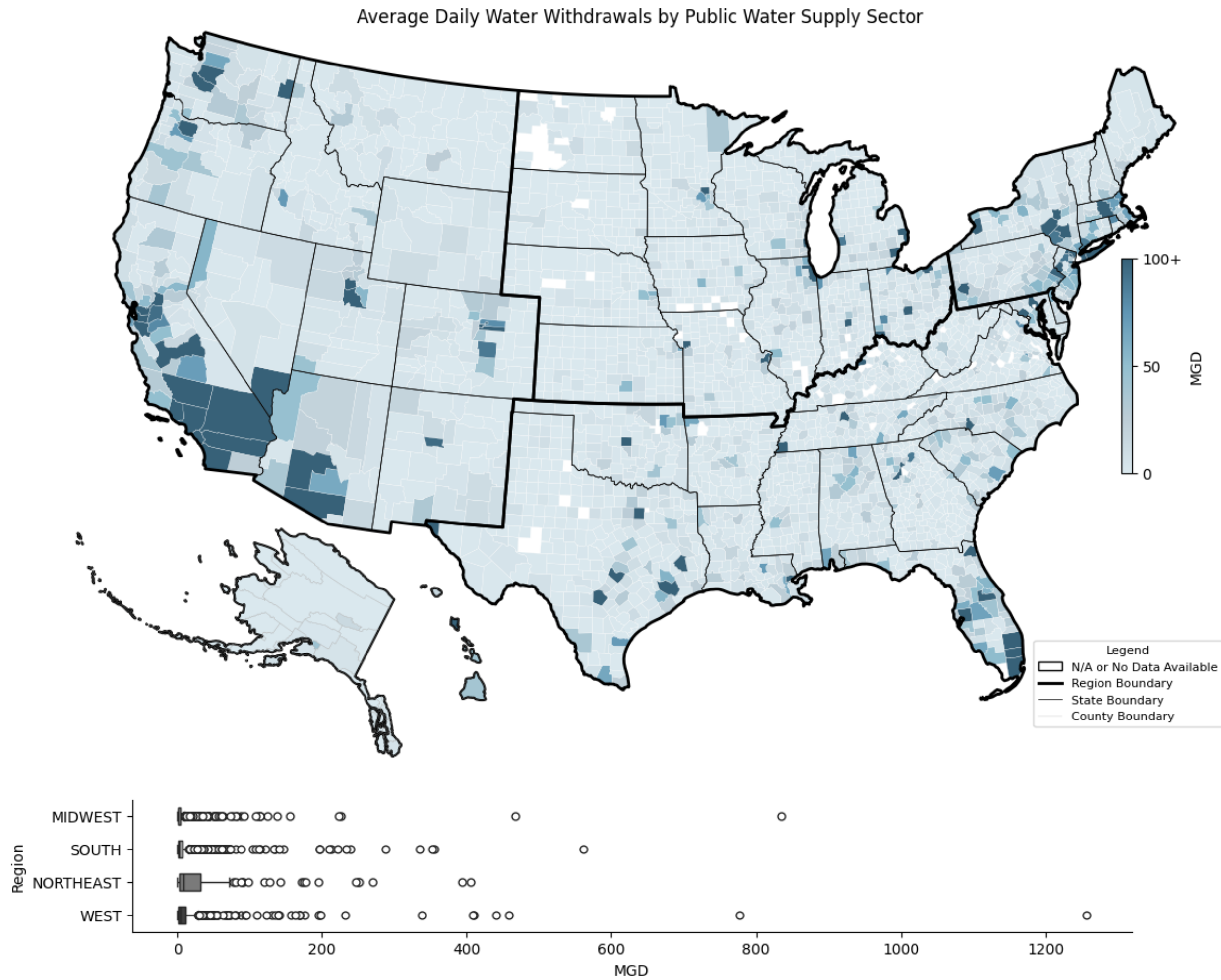

Figure 2.21 Map of Daily Average Water Withdrawals (MGD) by the Public Water Supply Sector by County

Regionally, the Northeast region has the highest median average daily water use by the public water supply sector. Water in public water supply is particularly tied to population metrics so it is unsurprising that the top three states (California [5,148 MGD], Texas [2,885 MGD], and New York [2,425 MGD]) correspond to states with high populations. Los Angeles County, California (1,256 MGD); Cook County, Illinois (834 MGD); and Maricopa County, Arizona (776 MGD) withdraw the most water for public water supply daily. These counties contain the highly populated cities of Los Angeles, Chicago, and Phoenix, respectively.

Figure 2.22 shows the daily average water processed by the public water supply sector broken down by water source and region. Across the entire United States, the largest source of public water supply is from fresh surface water (23,264 MGD), followed by fresh groundwater (14,887 MGD). Regionally, the South region withdraws the most fresh surface water and the most fresh groundwater daily. The West region is the second highest, with a relatively even split between fresh surface and fresh groundwater.

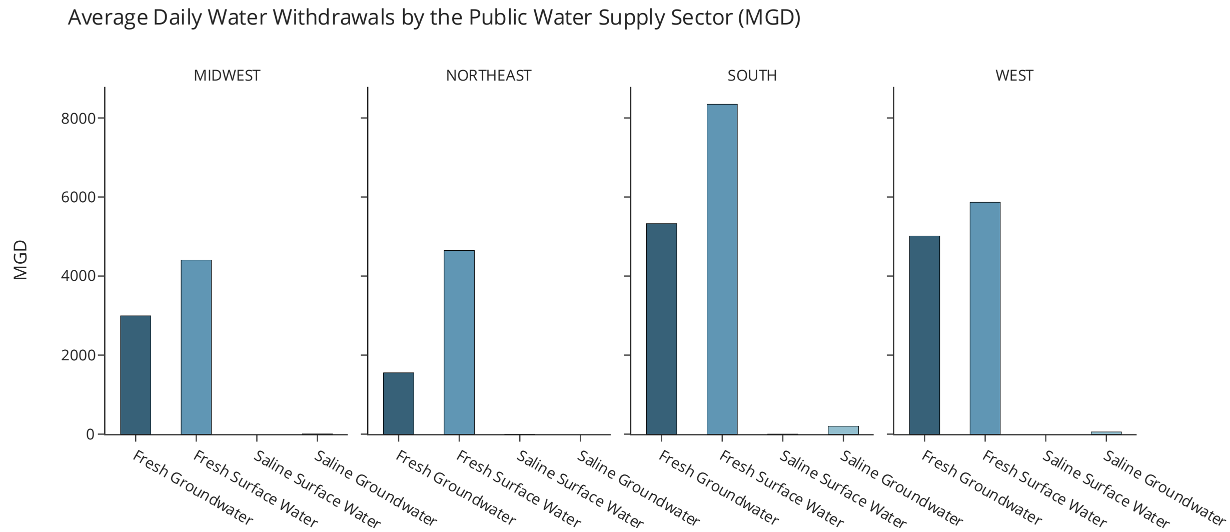

Figure 2.22 Daily Average Water Withdrawals (MGD) by the Public Water Supply Sector by Water Source

2.4.2 Energy in the Public Water Supply Sector

The public water supply sector requires energy for the withdrawal (local surface and groundwater pumping), treatment, distribution, and interbasin transfer of water. Due to data availability limitations, it is assumed that all energy used in the public water supply sector comes from electricity. Figure 2.23 shows a map of the daily average energy demand by the public water supply sector by county.

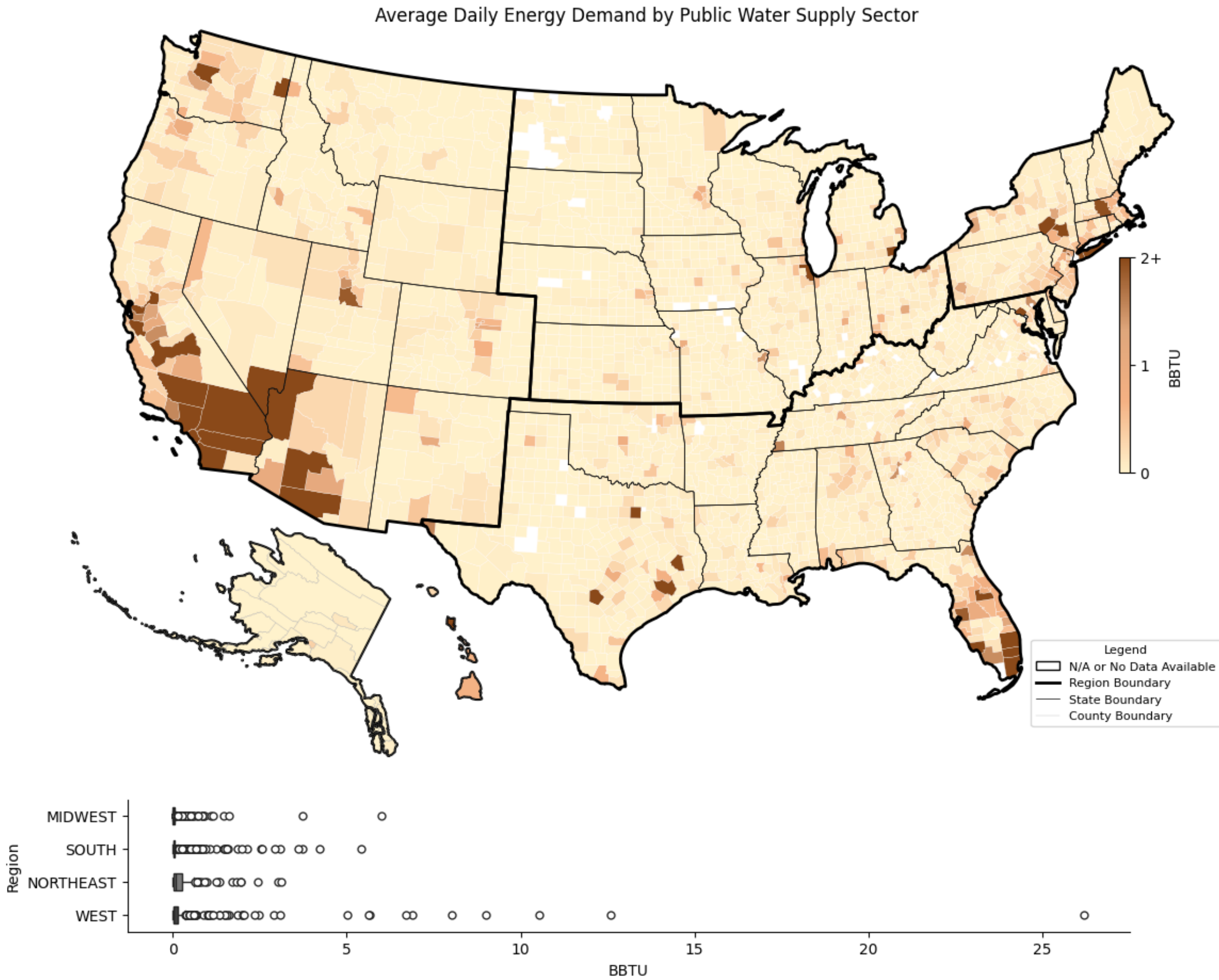

Figure 2.23 Map of Daily Average Energy Demand (BBTU) of the Public Water Supply Sector by County

Regionally, the Northeast has the highest median energy use in the public water supply sector, though the West region contains the highest outlier counties. The top three states in aggregate are California (94 BBTU), Florida (38 BBTU), and Texas (26 BBTU). Los Angeles County, California (26 BBTU); Contra Costa County, California (12 BBTU); and Kern County, California (10 BBTU) use the most energy for public water supply withdrawals, treatment, distribution, and transfers daily.

Figure 2.24 shows the daily average energy demand of the public water supply sector by application. Across all regions, the largest energy demand is for pumping water from surface and groundwater sources (170 BBTU), followed by energy for distribution of water (136 BBTU). Regionally, the West stands out in the plot below due to its high energy demand related to interbasin water transfers. Very little energy demand goes toward this purpose in other regions. The need for interbasin transfers in the West region may increase over time with growing populations and persistent drought.

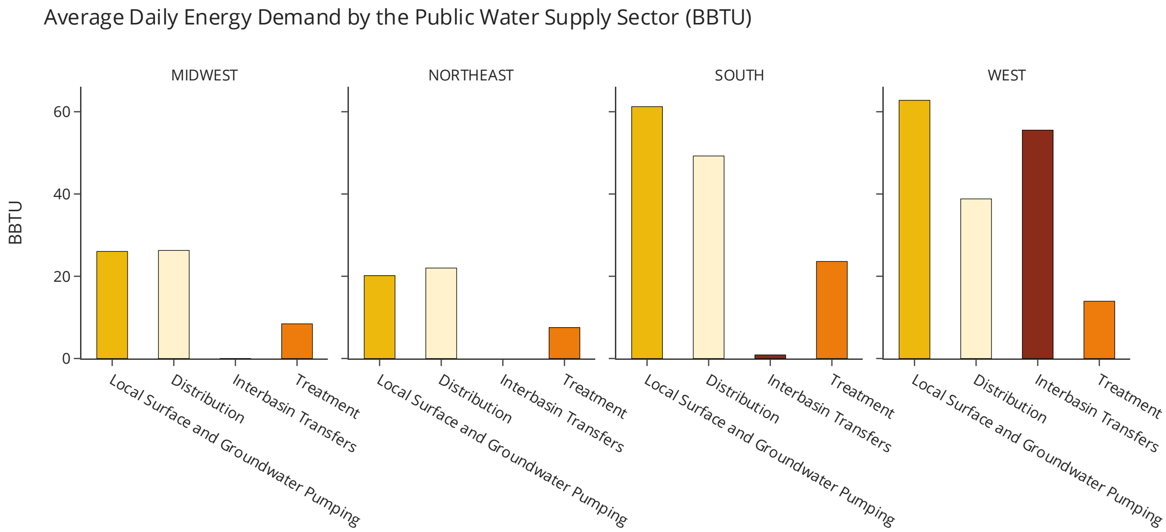

Figure 2.24 Daily Average Energy Demand (BBTU) of the Public Water Supply Sector by Application and Region

2.4.3 Energy Intensity of Water in the Public Water Supply Sector

Figure 2.25 shows the daily average energy intensity of the public water supply sector by county. This measurement shows the average energy (BBTU) required to process (pump, treat, transfer, and/or distribute) each unit of water (MG) in the public water supply sector.

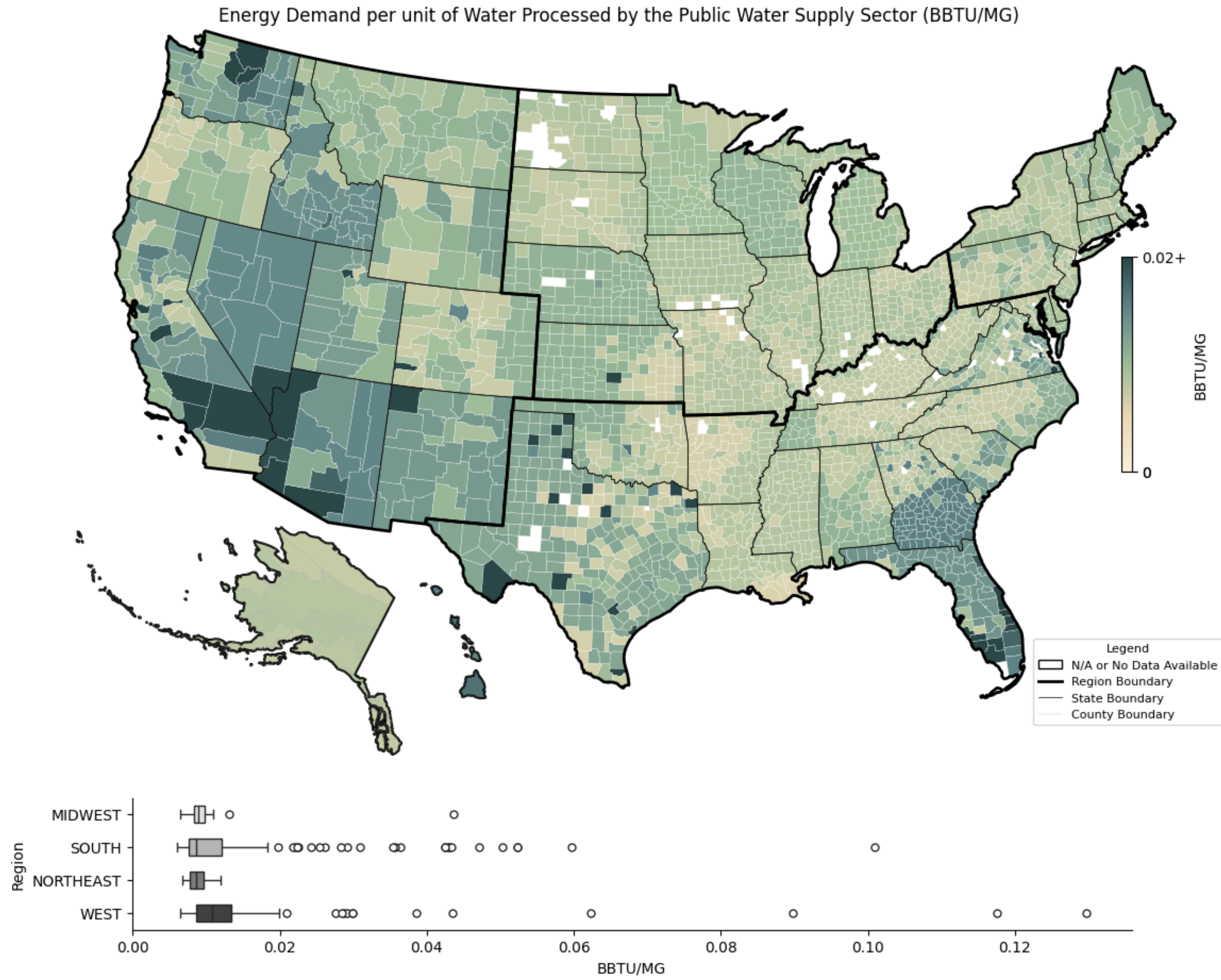

Figure 2.25 Map of Daily Average Energy Intensity (BBTU per MG of Water Processed) of the Public Water Supply Sector by County

The West region shows the highest median energy intensity in the public water supply sector across all regions. Though they may have high energy intensity counties, the other regions are generally more consistent on a median energy intensity basis. Dolores County, Colorado (0.13 BBTU/MG); Mohave County, Arizona (0.12 BBTU/MG); and Potter County, Texas (0.10 BBTU/MG) require the highest amount of energy per unit of public water supply processed on a county level.

Figure 2.26 shows average daily energy intensity of public water supply applications. For all water used for public water supply in the United States, the highest energy intensity is in local surface and groundwater pumping (0.0044 BBTU/MG), followed by distribution (0.0035 BBTU/MG). The West region has the highest energy intensity for public water supply in aggregate due to interbasin transfers, which account for approximately one-third of the sector's energy intensity.

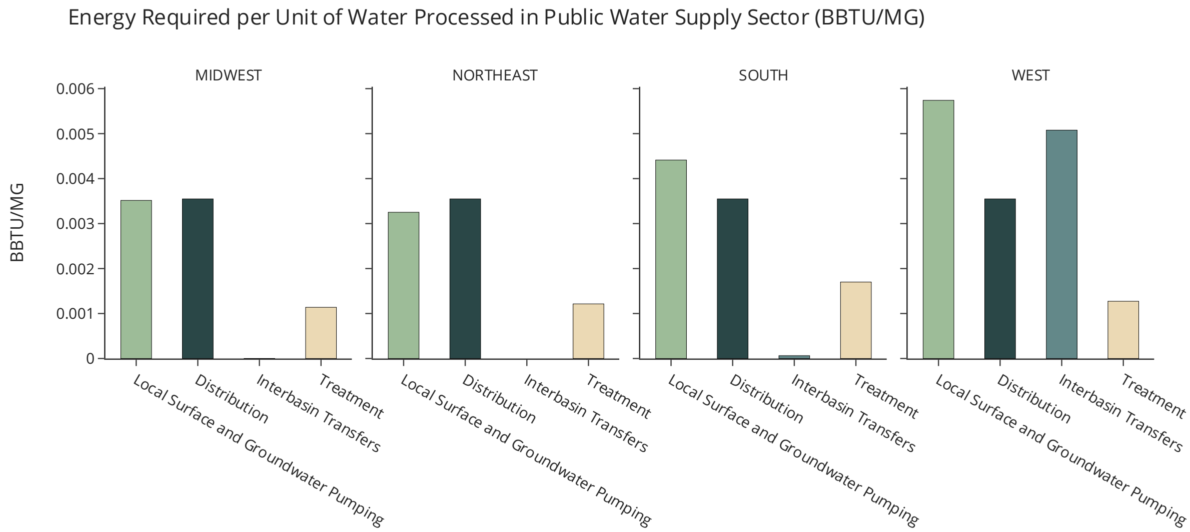

Figure 2.26 Average Daily Energy Intensity (BBTU/MG) of Public Water Supply Applications

Since this dataset was created, new estimates have been developed (Siddik et al. 2023) on interbasin transfers for the United States. These new data may increase the energy required for public water supply estimates in various regions. Though many of the newly identified flows are for flood control purposes, these new estimates indicate that there may be additional flows for public water supply in states in the Northeast region and in the state of Iowa in particular.

2.5 Industrial Sector

2.5.1 Water in the Industrial Sector

Industrial water use includes water used in industrial production of goods and services and includes both self-supply withdrawals as well as deliveries from public water supply. Figure 2.27 shows a map of the daily average water use in the industrial sector by county.

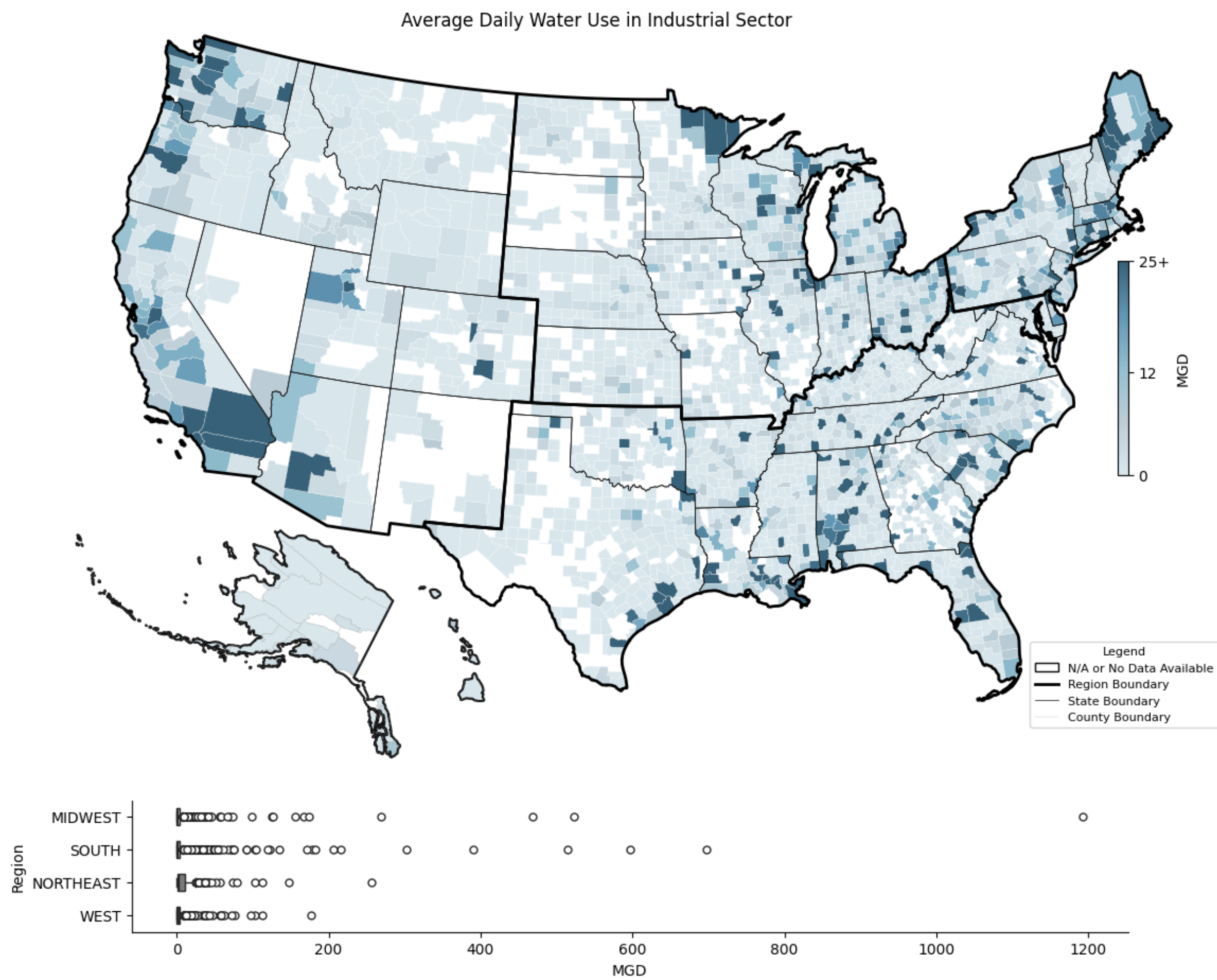

Figure 2.27 Map of Daily Average Water Use (MGD) in the Industrial Sector by County

Regionally, water use in the industrial sector is generally consistent across the United States. The South region and Midwest region contain the highest outlier counties, but the Northeast has the highest median water use overall. The top three states for water use in the industrial sector are Indiana (2,446 MGD), Louisiana (2,184 MGD), and Texas (1,165 MGD). At a county level, Lake County, Indiana (1,193 MGD); Brazoria County, Texas (698 MGD); and St. Charles County, Louisiana (596 MGD) withdraw the most amount of water daily for industrial applications.

Figure 2.28 shows the daily average water demand of the industrial sector by water source and region. Across all regions, the largest water flow to the industrial sector is self-supply from fresh surface water (11,501 MGD), followed by municipal deliveries from public water supply (5,095 MGD). Regionally, the South and Midwest regions use the most water for industrial applications, mostly consisting of fresh surface water. The West region and Northeast region use lower quantities on a daily basis.

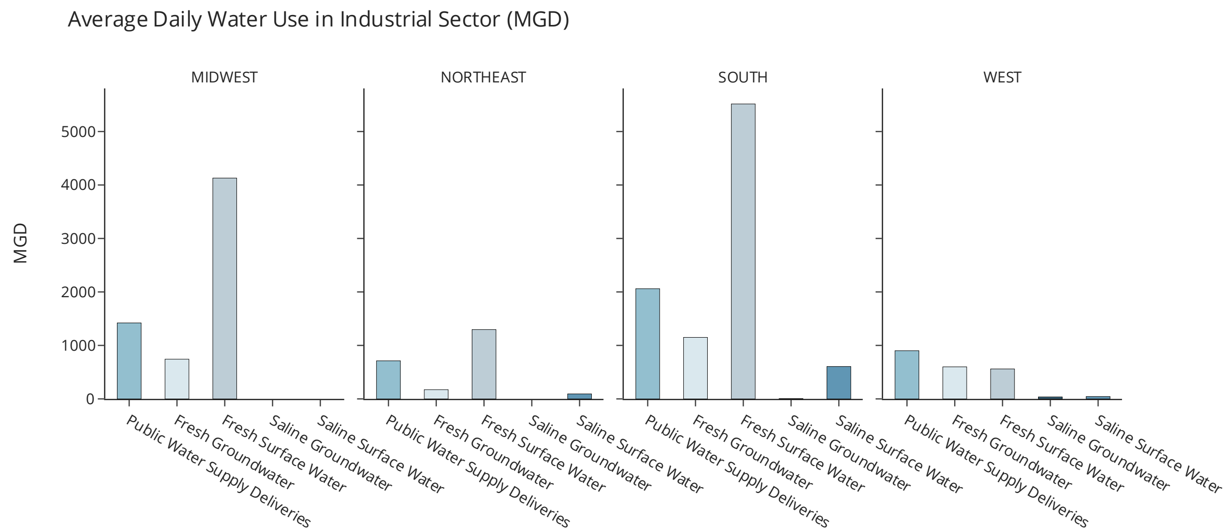

Figure 2.28 Daily Average Water Use (MGD) in the Industrial Sector by Water Source and Region

2.5.2 Energy in the Industrial Sector

Industrial energy demand consists of electricity and direct fuel demand inclusive of natural gas, petroleum, biomass, coal, solar, and wind (U.S. EIA 2021). Figure 2.29 shows a map of the daily average energy demand by the industrial sector by county.

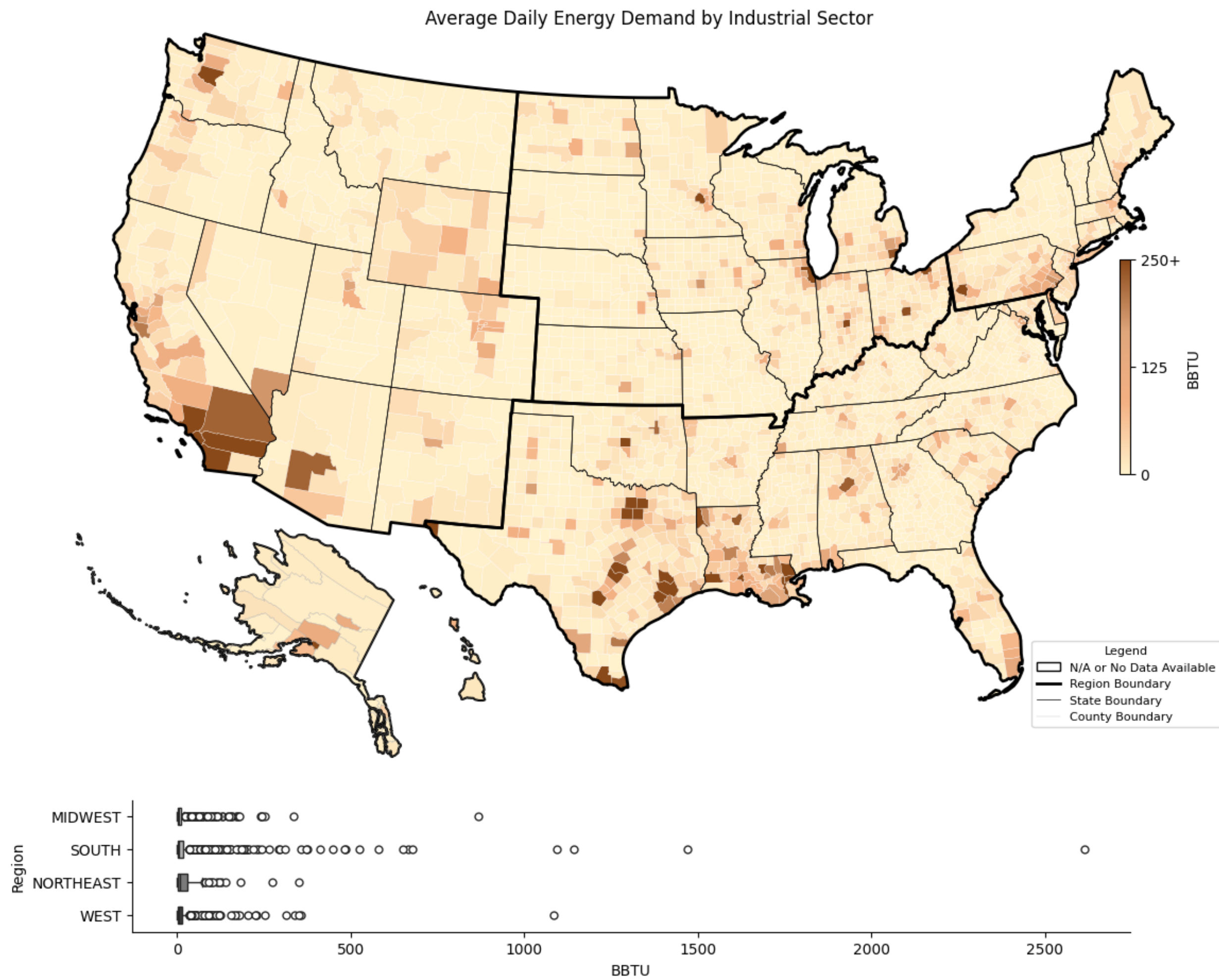

Figure 2.29 Map of Daily Average Energy Demand (BBTU) of the Industrial Sector by County

The top three states for energy use in the industrial sector are Texas (15,823 BBTU), Louisiana (6,961 BBTU), and California (4,178 BBTU). At a county level, Harris County, Texas (2,613 BBTU); Dallas County, Texas (1,470 BBTU); and Tarrant County, Texas (1,141 BBTU) are estimated to have the highest industrial sector energy demand. Note that energy demand estimates for the industrial sector are determined based on population-based downscaling of state-level energy demand. Therefore, some counties will be inconsistent between their water and energy demand at the county level. Future research and data efforts in this area can lead to improved methods for downscaling industrial energy demand to specific counties.

Figure 2.30 shows the daily average energy demand by the industrial sector by energy source. Across the entire United States, natural gas (25,827 BBTU) and petroleum (22,347 BBTU) are the top two sources of energy in the industrial sector. Looking at the regions individually, we note that the South has substantially higher energy demand for industrial applications, mostly consisting of natural gas and petroleum, compared to other regions. Comparatively small amounts of electricity are used in the industrial sector across all regions. Severe weather events that disrupt the supply chains of fuel and other resources can intensify competition between the electricity generation and industrial sectors. Additionally, grid impacts of potential future industrial electrification efforts may be significant, particularly in the South.

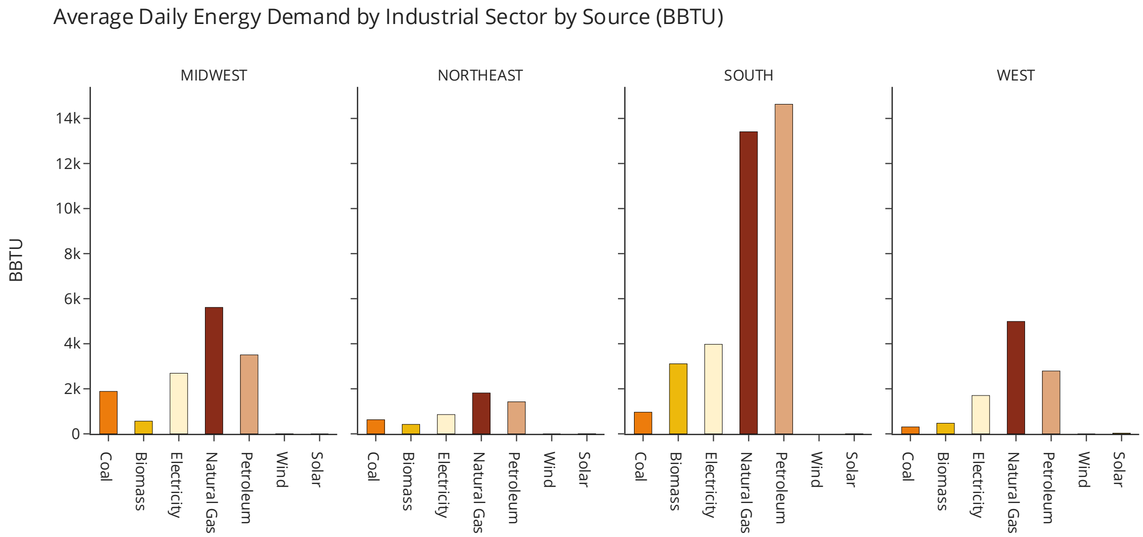

Figure 2.30 Daily Average Energy Demand (BBTU) by the Industrial Sector by Energy Source and Region

2.5.3 Water versus Energy Demand in the Industrial Sector

The dataset used in this report has limited industrial subsector granularity. For this reason, we are unable to produce energy or water intensity figures under the same framework as other sectors shown in this report. Figure 2.31, however, shows county level water demand plotted against county level energy demand by the industrial sector. This plot shows how regions compare in their daily average demands of water and energy. Water demand is inclusive of self-supply withdrawals (from surface and groundwater sources) as well as public water supply deliveries. Energy demand consists of electricity deliveries as well as direct fuel (e.g., natural gas) and resource (e.g., solar) usage.

We see considerable fanning in the data across all regions, where a high amount of energy demand in the industrial sector for a county may not necessarily mean a high amount of water demand, or vice versa. This could be due to either the nature of the industrial facilities that reside in each county—where some industries, for example, are heavily reliant on energy but less so on water—or the pattern in the data could be a result of the downscaling methodology of state level energy demand. Future research can work to investigate the relationship shown in this plot in higher detail should additional data become available.

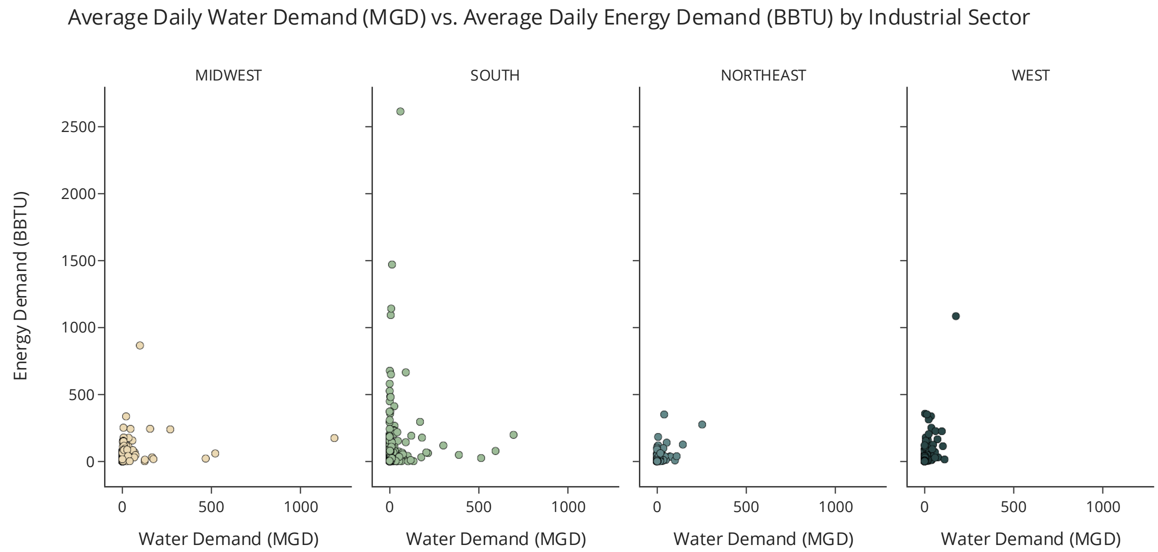

Figure 2.31 Average Daily Water Demand (MGD) vs. Average Daily Energy Demand (BBTU) by the Industrial Sector for each U.S. County by Region

2.6 Commercial Sector

2.6.1 Water in the Commercial Sector

The commercial sector includes "motels, hotels, restaurants, office buildings, other commercial facilities, military and nonmilitary institutions" (Dieter et al. 2018). No withdrawal (self-supply) values were available or assumed for the commercial sector. All water for the commercial sector is assumed to be delivered from the public water supply.

Figure 2.32 shows the county level public water deliveries to the commercial sector in each county of the United States. Most counties with high water use in the commercial sector correspond to areas with higher population, such as the areas surrounding Los Angeles, California and Chicago, Illinois (Dieter et al. 2018).

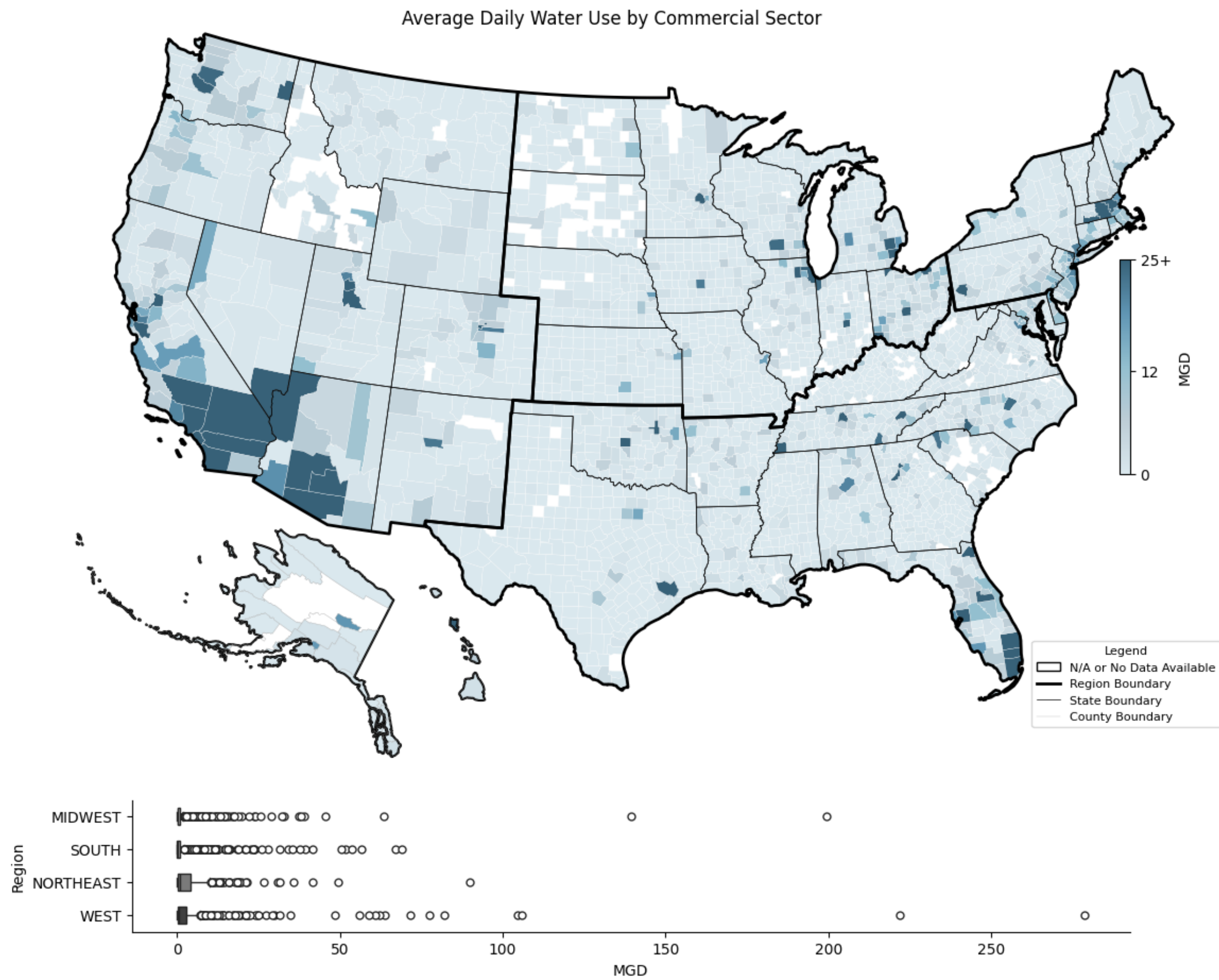

Figure 2.32 Map of Average Daily Water Use (MGD) in the Commercial Sector by County

2.6.2 Energy in the Commercial Sector

Energy demand in the commercial sector consists of energy for various applications, including lighting, water heating, space conditioning, refrigeration, and running equipment (U.S. EIA 2024). Figure 2.33 shows the county level energy demand by the commercial sector.

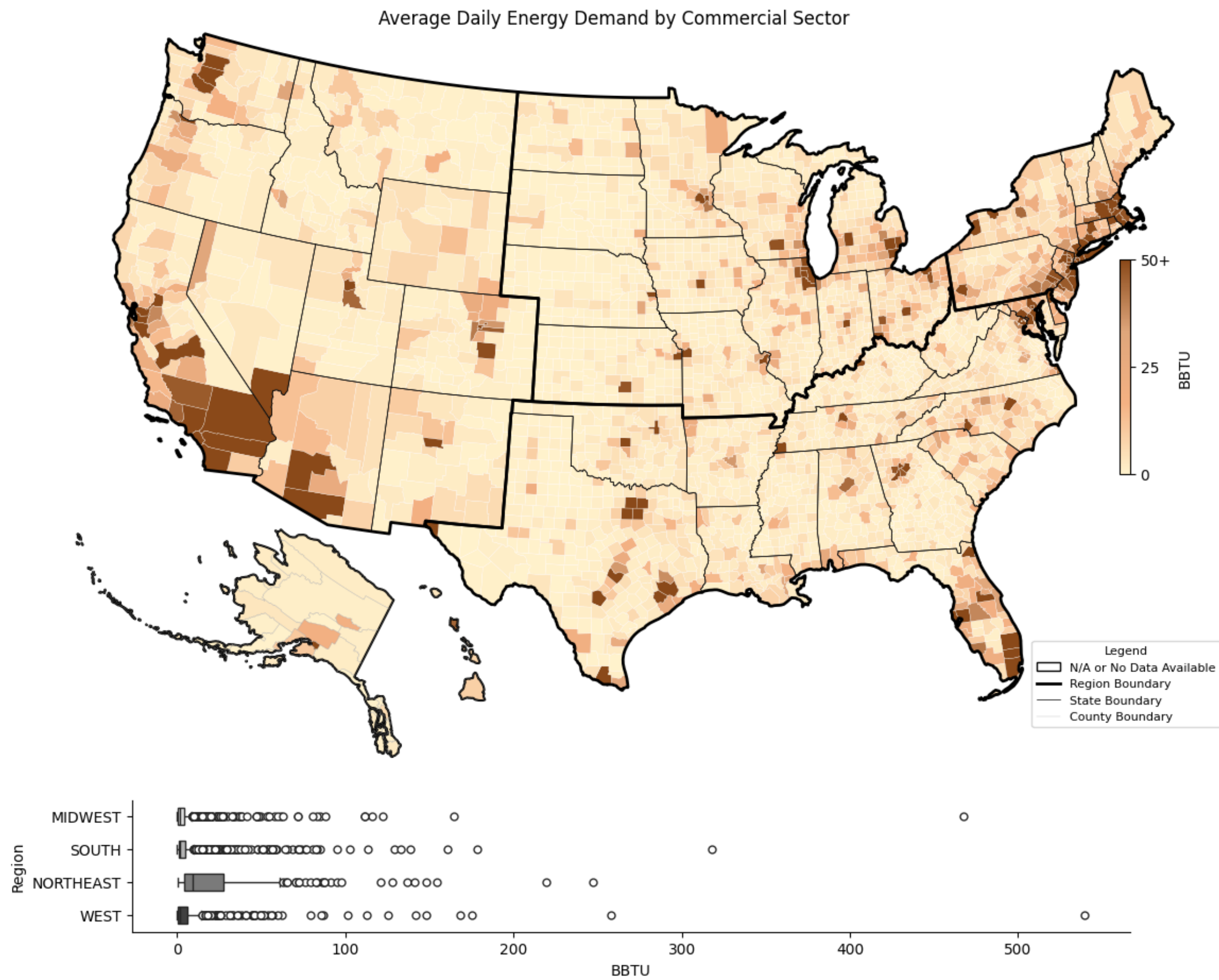

Figure 2.33 Map of Average Daily Energy Demand (BBTU) in the Commercial Sector by County

Regionally, the Northeast region has the highest median energy demand in the commercial sector, concentrated mostly in the states of New York, New Jersey, and Massachusetts. The top three states across all regions are California (2,077 BBTU), Texas (1,923 BBTU), and New York (1,858 BBTU). Los Angeles County, California (539 BBTU); Cook County, Illinois (467 BBTU); and Harris County, Texas (317 BBTU) use the most energy on an average daily basis across all counties. Note that, just as with the industrial sector, energy demand estimates for the commercial sector are determined based on population-based downscaling of state-level energy values. Therefore, some counties will be inconsistent between their water and energy demand and county level.

Figure 2.34 shows the breakdown in energy deliveries by source to the commercial sector. The largest daily average flow across the entire United States is from electricity (5,592 BBTU), followed by natural gas (2,881 BBTU). On a regional basis, the South region uses the most electricity daily (5,592 BBTU) in the commercial sector, whereas all other regions are fairly equivalent around 2,000–2,500 BBTU per day. The Midwest region uses the most amount of natural gas across all regions, though not by a substantial margin; the West region uses the least amount of natural gas. These results, in addition to the industrial sector breakdown provided later in this report, raise interesting questions about regional capabilities to achieve a net-zero economy. While the South has a large amount of electricity use in the commercial sector, there is also substantial amounts of natural gas and petroleum use. Therefore, planners and policymakers need to consider the potential increase in grid demand if direct fossil-fuel use were to switch to electricity demand.

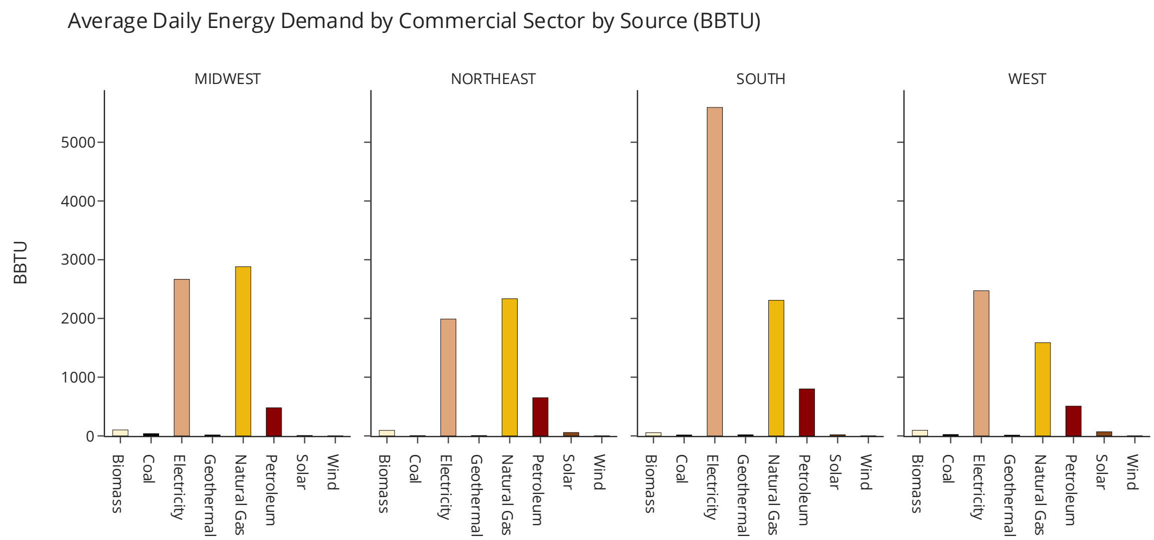

Figure 2.34 Average Daily Energy Demand (BBTU) by Source in the Commercial Sector

2.6.3 Water versus Energy Demand in the Commercial Sector

Though we cannot produce energy or water intensity figures for the commercial sector under the same framework as other sectors shown in this report, Figure 2.35 provides a plot of county level water demand plotted against county level energy demand by the commercial sector. Water demand only includes public water supply deliveries since no self-supply withdrawals are assumed or provided for in the commercial sector. Energy demand consists of electricity deliveries as well as direct fuel (e.g., natural gas) and resource (e.g., solar) usage.

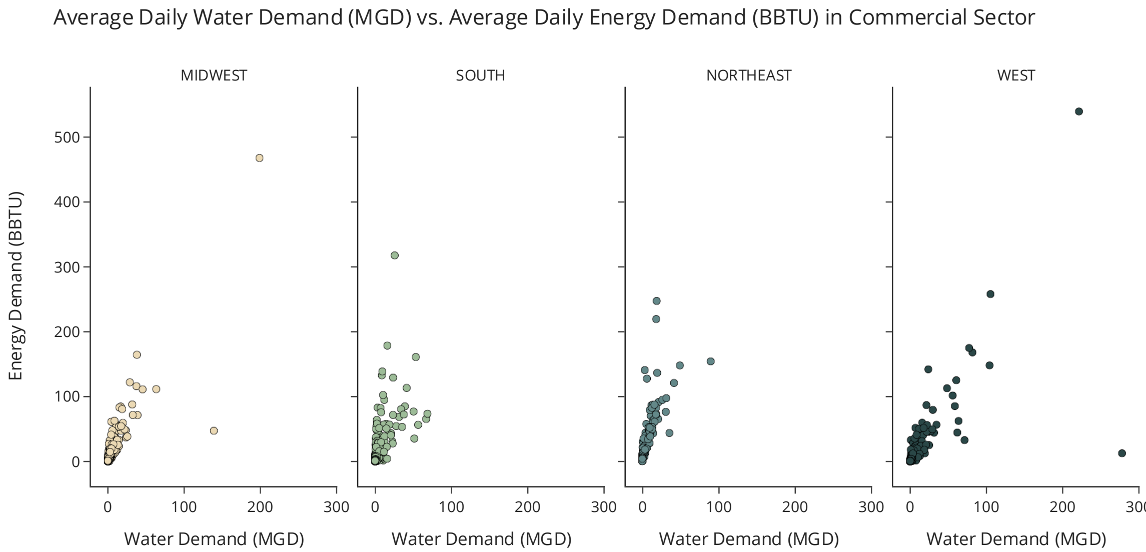

Figure 2.35 Average Daily Water Demand (MGD) vs. Average Daily Energy Demand (BBTU) by the Commercial Sector for each U.S. County by Region

The Midwest and Northeast regions demonstrate a more linear relationship where water demand consistently increases on a per-county level with energy demand in the commercial sector. The South and West regions demonstrate more variability where high energy demand does not necessarily necessitate high water demand, and vice versa.

2.7 Residential Sector

2.7.1 Water in the Residential Sector

Water in the residential sector is predominantly used for “drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens” (Dieter et al. 2018). Figure 2.36 shows a map of the daily average water demand by the residential sector by county. Water use by the residential sector includes both self-supply withdrawals (e.g., groundwater from wells) as well as deliveries from public water suppliers.

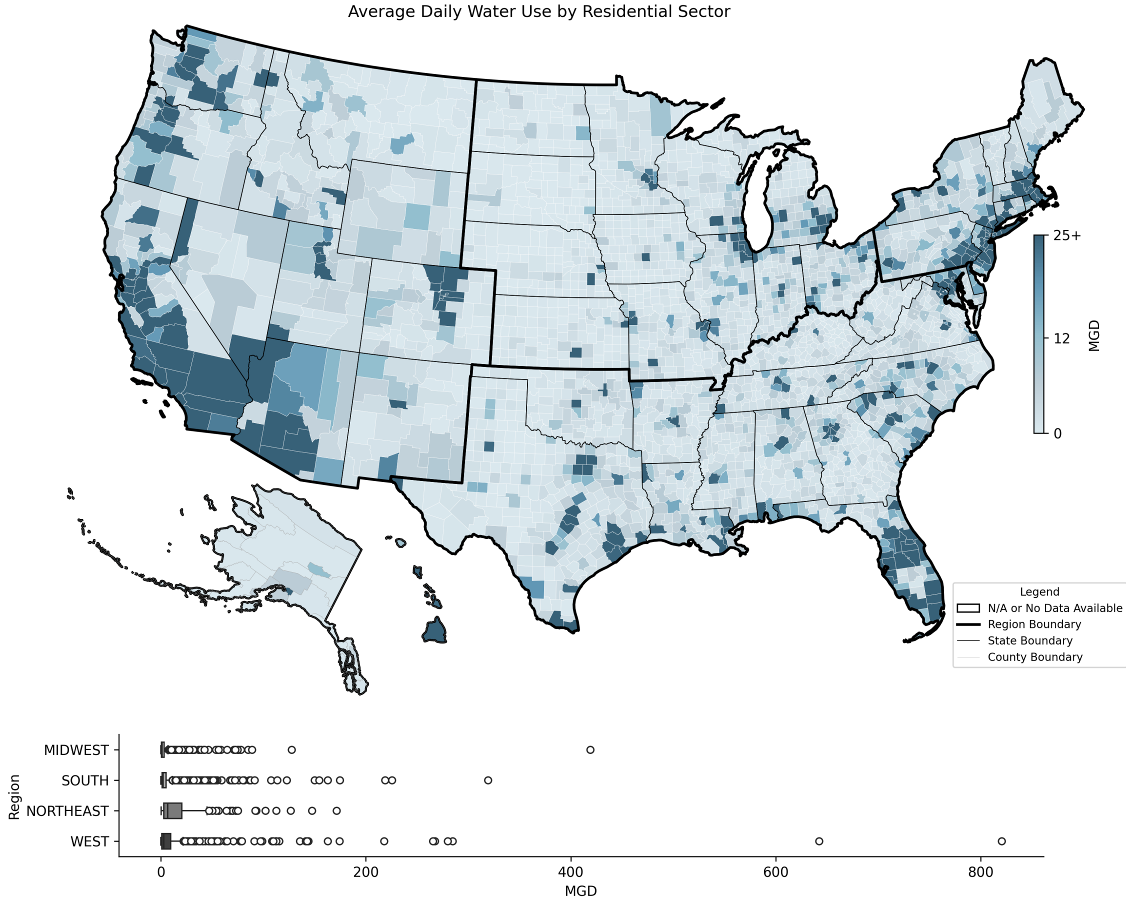

Figure 2.36 Map of Daily Average Water Use (MGD) in the Residential Sector by County

The top three states are California (3,355 MGD), Texas (2,261 MGD), and Florida (1,679 MGD). Not surprisingly, water use in the residential sector is highly correlated with population. Los Angeles County, California (820 MGD); Maricopa County, Arizona (642 MGD); and Cook County, Illinois (419 MGD) have the highest daily residential water demand.

Figure 2.37 shows the daily average water demand by the residential sector by water source in each region. The largest source of water to the residential sector across all regions is from public water deliveries (22,952 MGD), followed by fresh groundwater (self-supply) (3,209 MGD) (Dieter et al. 2018). The South region has the highest daily water demand of all regions, closely followed by the West region.

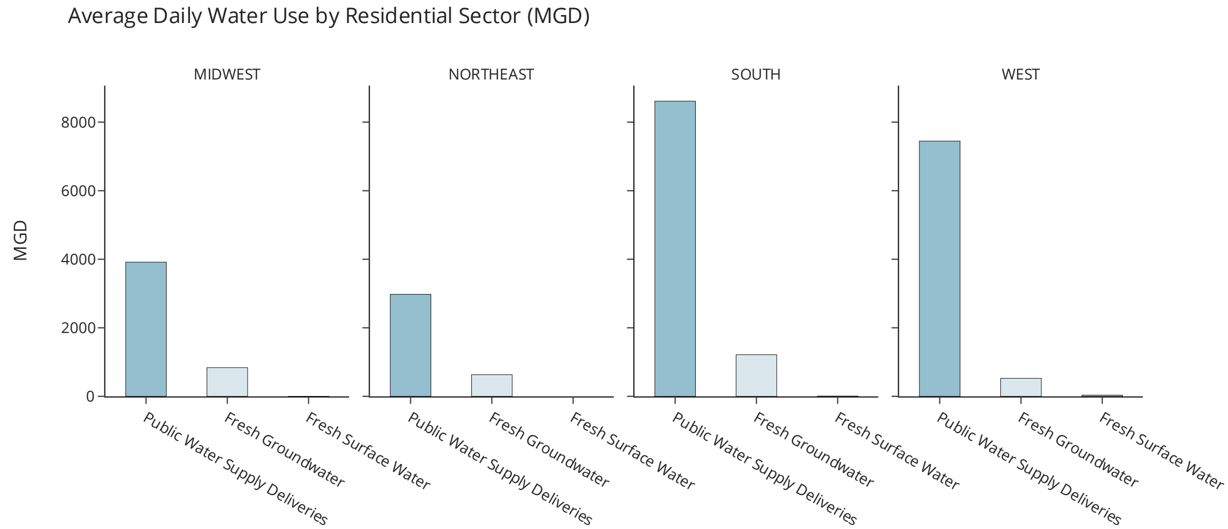

Figure 2.37 Daily Average Water Demand (MGD) by the Residential Sector by Water Source

2.7.2 Energy in the Residential Sector

Residential energy demand consists of both electricity and direct fuel demand inclusive of natural gas, petroleum, biomass, geothermal, and solar. Figure 2.38 shows a map of the daily average energy demand by the residential sector by county.

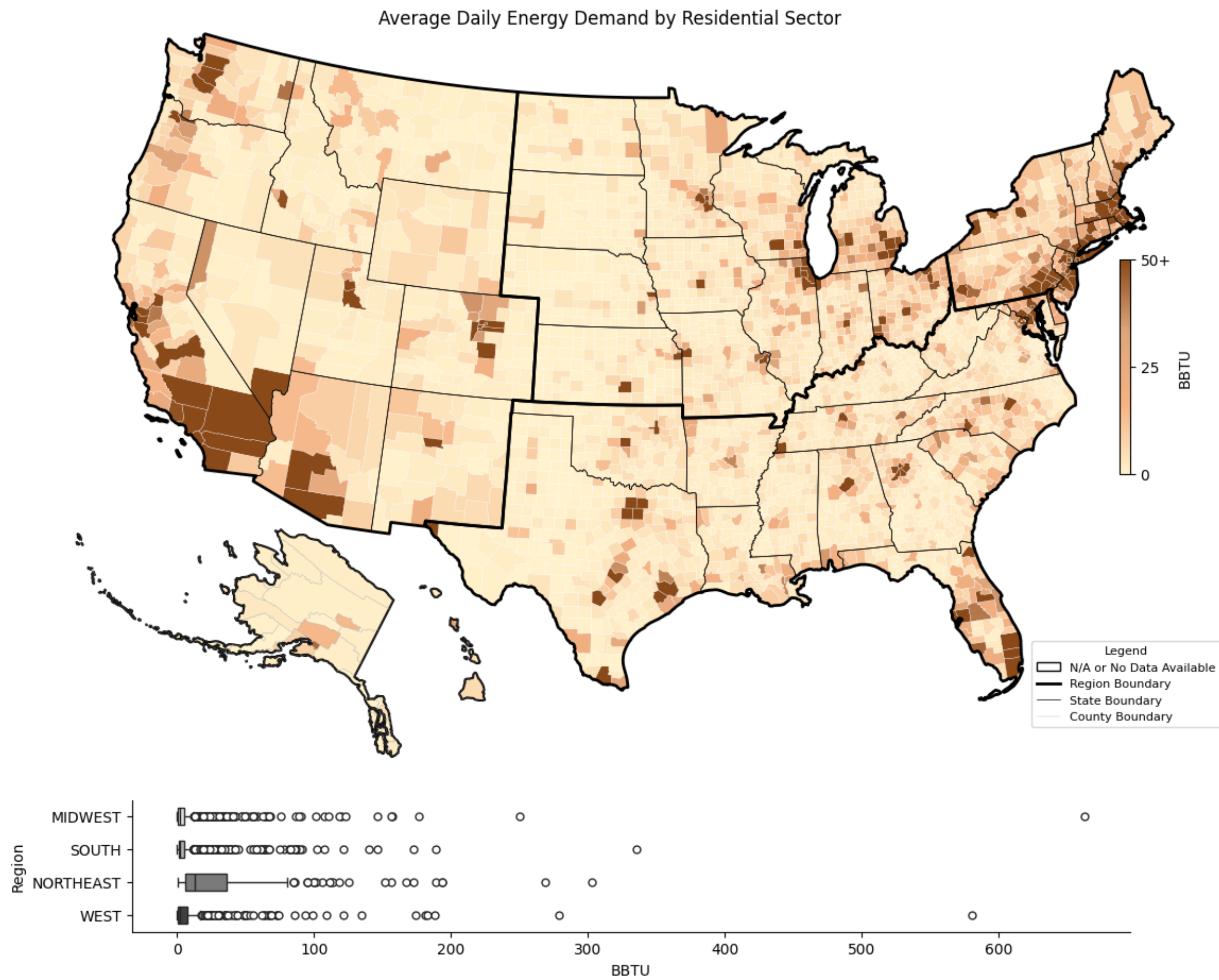

Figure 2.38 Map of Daily Average Energy Use (BBTU) of the Residential Sector by County

The Northeast region has the highest median energy use in the residential sector compared to all other regions. The top three states are New York (2,273 BBTU), California (2,235 BBTU), and Texas (2,030 BBTU). Cook County, Illinois (663 BBTU); Los Angeles County, California (580 BBTU); and Harris County, Texas (2,030 BBTU) have the highest county level energy demand by the residential sector. Note that energy demand estimates for the residential sector are determined based on population-based downscaling of state-level energy demand. Therefore, some counties will be inconsistent between their water and energy demand and county level.

Figure 2.39 shows the daily average energy demand by the residential sector by energy source. Across the entire United States, the largest supplier of energy to the residential sector is from natural gas (13,136 BBTU), followed very closely by electricity (13,125 BBTU). There are very clear regional differences in energy source where the South region heavily relies on electricity at a rate almost double that of natural gas, while in other regions, natural gas is the main supplier. In the West region, however, it is nearly evenly split between electricity and natural gas.

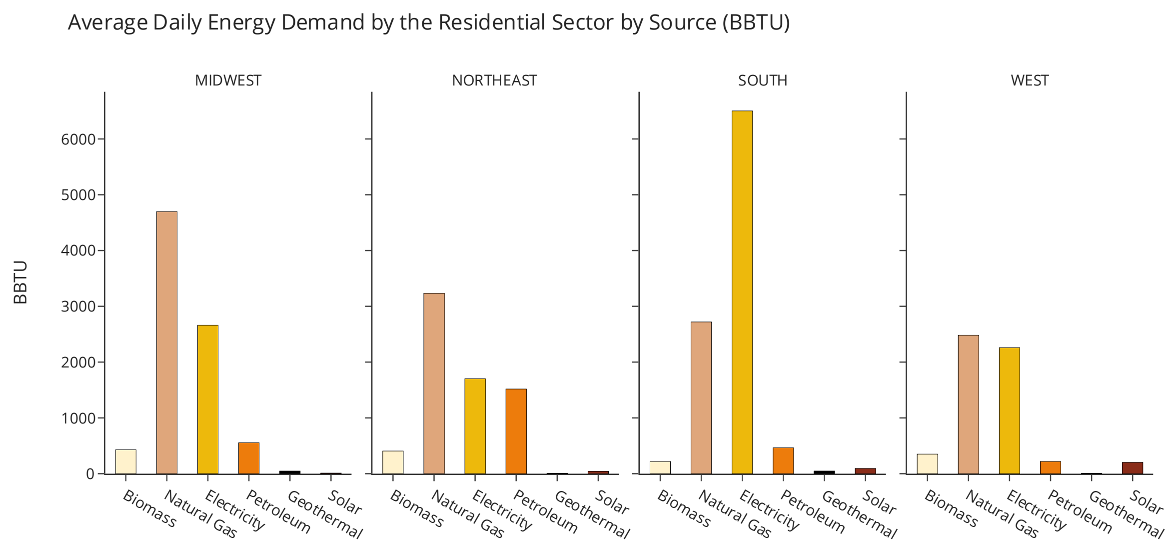

Figure 2.39 Daily Average Energy Demand (BBTU) by the Residential Sector by Energy Source

2.7.3 Water versus Energy Demand in the Residential Sector

Though we cannot produce energy or water intensity figures under the same framework as other sectors shown in this report, Figure 2.40 provides a plot of county level water demand plotted against county level energy demand by the residential sector. Water demand is inclusive of self-supply withdrawals (from surface and groundwater sources) as well as public water supply deliveries. Energy demand consists of electricity deliveries as well as direct fuel (e.g., natural gas) and resource (e.g., solar) usage.

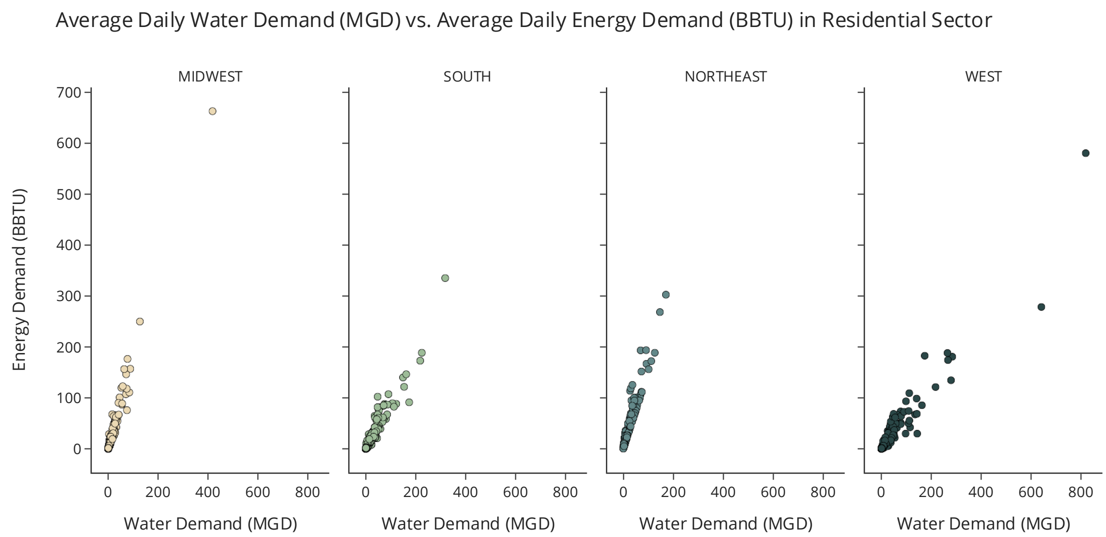

Figure 2.40 Average Daily Water Demand (MGD) vs. Average Daily Energy Demand (BBTU) in the Residential Sector for Each U.S. County by Region

Figure 2.40 shows how regions compare in their daily average demands of water and energy. The Midwest and Northeast regions demonstrate a more linear relationship where water demand consistently increases on a per-county level with energy demand. The South and West regions, on the other hand, demonstrate more fanning, where high energy demand does not necessarily necessitate high water demand, and vice versa. We can also see that the residential sector in the West demonstrates higher water demand on a per-county level than other regions.

2.8 Transportation Sector

2.8.1 Water in the Transportation Sector

No water use is assumed for the transportation sector. Only energy demand by the transportation sector is included in this report.

2.8.2 Energy in the Transportation Sector

Energy used in the transportation sector includes, among many other uses, gasoline used in cars, fuel used in airplanes, and electricity used in public transit systems (U.S. EIA 2016, 2021). Figure 2.41 shows a map of the daily average energy demand by the transportation sector inclusive of petroleum, biomass, natural gas, and electricity.

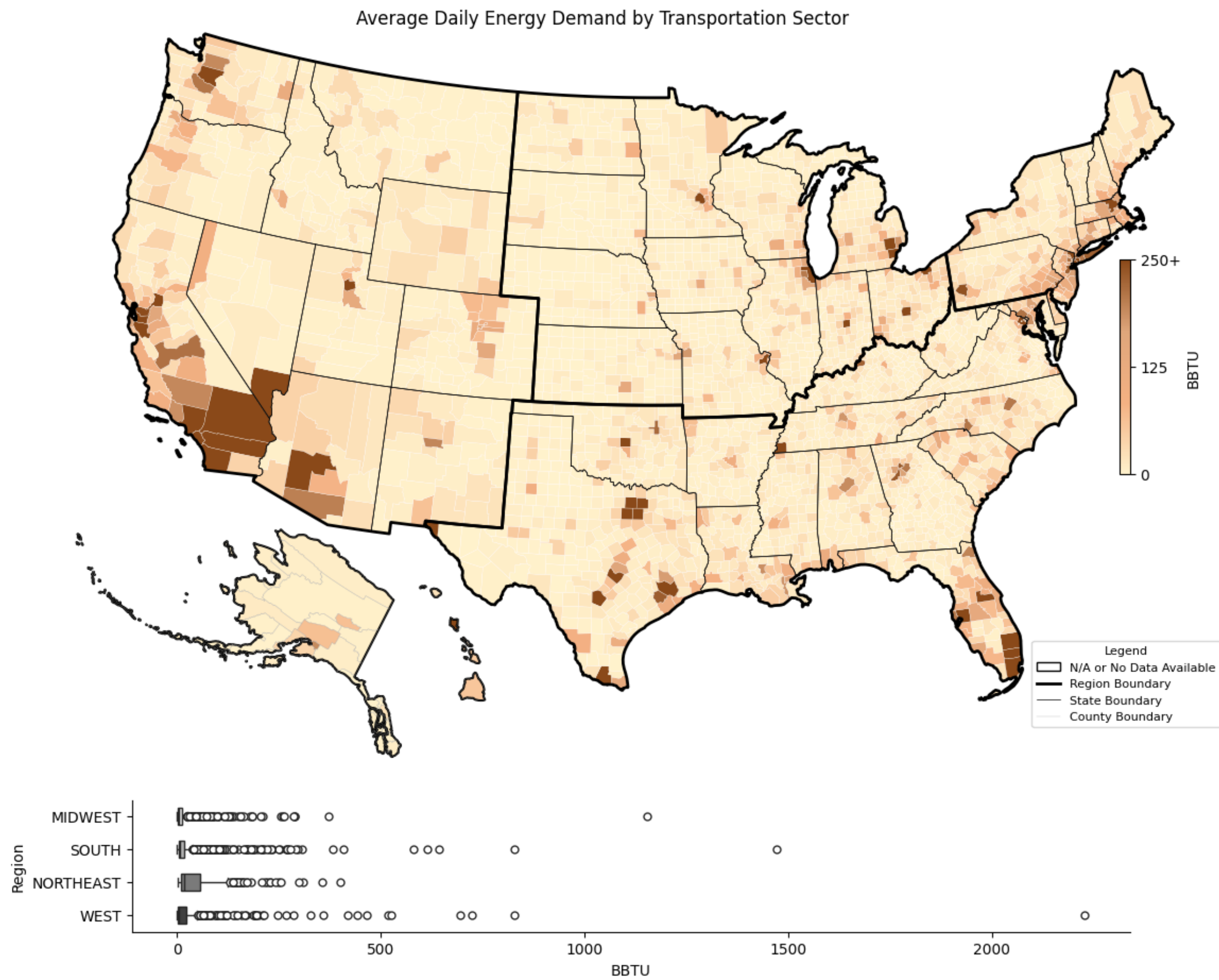

Figure 2.41 Map of Daily Average Energy Use (BBTU) of the Transportation Sector by County

The top three states for energy use in the transportation sector are Texas (8,906 BBTU), California (8,576 BBTU), and Florida (4,372 BBTU). The top three counties are Los Angeles County, California (2,228 BBTU); Harris County, Texas (1,471 BBTU); and Cook County, Illinois (1,153 BBTU).

Figure 2.42 shows the daily average energy demand by the transportation sector by energy source. The largest supplier of energy to the transportation sector across the entire United States is petroleum (72,386 BBTU), followed far behind by biomass (3,040 BBTU). The South region uses the most petroleum in the transportation sector on a daily basis across all regions. Transportation electrification will have significant impacts on electricity demand across the country.

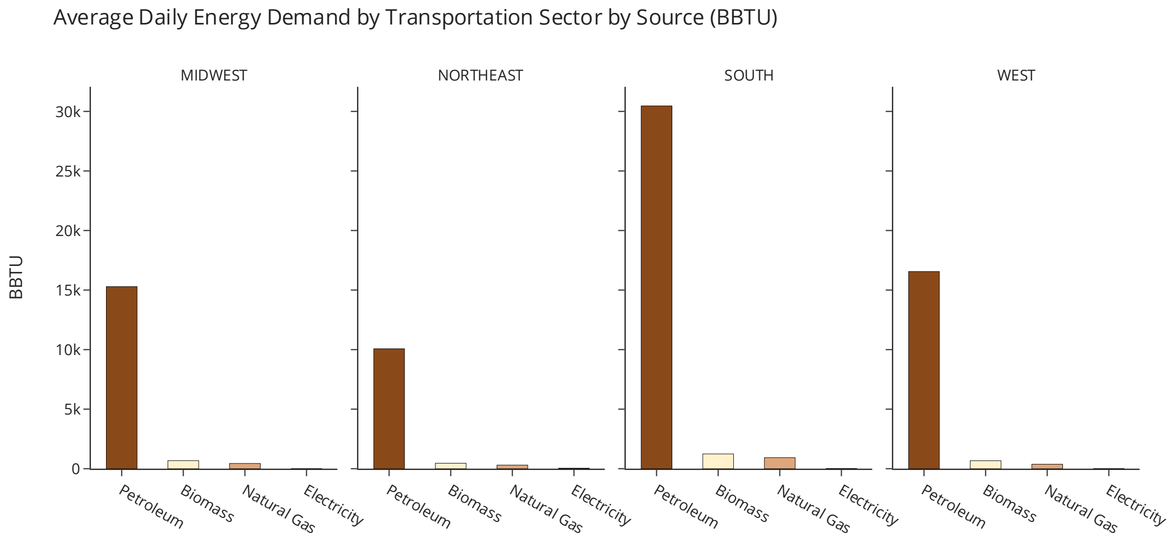

Figure 2.42 Daily Average Energy Demand (BBTU) by the Transportation Sector by Energy Source

2.9 Wastewater Treatment Sector

2.9.1 Water in the Wastewater Treatment Sector

Water flows in the wastewater treatment sector include inflows from municipal and industrial sources (residential, commercial, and industrial wastewater) and infiltration (flows that enter the system through non-sealed connections such as defective joints) (U.S. EPA 2016). Figure 2.43 shows a map of the daily average water processed by the wastewater treatment sector by county (municipal deliveries and infiltration).

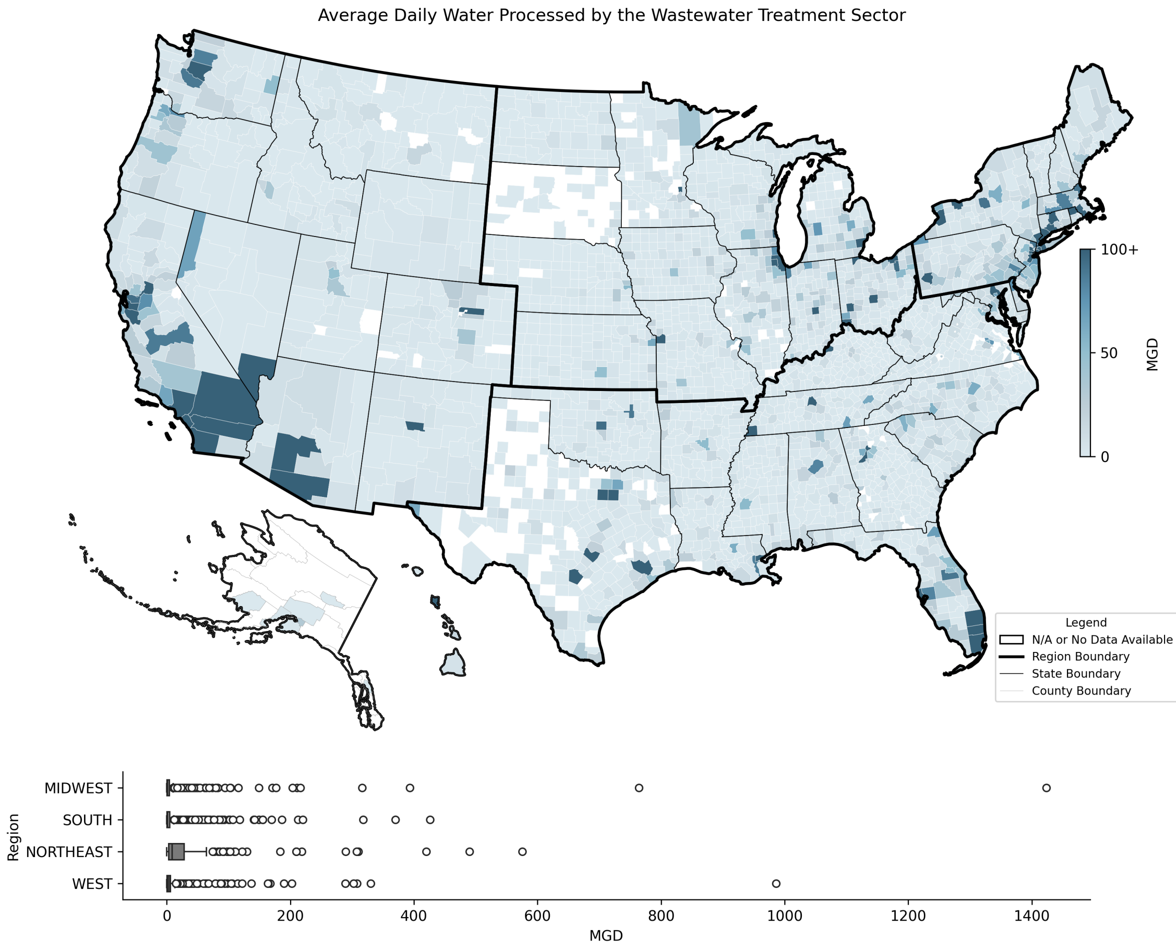

Figure 2.43 Map of Daily Average Water Processed (MGD) by the Wastewater Treatment Sector by County

On a regional level, the Northeast region has the highest median water processed by the wastewater treatment sector across all regions, though the Midwest region contains the largest outlier counties. The top three states are California (3,475 MGD), New York (2,815 MGD), and Illinois (2,215 MGD). Cook County, Illinois (1,423 MGD); Los Angeles County, California (986 MGD); and Wayne County, Michigan (764 MGD) have the highest amount of water processed on a daily basis by their wastewater treatment sectors.

Figure 2.44 shows the daily average water processed by the wastewater treatment sector by source (municipal deliveries or infiltration) in each region. Nearly all water that is processed by wastewater treatment facilities in the United States is from municipal sources (i.e., residential, commercial, and industrial wastewater) (32,471 MGD). Comparatively little is from infiltration (805 MGD). The South has the highest daily water processed by wastewater treatment, followed closely behind by the Midwest. The Northeast region has both the highest quantity of infiltration inflows and the highest ratio of infiltration flows compared to its municipal and industrial deliveries in its wastewater treatment system. This indicates that efforts to improve pipeline infrastructure in this region may be particularly beneficial from both a water process perspective as well as an energy demand perspective.

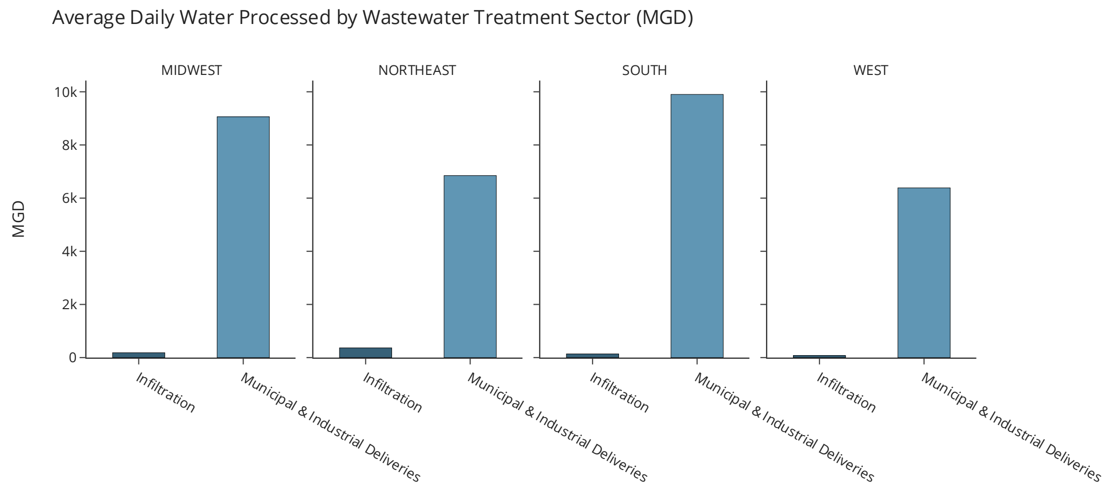

Figure 2.44 Daily Average Water Processed (MGD) by the Wastewater Treatment Sector by Water Source

2.9.2 Energy in the Wastewater Treatment Sector

Energy demand by the wastewater treatment sector is determined by the level of water treatment applied (primary, secondary, or advanced). Due to data availability limitations, it is assumed that all energy used in the public water supply sector comes from electricity. Figure 2.45 shows a map of daily average energy demand (BBTU) of the wastewater treatment sector by county.

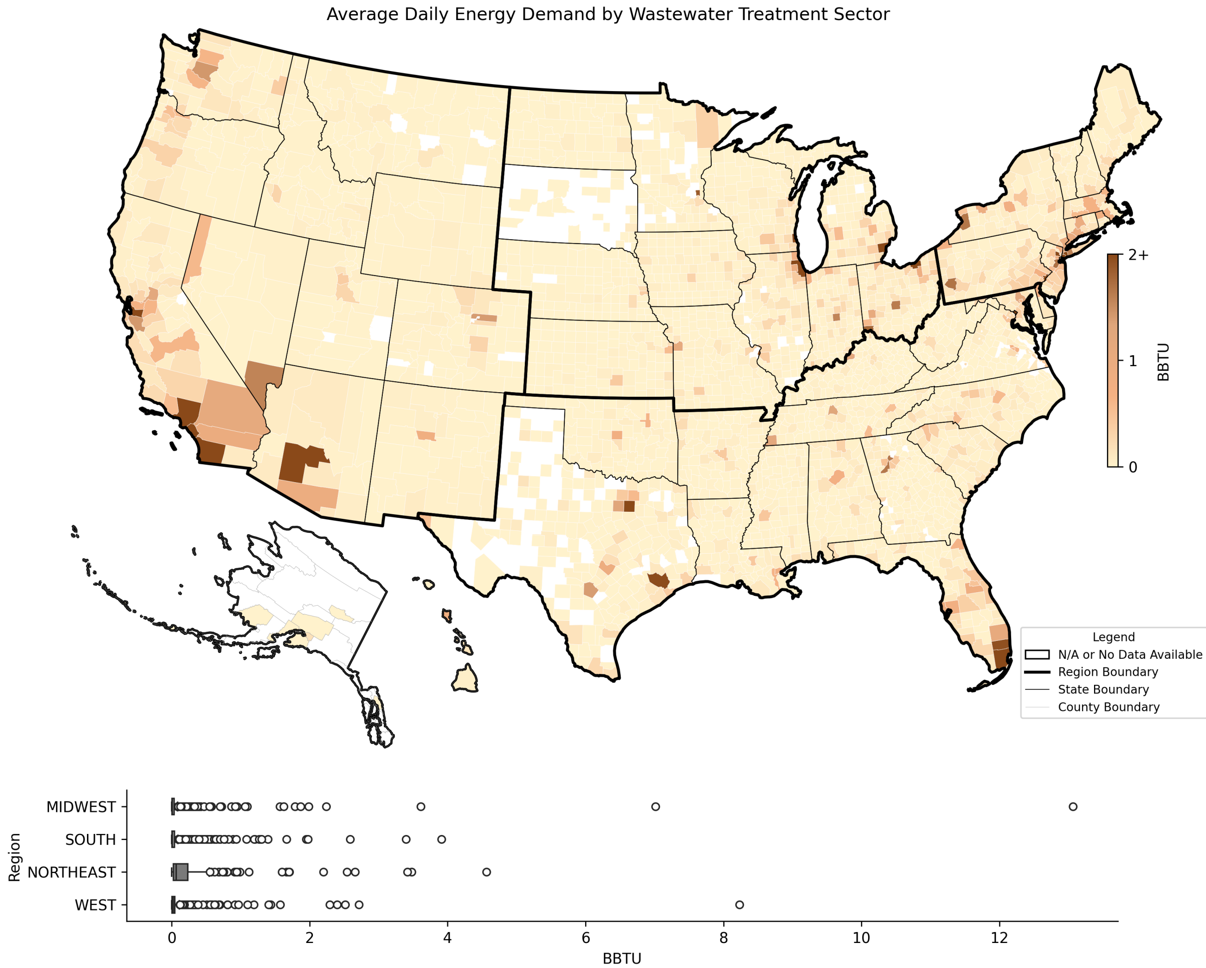

Figure 2.45 Map of Daily Average Energy Demand (BBTU) of the Wastewater Treatment Sector by County

The states with the highest energy use in wastewater treatment are California (27 BBTU), New York (23 BBTU), and Illinois (20 BBTU). Since energy demand in wastewater treatment is directly correlated with the total water treated, it is unsurprising that the same counties that have the highest amount of water treated also have the highest energy demand in wastewater treatment: Cook County, Illinois (13 BBTU); Los Angeles County, California (8 BBTU); and Wayne County, Michigan (7 BBTU).

Figure 2.46 shows a diagram of daily average energy demand (BBTU) of the wastewater treatment sector by treatment type. There are three treatment types included in this analysis: primary, secondary, and advanced. Primary treatment is the least intensive treatment type and predominantly consists of solid waste removal. Secondary treatment is more intensive and involves purification processes such as biofiltration, aeration, and oxidation ponds. Advanced (also referred to as tertiary) involves removing phosphates and nitrates from the water supply (Organica 2017). The Midwest and South regions both have very high proportions of advanced treatment in their wastewater sectors (U.S. EPA 2016). Given that this is the most energy-intensive of the three treatment types, there is a stronger vulnerability from electricity supply disruptions in these regions in particular.

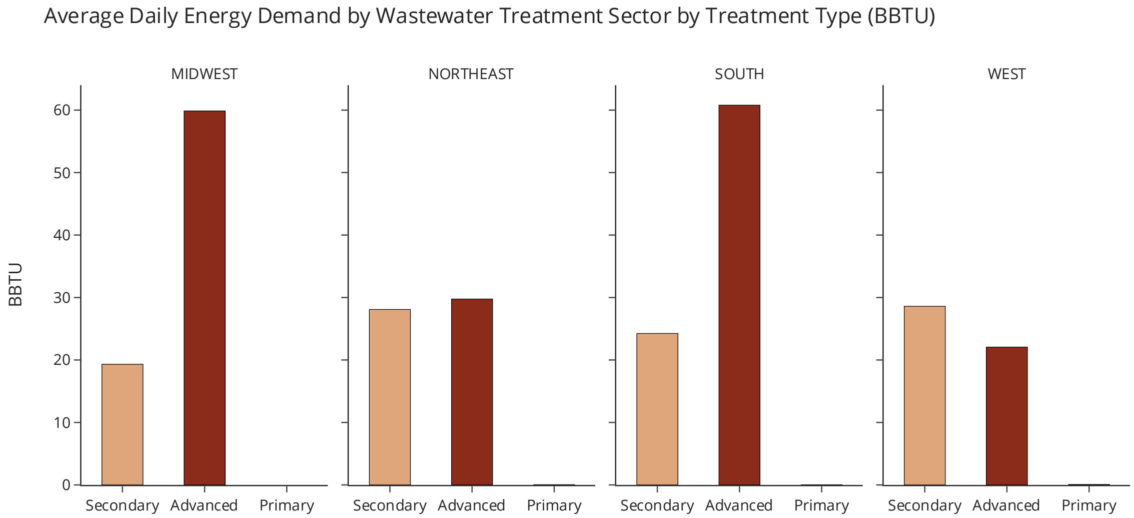

Figure 2.46 Daily Average Energy Demand (BBTU) by the Wastewater Treatment Sector by Treatment Type

2.9.3 Energy Intensity of Water Processing in the Wastewater Treatment Sector

Figure 2.47 shows a map of daily average energy intensity (BBTU per MG of water processed) of the wastewater treatment sector by county. The top three counties are Surry County, Virginia; Winston County, Alabama; and San Juan County, Colorado, which each have intensities of 0.01 BBTU/MG. Note that for the state of South Carolina, wastewater treatment facility level data was not available. Therefore, county level water estimates for this state were determined from estimates of county level discharges to wastewater treatment by the residential, commercial, and industrial sectors. County level energy estimates were determined through an average energy intensity metric since no information was available on the various types of treatment plants and water treatment quantities. As a result, the energy intensity estimates for South Carolina are equivalent across all counties.

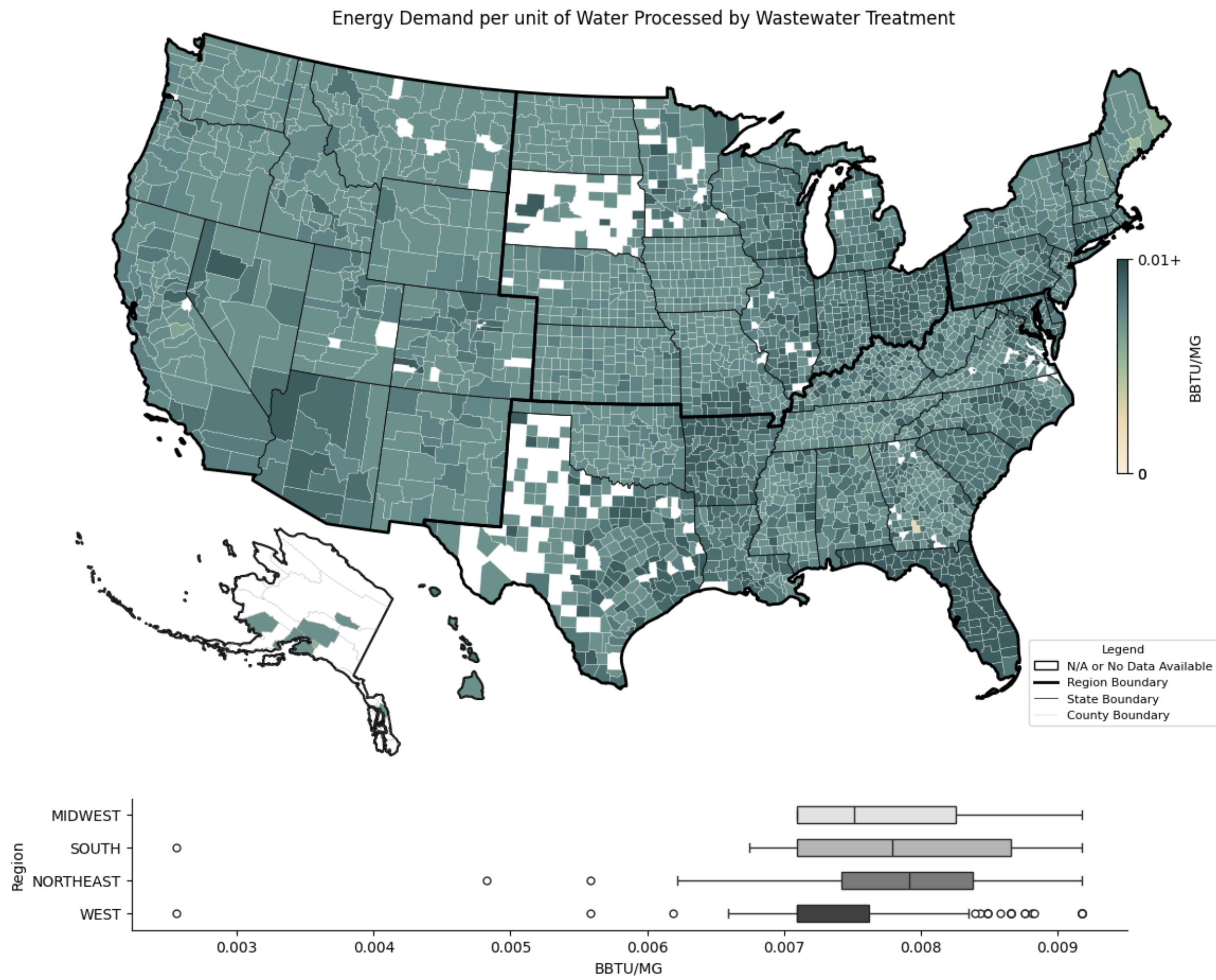

Figure 2.47 Map of Daily Average Energy Intensity (BBTU per MG of Water Processed) of the Wastewater Treatment Sector by County

Figure 2.48 shows the energy intensity of wastewater treatment by treatment type. Advanced treatment has the highest intensity (0.0091 BBTU/MG), followed by secondary (0.0070 BBTU/MG), and primary (0.0025 BBTU/MG) (Pabi et al. 2013). Note that, given available data at the time of collection, the energy intensity is assumed to be the same across all regions by type.

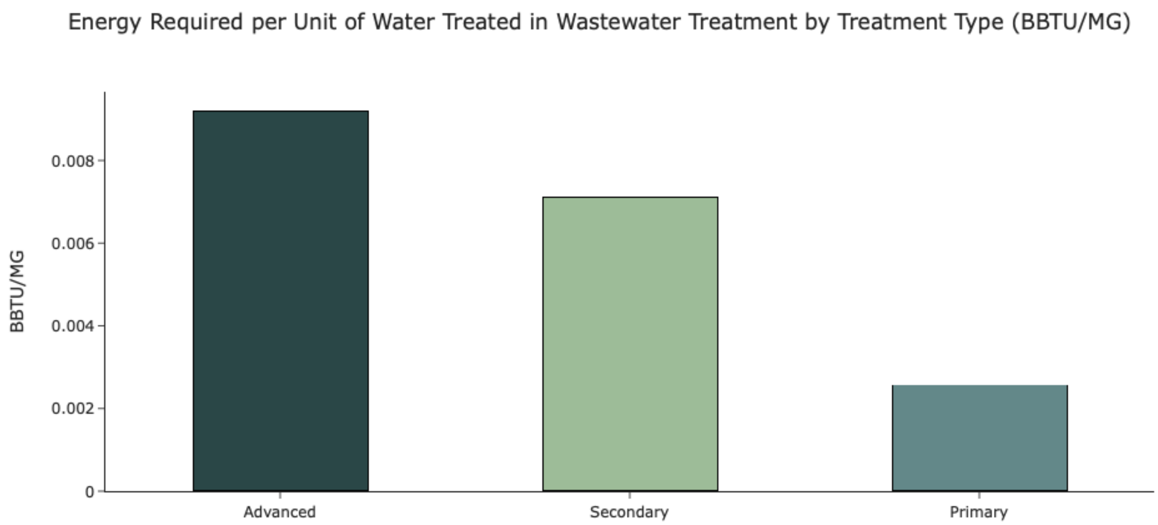

Figure 2.48 Energy Intensity (BBTU required per MG of Water Processed) of Wastewater Treatment by Treatment Type

3.0 Additional Comparisons

3.1 Energy and Water Across all Sectors

3.1.1 Water Across all Sectors

Figure 3.1 shows total water withdrawals (from both surface and groundwater sources) across all sectors in each county, not including water used in hydropower generation. The total value in each county includes water withdrawals for thermoelectric generation, mining, agriculture, public water supply, and by the industrial and residential sectors.

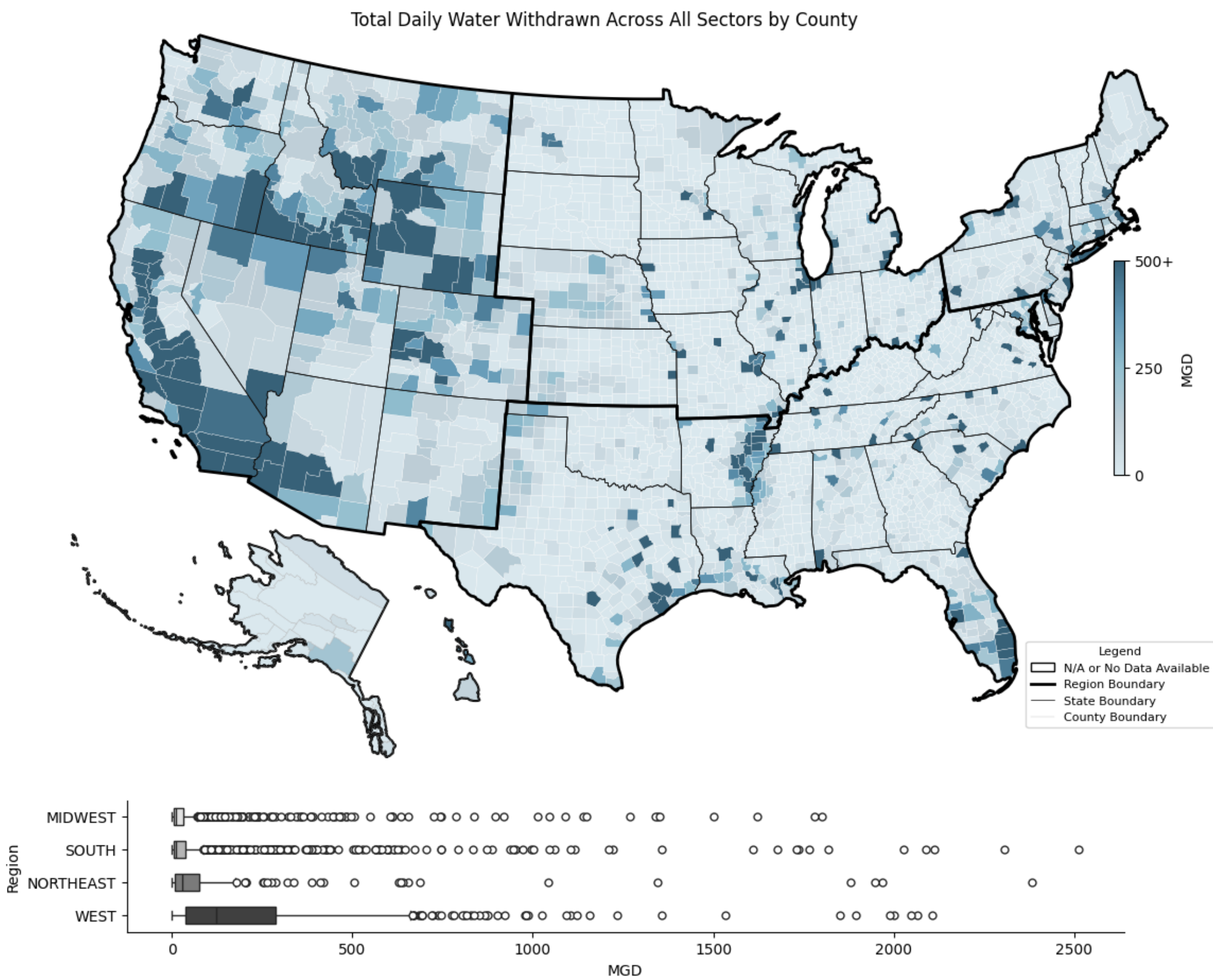

Figure 3.1 Total Daily Water Withdrawn (MGD) Across All Sectors by County

The West region has the highest median water withdrawals across all regions, predominantly due to agriculture water use. On a county level, Limestone County, Alabama (2,513 MGD); York County, Pennsylvania (2,382 MGD); and Oconee County, South Carolina (2,308 MGD), in the South and Northeast regions, withdraw the most water daily, driven by thermoelectric cooling.

Figure 3.2 shows a bar chart of total water withdrawals by sector and region. Note that water use for hydropower generation is not included in electricity generation water withdrawals.

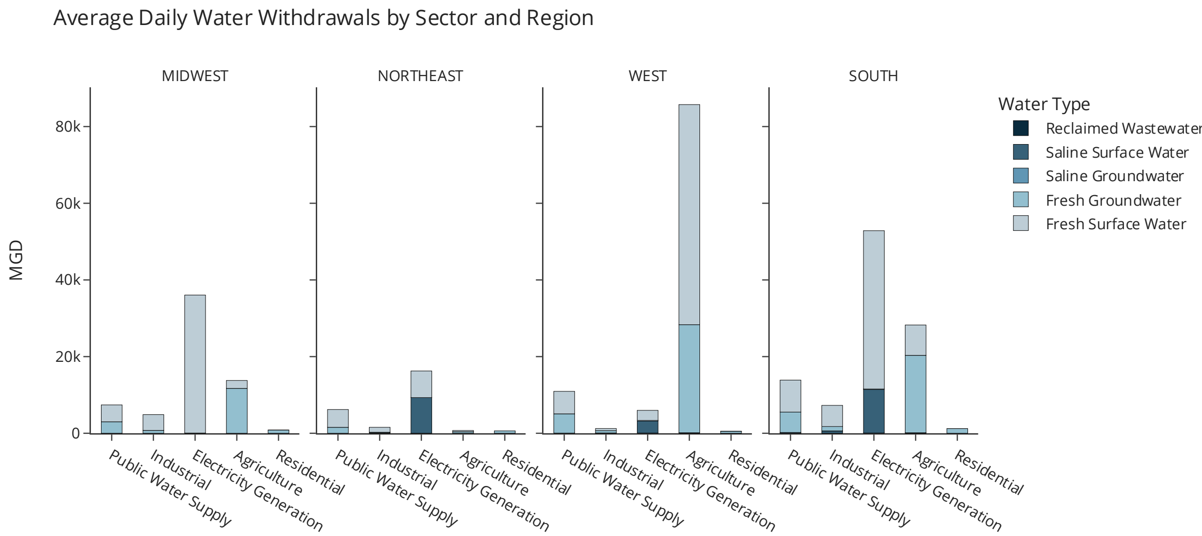

Figure 3.2 Average Daily Water Withdrawals by Sector and Region, Excluding Hydropower Water Use

Figure 3.2 demonstrates how important water supply for the agriculture sector is in the West region. The water demand, almost entirely driven by crop irrigation, far outpaces other sector water use and is mostly made up of fresh surface water supplies. In contrast, looking at the South region, agriculture withdraws approximately half the water of the electricity generation daily. The same pattern holds for the Midwest region and in the Northeast region, agriculture is the second lowest water demand, just ahead of the residential sector. From this plot, we can see how different vulnerabilities to supply disruptions differ across regions. The Midwest region, for example, relies on groundwater supplies for their agriculture sector. Under decreased groundwater supply, there may be increased competition for surface water supply with the electricity generation sector.

3.1.2 Energy Across all Sectors

Figure 3.3 shows total daily energy demand across all sectors by county. Total energy demand includes all electricity and energy use by the electricity generation, transportation, residential, commercial, industrial, agricultural, wastewater treatment, and public water supply sectors.

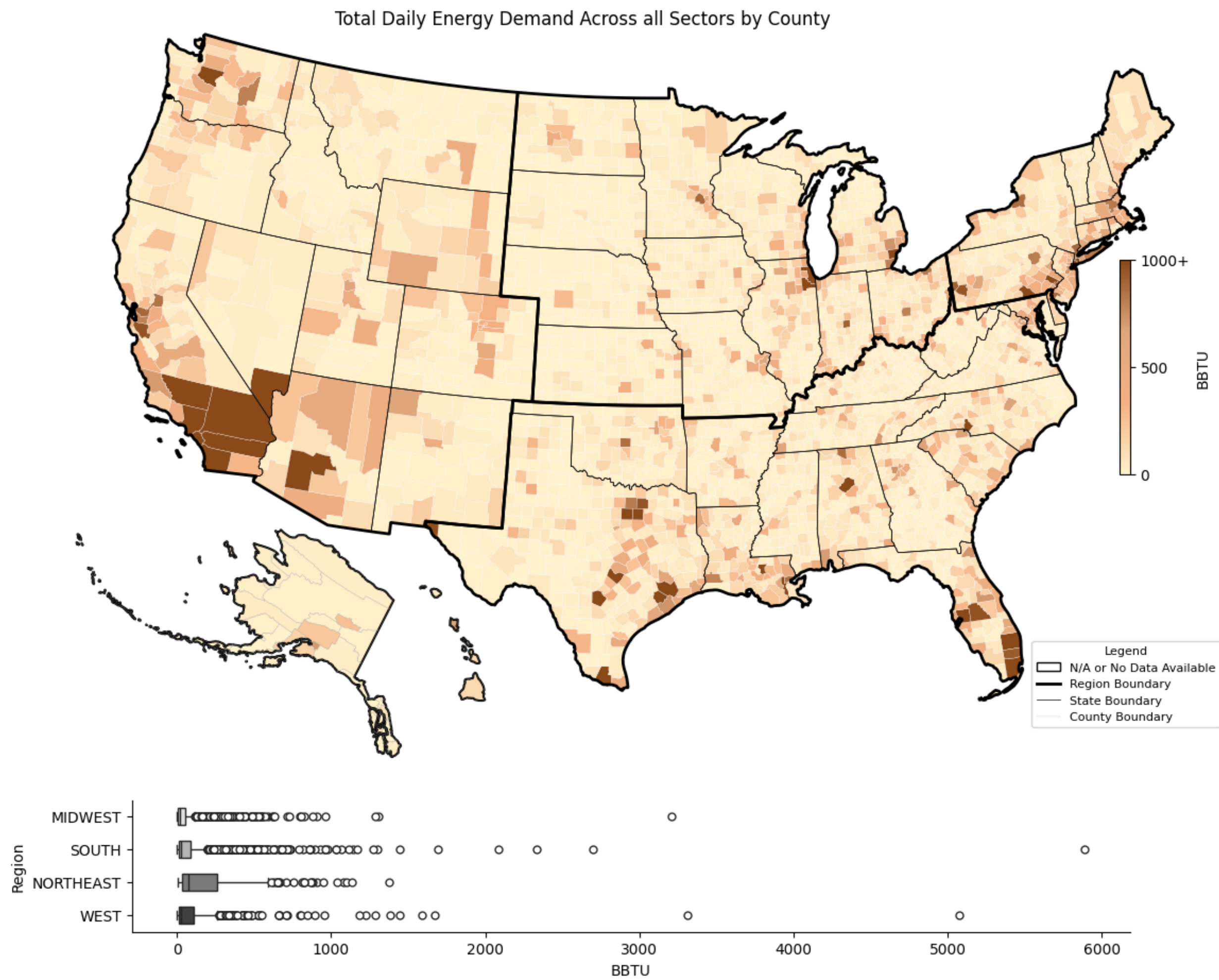

Figure 3.3 Total Daily Energy Demand (BBTU) Across all Sectors

While regionally we can see that the median energy demand is comparative for the Midwest, South, and West regions, individual counties differ substantially. Harris County, Texas (5,888 BBTU); Los Angeles County, California (5,076 BBTU); and Maricopa County, Arizona (3,311 BBTU) have the highest daily energy demand across all sectors.

Figure 3.4 shows the average daily energy demand across sectors and region. Demand includes direct fuels and energy (e.g., natural gas) and electricity demand. From this plot, we can see how the electricity generation sector, the transportation sector, and the industrial sector are the three largest energy users across almost all regions. In the Northeast region, however, the residential and commercial sector both have higher energy demands than the industrial sector, breaking the pattern. Agriculture, public water supply, and the wastewater treatment sector have comparatively little energy demand to other sectors.

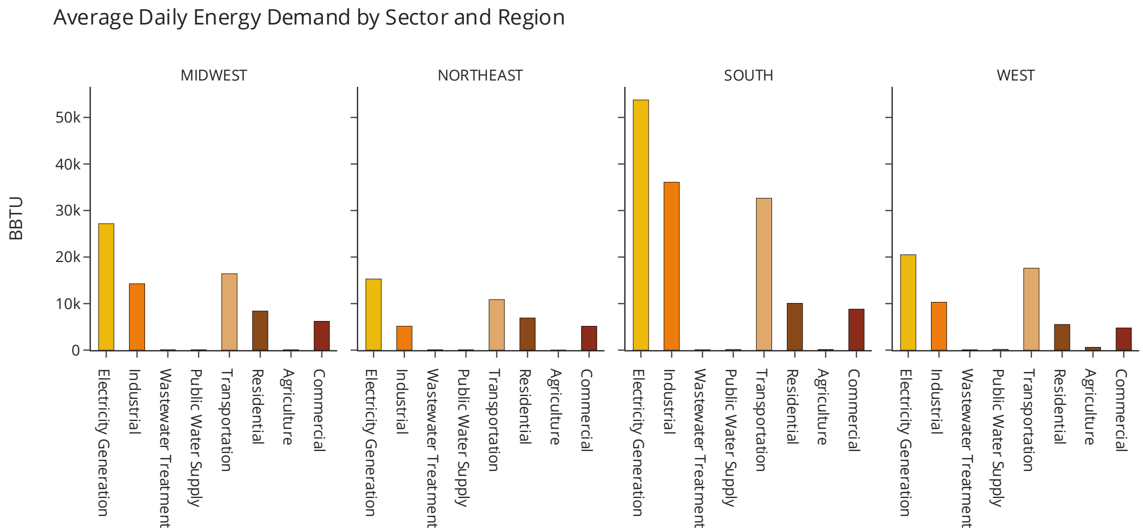

Figure 3.4 Average Daily Energy Demand (BBTU) by Sector and Region

3.2 Water Sector Aggregates

3.2.1 Water Withdrawn and Processed by Water Sectors

Figure 3.5 shows the average daily water withdrawn or processed by the agriculture, public water supply, and wastewater treatment sectors in total. This includes surface and groundwater withdrawals for crop irrigation, golf irrigation, aquaculture, livestock, public water supply, and water processed by wastewater facilities. This map shows water withdrawals by water sectors occur mostly in the West region, with a few other areas of high value in the South region.

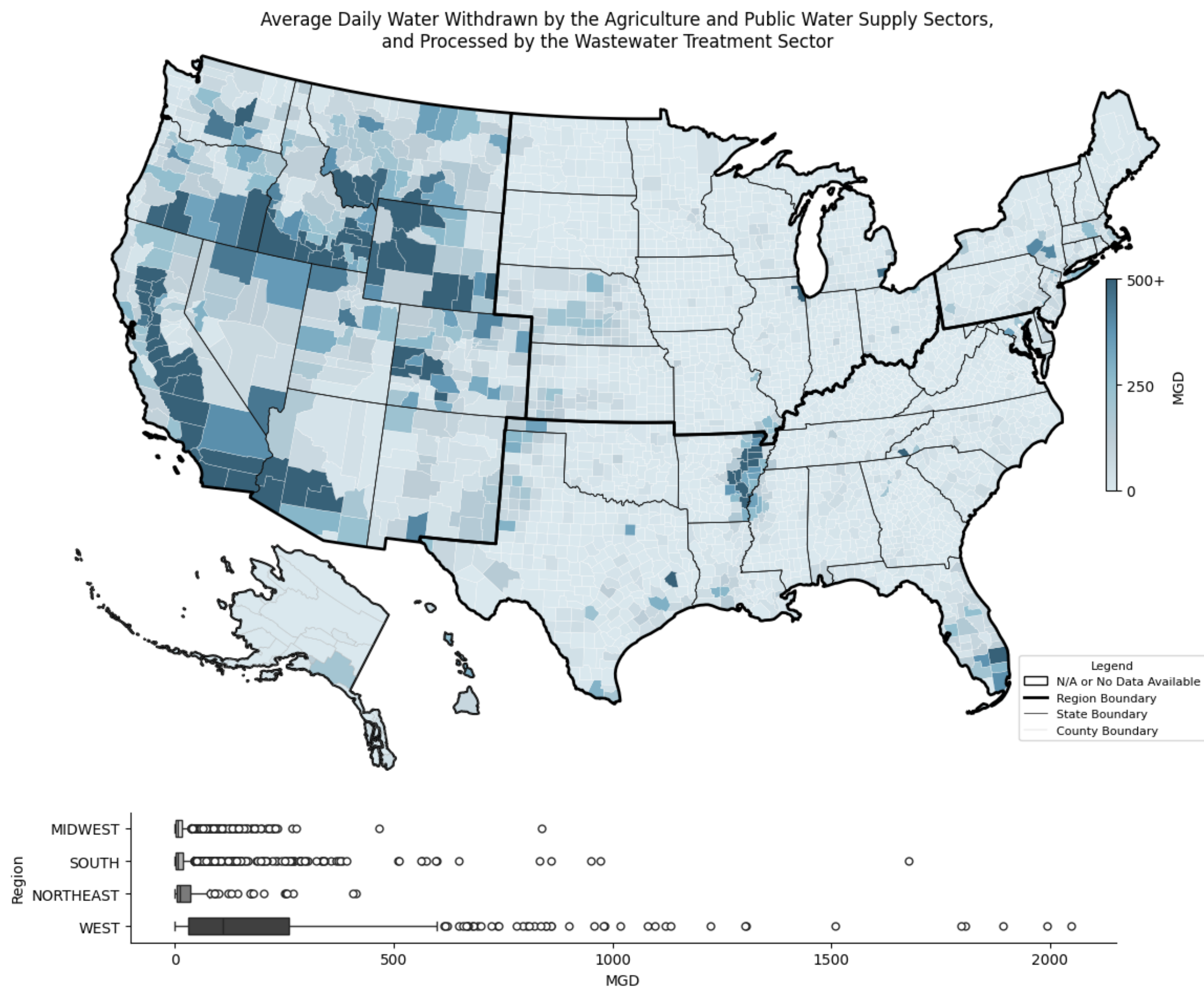

Figure 3.5 Average Daily Water Withdrawn or Processed (MGD) by the Agriculture, Public Water Supply, and Wastewater Treatment Sectors in Aggregate

Figure 3.6 shows the average daily water withdrawn or processed by each of the water sectors by region. Agriculture in the West has the highest daily water use of any water sector and region, followed by agriculture in the South. Water sectors in the Midwest and Northeast have low daily water use, and they are relatively comparable across sectors.

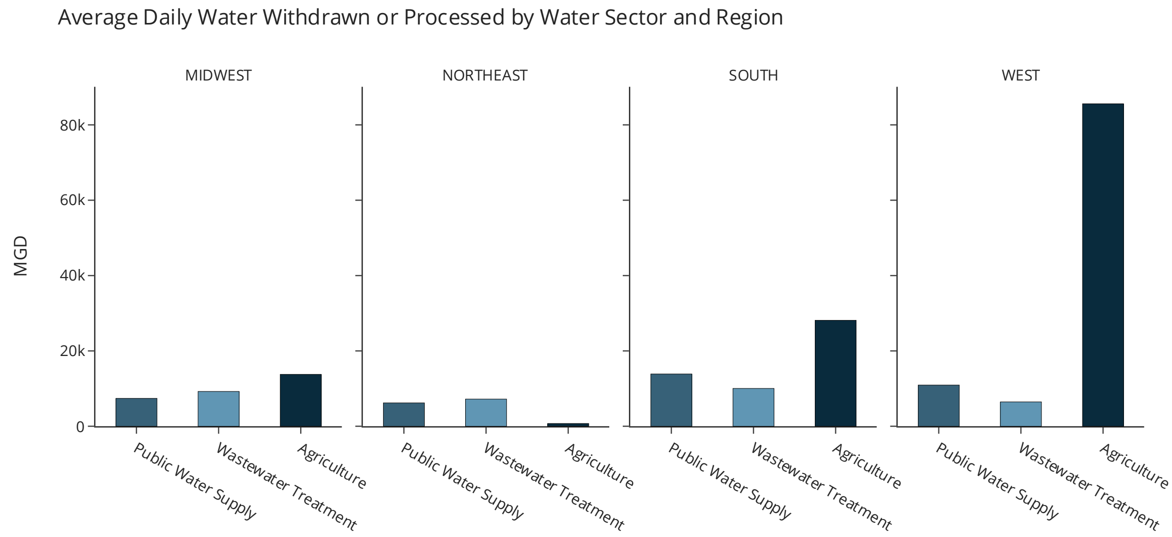

Figure 3.6 Average Daily Water Withdrawn or Processed (MGD) by Water Sector and Region

3.2.2 Energy Demand by Water Sectors

Figure 3.7 shows the average daily energy demand by the agriculture, public water supply, and wastewater treatment in aggregate. The results shown in this plot demonstrate that, much like the water demand for these sectors, the West region has consistently higher values than other regions.

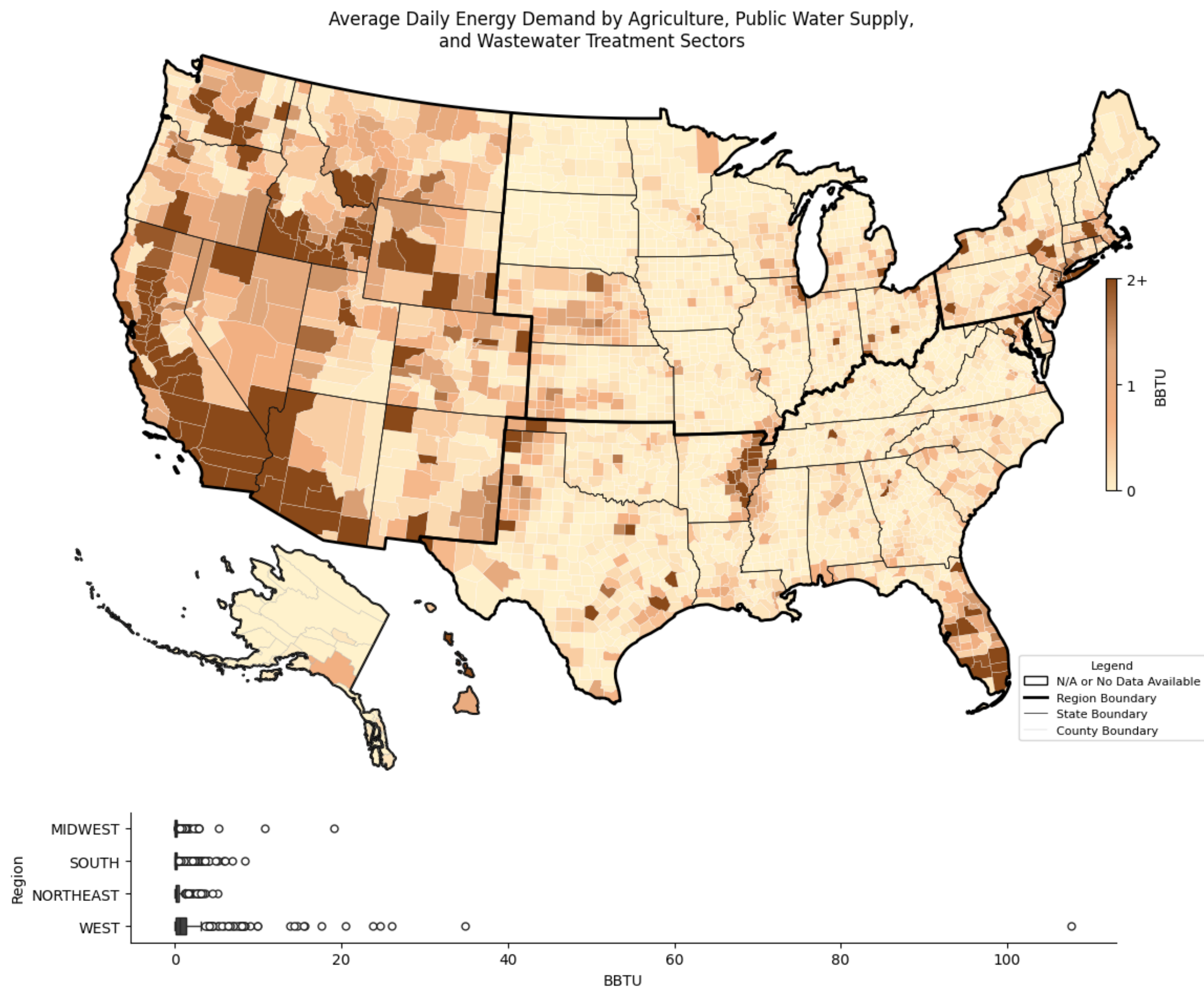

Figure 3.7 Average Daily Energy Demand (BBTU) by the Agriculture, Public Water Supply, and Wastewater Treatment Sectors in Aggregate

Looking at the individual sector breakdown in energy demand shown Figure 3.8, we can see that most of the energy demand across water sectors is due to pumping water in agriculture. The United States requires nearly 815 BBTU of energy daily to supply water in agricultural services when both direct pumping and interbasin transfers are included. The public water supply is the second highest at approximately half that amount.

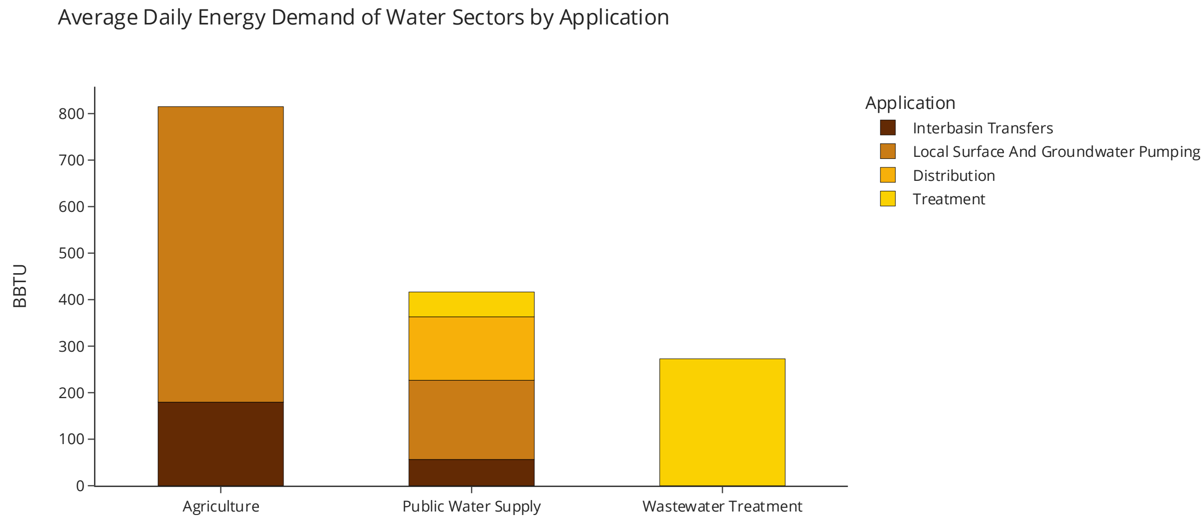

Figure 3.8 Average Daily Energy Demand (BBTU) of Agriculture, Public Water Supply, and Wastewater Treatment Sectors by Application Across the United States

Figure 3.9 shows the same information as Figure 3.8 but split up by region rather than sector. As shown by the figure, the energy demand of water sectors in the West is highest, mostly driven by agriculture. This plot also shows how large a role interbasin transfers play in water sector energy demand in the West region.

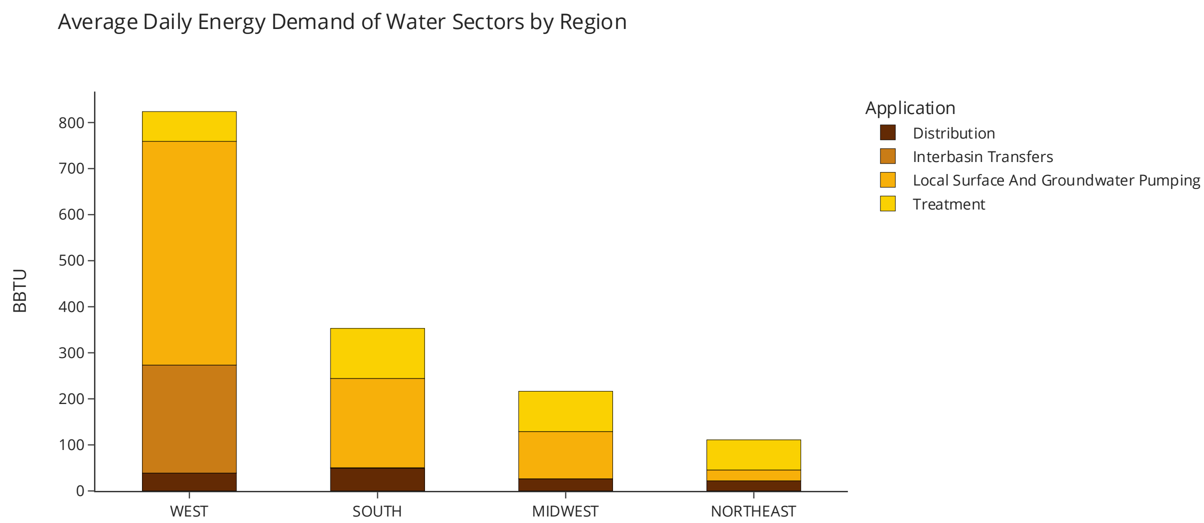

Figure 3.9 Average Daily Energy Demand (BBTU) of the Agriculture, Public Water Supply, and Wastewater Treatment Sectors by Region

3.3 Energy Sector Aggregates

3.3.1 Water Withdrawn by Energy Sectors

Figure 3.10 shows water withdrawals across energy sectors and can be considered the combined direct and indirect water use of thermoelectric electricity generation. This includes water withdrawals for thermoelectric cooling; water withdrawals for crop irrigation and refinement of corn products for ethanol fuel production; and water withdrawn for coal, natural gas, and petroleum mining. Most water across these sectors and subsectors is used in thermoelectric cooling, with very little used for ethanol production and mining. Note that the figure below does not include water used in hydroelectric generation, which is plotted separately in Figure 2.9.

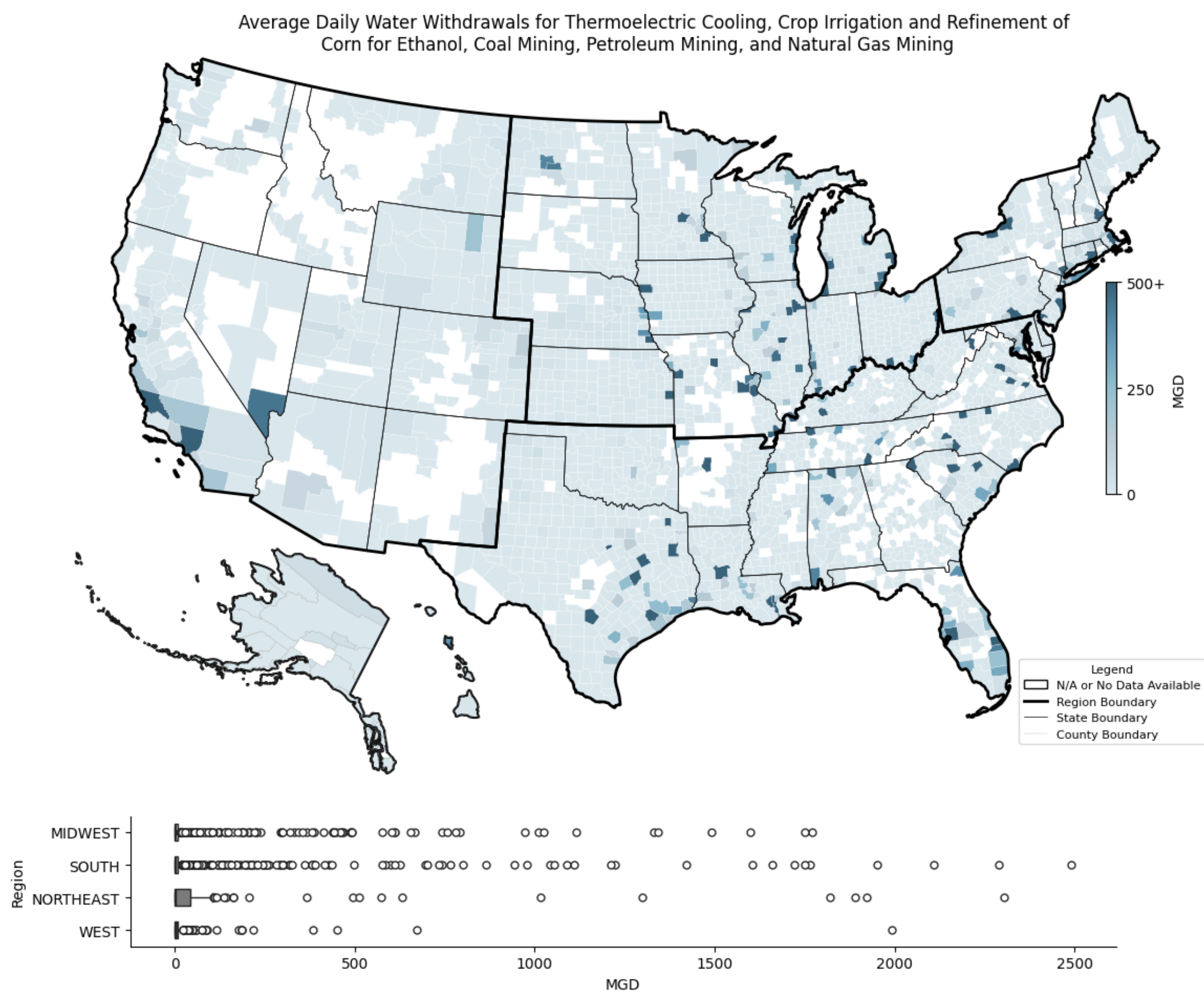

Figure 3.10 Average Daily Water Withdrawals (MGD) for Thermoelectric Cooling, Crop Irrigation and Refinement of Corn for Ethanol, Coal Mining, Petroleum Mining, and Natural Gas Mining Combined

Figure 3.11 shows the breakdown in water demand for thermoelectric generation resources by water application and region. This plot shows both direct and indirect water use of various generation technologies and demonstrates how almost all water used for thermoelectric generation is for thermoelectric cooling. However, when looking at biomass in the Midwest region, it is interesting to see how much more water is used in the production of corn for ethanol compared to biomass cooling in that region. Note that the water used in corn growth for ethanol in this figure represents any corn grown for ethanol in that region and not just the ethanol that is consumed in that region. The Midwest region is a large supplier of corn products, portions of which are exported to other portions of the United States to be used in biomass facilities.

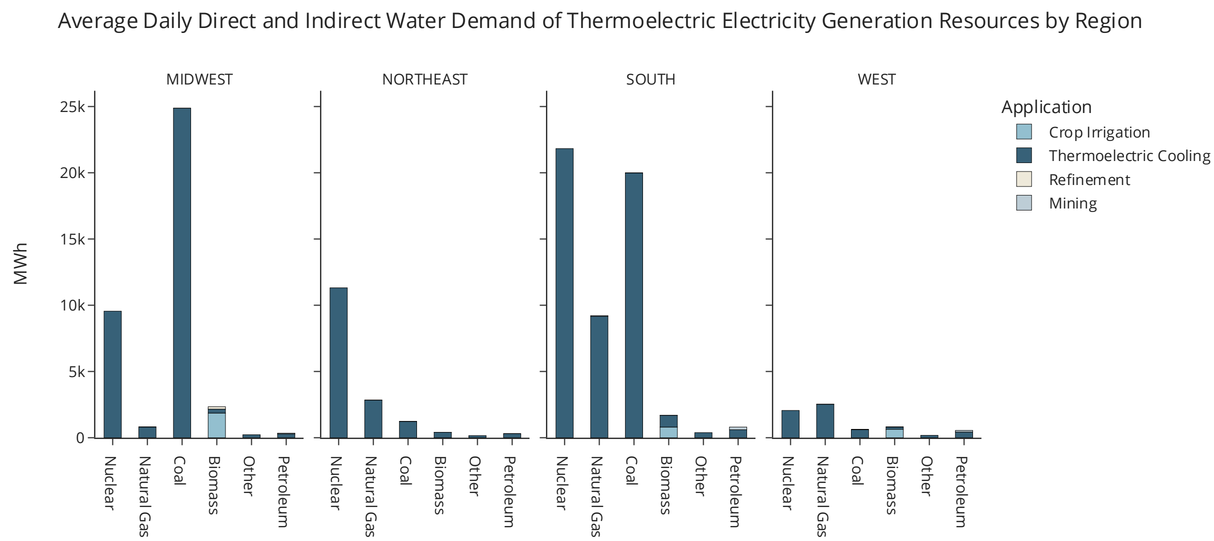

Figure 3.11 Average Daily Direct and Indirect Water Demand for Thermoelectric Cooling; Crop Irrigation and Refinement of Corn for Ethanol; and Mining of Petroleum, Natural Gas, and Coal

4.0 Conclusion

The Integrated Water Power Resilience Project strives to identify opportunities for enhancing resilience in both water and power sectors through synchronized planning, investment, and operations. Given the interdependence of water and power across economic sectors and their vulnerability to similar natural and human-made threats, both play a pivotal role in the well-being of communities and society. Opting for a joint approach to manage these sectors for resilience, rather than separately, offers substantial economic, social, and environmental benefits due to the interconnected nature of water and power systems. To support this initiative and future research in this domain, county level water and energy flow data were generated to analyze, compute, and visually represent the interconnections between various sectors in water and energy.

This report provided various visualizations of water and energy demand across nine different economic sectors, including:

1. Agriculture Sector
2. Commercial Sector
3. Electricity Generation Sector
4. Industrial Sector
5. Mining Sector
6. Public Water Supply Sector
7. Residential Sector
8. Transportation Sector
9. Wastewater Treatment Sector

From this sectoral analysis, we show that there are regional differences in water and energy demands and interdependencies and that these visualizations can provide high-level insights into upstream dependencies. We note a number of informative takeaways:

- The South and Midwest regions rely more heavily on water withdrawals for thermoelectric cooling compared to other regions. Consequently, heightened drought conditions in these regions could present significant challenges to thermoelectric resources, necessitating consideration in future grid planning endeavors. This observation, however, is dependent on the 2015 resource mix and cooling water practices in these regions. Efforts to shift away from high water intensity generation technologies could help to alleviate this vulnerability.
- Energy-intensive water activities in the West region, such as interbasin water transfers in agriculture and public water supply sectors, have the potential to influence the quantity, time, and location of electricity demand, adding more stress in the electricity grid. Considering this, generation and transmission capacity planning should incorporate insights from these downstream water sectors to ensure resource adequacy.

- The critical need for collaborative and integrated planning for water and energy in agricultural services in the West becomes increasingly evident under the backdrop of growing drought conditions. Policymaking efforts in the West that define planning and integration requirements can wield substantial influence in addressing these challenges.
- Electrification of transportation and industrial processes will have broad implications to mining and electric generation and associated water use. This transformation will need to be accounted for in planning considerations across sectors.

5.0 References

Dieter, Cheryl A., Molly A. Maupin, Rodney R. Caldwell, Melissa A. Harris, Tamara I. Ivahnenko, John K. Lovelace, Nancy L. Barber, and Kristin S. Linsey. 2018. *Estimated use of water in the United States in 2015.* (Reston, VA: U. S. Geological Survey). http://pubs.er.usgs.gov/publication/cir1441.

Hall, Douglas G., Shane J. Cherry, Kelly S. Reeves, Randy D. Lee, Gregory R. Carroll, Garold L. Sommers, and Kristine L. Verdin. 2004. *Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources.* Idaho National Laboratory (Idaho Falls, ID). https://www1.eere.energy.gov/water/pdfs/doewater-11111.pdf.

Mongird, Kendall, Jennie S. Rice, Konstantinos Oikonomou, and Juliet Homer. 2023. "Energy-water interdependencies across the three major United States electric grids: A multi-sectoral analysis." *Utilities Policy* 85: 101673. https://doi.org/10.1016/j.jup.2023.101673. https://www.sciencedirect.com/science/article/pii/S0957178723001856.

Organica. 2017. "Primary, Secondary, and Tertiary Wastewater Treatment: How Do They Work?" Accessed March 8. https://www.organicawater.com/primary-secondary-tertiary-wastewater-treatment-work/.

Pabi, S., L. Reekie, A. Amarnath, and R. Goldstein. 2013. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries.* Electric Power Research Institute (Palo Alto, CA, USA). https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/electricity_use_and_management_in_the_municipal_water_supply_and_wastewater_industries.pdf.

Siddik, Md Abu Bakar, Kerim E. Dickson, James Rising, Benjamin L. Ruddell, and Landon T. Marston. 2023. "Interbasin water transfers in the United States and Canada." *Scientific Data* 10 (1): 27. https://doi.org/10.1038/s41597-023-01935-4. https://doi.org/10.1038/s41597-023-01935-4.

Tennessee Valley Authority. 2024. "Browns Ferry Nuclear Plant." Accessed March 7. https://www.tva.com/energy/our-power-system/nuclear/browns-ferry-nuclear-plant.

Tidwell, Vincent C., Peter H. Kobos, Len Malczynski, Geoff Klise, William E. Hart, and Cesar Castillo. 2009. *Decision Support for Integrated Water-Energy Planning.* Sandia National Laboratories (Albuquerque, NM). https://www.osti.gov/servlets/purl/976952/.

U.S. Census Bureau American Community Survey Office. 2019. Census Regions and Divisions of the United States.

U.S. EIA. 2016. *Electric Power Annual 2015.* U.S., EIA (Washington D.C., USA). https://www.eia.gov/electricity/annual/archive/2015/pdf/epa.pdf.

---. 2021. *State Energy Data System (SEDS): 1960-2019 (complete).* U.S. EIA (Washington D.C., USA). https://www.eia.gov/state/seds/seds-data-complete.php?sid=US.

---. 2022. *Form EIA-923 detailed data with previous form data (EIA-906/920).* U.S. EIA (Washington D.C., USA). https://www.eia.gov/electricity/data/eia923/.

U.S. EPA. 2016. "Clean Watersheds Needs Survey 2012." U.S. EPA. Accessed Jan 12. https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2012-report-and-data#access.

US EIA. 2017. "Hydroelectric generators are among the United States' oldest power plants." Accessed March 25. https://www.eia.gov/todayinenergy/detail.php?id=30312.

---. 2024. "Commercial Sector." Accessed March 7. https://www.eia.gov/tools/glossary/index.php?id=Commercial%20sector.

Appendix A – Water and Energy Inflows and Outflows by Sector

This table documents water and energy inflows and outflows for each sector included in the analysis. This table is adapted from Mongird et al. (2023).

Table 1. Economic Sectors, Subsectors, Applications, and Their Potential Water and Energy Inflows and Outflows.

Sector	Subsectors	Applications/Types	Subtypes	Water inflows	Energy inflows
Mining	Coal mining	Underground		SW[1], GW[2], SGW[3]	N/A[4]
		Surface			
	Natural gas mining	Unconventional		SW, GW	
	Petroleum mining	Conventional		SW, GW	
		Unconventional			
	Other mining (non-energy)			SW, GW, SGW	
Electricity Generation	Biomass-fired generation	Combined cycle	OT[5], TW[6], CX[7]	SW	Biomass supply
		Steam	OT, TW, PD[8], CX	SW, GW, SSW, RC[9]	
		Combustion-turbine	TW, CX	SW	
		Internal combustion		SW, GW	
		Fuel cell	CX	SW	
	Coal-fired generation	Combined cycle	CX	SW	Coal supply
		Steam	OT, TW, PD, CX	SW, GW, SGW, SSW, RC	
	Natural gas-fired generation	Combined cycle	OT, TW, PD, CX	SW, GW, SGW, SSW, RC	Natural gas supply
		Steam			
		Combustion-turbine		SW, GW, SSW, RC	
		Fuel cell	CX	SW	
		Compressed air			
		Internal combustion	OT, TW, CX	SW, GW	
	Nuclear generation	Steam	OT, TW, PD, CX	SW, GW, SSW, RC	Nuclear fuel
	Petroleum-fired generation	Combined cycle	OT, TW, PD, CX	SW, GW, SGW, SSW, RC	Petroleum supply
		Combustion-turbine		SW, GW, SSW, RC	
		Internal combustion			
		Steam		SW, GW, SGW, SSW, RC	
		Other	CX	SW	
	Other generation	Combined cycle	TW, CX	SW, GW, SSW	Other resources/fuel
		Steam	OT, TW, PD, CX	SW, GW, SGW, SSW, RC	
		Combustion-turbine	CX	SW	

Sector	Subsectors	Applications/Types	Subtypes	Water inflows	Energy inflows
		Internal Combustion			
		Fuel cell			
		Other			
	Solar generation	Concentrating solar power		N/A	Solar resource
		Photovoltaic			
	Geothermal generation	Steam		N/A	Geothermal resource
		Binary-cycle			
	Hydroelectric generation	Instream		SW	Hydroelectric resource
	Wind generation			N/A	Wind resource
Agriculture	Crop irrigation	Corn irrigation for ethanol		SW, GW	Electricity, natural gas supply, petroleum supply
		Other crop irrigation			
	Golf irrigation			SW, GW, RC	Electricity
	Livestock			SW, GW	
	Aquaculture			SW, GW, SSW	
Public Water Supply		Pumping		SW, GW, SSW, SGW	Electricity
		Treatment			
		Distribution			
		Interbasin transfers			
Residential		End-use applications		Public water supply deliveries, SW, GW	Electricity, biomass supply, natural gas supply, petroleum supply, solar resource, geothermal resource
Commercial		End-use applications		Public water supply deliveries	Electricity, biomass supply, coal supply, natural gas supply, petroleum supply, wind resource, solar resource, geothermal resource
Industrial		Ethanol refinement		Public water supply deliveries, SW, GW, SSW, SGW	Electricity, biomass supply, coal supply, natural gas supply, petroleum supply, solar, wind resource
		Other industrial applications			
Transportation				N/A	Electricity, petroleum supply, natural gas supply, biomass supply
Wastewater Treatment	Municipal deliveries	Primary treatment		Residential sector, commercial sector, industrial sector	Electricity
		Secondary treatment			
		Advanced treatment			
	Infiltration	Primary treatment		Water infiltration	
		Secondary treatment			
		Advanced treatment			

[1] fresh surface water, [2] saline surface water, [3] saline groundwater, [4] not applicable, [5] once-through cooling, [6] tower cooling, [7] complex cooling, [8] pond cooling, [9] reclaimed water

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov