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Analytical methods and strategies for using the energy-water nexus to achieve cross-cutting efficiency gains

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Analytical methods and strategies for using the energy-water nexus to achieve cross-cutting efficiency gains

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Analytical methods and strategies for using the energy-water nexus to achieve cross-cutting efficiency gains

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Energy and water resources share an important interdependency. Large quantities of energy are required to move, purify, heat, and pressurize water, while large volumes of water are necessary to extract primary energy, refine fuels, and generate electricity. This relationship, commonly referred to as the energy-water nexus, can introduce vulnerabilities to energy and water services when insufficient access to either resource inhibits access to the other. It also creates areas of opportunity, since water conservation can lead to energy conservation and energy conservation can reduce water demand.

This dissertation analyzes both sides of the energy-water nexus by (1) quantifying the extent of the relationship between these two resources and (2) identifying strategies for synergistic conservation. It is organized into two prevailing themes: the energy consumed for water services and the water used in the power sector.

In Chapter 2, a national assessment of United States' energy consumption for water services is described. This assessment is the first to quantify energy embedded in water at the national scale with a methodology that differentiates consistently between primary and secondary uses of energy for water. The analysis indicates that

energy use in the residential, commercial, industrial, and power sectors for direct water and steam services was approximately 12.3±0.346 quadrillion BTU or 12.6% of 2010 annual primary energy consumption in the United States. Additional energy was used to generate steam for indirect process heating, space heating, and electricity generation.

Chapter 3 explores the potential energy and emissions reductions that might follow regional shifts in residential water heating technologies. Results suggest that the scale of energy and emissions benefits derived from shifts in water heating technologies depends on regional characteristics such as climate, electricity generation mix, water use trends, and population demographics. The largest opportunities for energy and emissions reductions through changes in water heating approaches are in locations with CO_2-intensive electricity mixes; however, these are generally areas that are least likely to shift toward more environmentally advantageous devices.

In Chapter 4, water withdrawal and consumption rates for 310 electric generation units in Texas are incorporated into a unit commitment and dispatch model (UC&D) of ERCOT to simulate water use at the grid scale for a baseline 2011 case. Then, the potential for water conservation in the power generation sector is explored. Results suggest that the power sector might be a viable target for cost-effective reductions in water withdrawals, but reductions in water consumption are more difficult and more expensive to target.

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Chapter 1

Introduction

1.1 Purpose and Motivation

Energy and water are vital to economic security and general well-being. Together they enable an ample food supply, safe drinking water, electricity production, and other elements of a high quality of life. They are also interrelated: energy is required to pump, treat, pressurize, and heat water, and water is critical to producing fuels and cooling power plants. Because of this relationship, there are cross-sectoral impacts, both good and bad.

The energy-water relationship can be constraining. Without enough energy, access to potable water and proper sanitation is hindered. Billions of people lack access to these basic services, partly due to the lack of high-quality energy infrastructure. With insufficient water, thermoelectric power plants cannot be adequately cooled, which can lead to devastating blackouts during times when power generation is critical. Hydroelectric facilities that require water to push turbines cannot operate at full capacity. Fuels that require water for mining, extraction, refining, and transportation are also vulnerable to disruption.

The energy-water interdependency can also be leveraged as an opportunity for simultaneous conservation of both resources. Reducing the amount of water for the public supply decreases the amount of energy required to treat, pump, distribute, prepare, and reclaim water. This opportunity is especially pronounced for water supplies that require high energy processes such as desalination, interbasin transfers via long pipelines, and thermal energy for heating. In these examples, saving water saves energy. Likewise, reducing energy consumption can curb water demand. Curtailing electricity use lessens the water withdrawn or consumed for power generation. Moderating demand for fuels that require water for cultivation (in the case of biomass and biofuels), extraction, processing, and transportation also saves water. This dissertation focuses on these opportunities to conserve both resources and reduce vulnerability to disruptions in water and power availability when either resource restricts access to the other.

The overall objective of this work is to assess the scale of synergistic conservation strategies that achieve cross-cutting energy and water savings in the United States (US). Although the relationship between these resources is well-acknowledged in the literature, systems-scale analyses quantifying the potential for (1) energy savings in the water sector and (2) water savings in the energy sector are limited. Accordingly, this dissertation explores each of these interdependencies to identify and quantify opportunities for more efficient resource use.

This dissertation has four major goals, which include:

1. Quantifying the energy consumed for water in the US,

2. Determining effective modes of energy conservation through regional changes to residential water heating technologies,

3. Calibrating a unit commitment and dispatch (UC&D) model to simulate 2011 power generation, generation costs, water consumption, and water withdrawals for electricity production in the Electric Reliability Council of Texas (ERCOT), and

4. Utilizing the UC&D model to assess the role of water prices in reducing water use across ERCOT.

The first two goals address the energy required for water services. Accounting is performed at the national level to remain consistent with governmental energy reporting. These goals were achieved using various analytical tools including *ab initio* methods of energy and water accounting, thermodynamic assessments, regression techniques, and spatial analysis. The third and fourth goals address the water required to produce electricity (and omit the consideration of water impacts for primary fuel production). These objectives address water use at the grid-scale. ERCOT, which manages electric power for 23 million Texas customers and represents 85% of the state's electric load, is modeled through a series of UC&D models that incorporate linear, mixed integer and quadratic optimization to simulate grid operation.

1.2 Scope and Organization

This dissertation is split into two sections: the first focuses on energy for water, the second on water for electric power. Each section had two major objectives: (1) quantifying the relevant magnitude of the energy-water nexus relationship at the scale of interest and (2) analyzing potential conservation schemes to reduce resource consumption.

Three substantive research chapters explore the four goals described above. Each chapter is organized with an introduction followed by a thorough review of the literature, methodology, results, and discussion.

Chapters 2 and 3 explore the energy consumed for water services. Chapter 2 performs a national assessment of energy for water utilizing top-down sectoral assessments of energy consumption in combination with bottom-up allocations of energy for water on component-wise and service-specific levels. Chapter 3 explores potential reductions in the energy consumed for water through changes to regional water heating technologies.

Chapter 4 assesses water conservation through changes implemented in the power sector. It begins by describing the calibration and use of a UC&D model to simulate a 2011 baseline scenario that quantifies generation, cost, and water use at the electricity generation unit specific level. The model is then modified to consider eight additional scenarios that evaluate the effect of imposing higher water prices for water withdrawn and consumed for power generation in ERCOT.

Finally, Chapter 5 summarizes the outcomes of this work and suggests directions of future research. Overall, this dissertation explores the extent of the energy-water interdependency for the aspects that were examined. Results confirm that fruitful opportunities remain for cross-cutting efficiency gains in energy and water systems.

Chapter 2

Quantifying US Energy Consumption for Water Services

2.1 Introduction

The relationship between energy and water, commonly referred to as the energy-water nexus, has received increasing attention in recent years in light of growing water and energy resource demand in the US. The US water system is comprised of many stages of collection, treatment, conveyance, distribution, end use preparation, reconditioning, and release, each of which has important energy implications. National water-related energy use is expected to increase as water-stressed states such as Texas, Florida, Arizona, and California shift towards more energy intensive technologies such as desalination plants and interbasin water pipelines to address current and future water-scarcity concerns. Although these shifts toward more energy intensive water are likely to have an appreciable impact on future energy demand, very little analysis has been done to quantify water-related energy use at the national level to establish a benchmark for today's conditions. Thus, there is a knowledge gap about the energy requirements of the water system. This chapter serves to fill that gap by quantifying a baseline estimate of 2010 water-related energy use in the US.

2.2 Background

The United States Geological Survey (USGS) estimates that total US water withdrawals in 2005 were approximately 410 billion gallons per day. Of this amount, 349 billion gallons per day were freshwater. Water is allocated to several categories of users that either collect water for their own internal uses ("self-supplied users") or draw their water from the public water supply. Table 2.1 organizes 2005 water withdrawals reported by the USGS into four categories that are consistent with the end use sectors defined by the Energy Information Administration (EIA). (These end use sectors include residential, commercial, industrial, and power, which deviate slightly from USGS's standard reporting notation.) The vast majority (89%) of water withdrawals were by self-supplied users, divided among the sectors as listed in Table 2.1. The public supply only accounted for 11% of 2005 water withdrawals by volume (Kenny et al., 2005).

Table 2.1: The US withdrew 410 billion gallons of water per day in 2005. Freshwater withdrawals represent 85% of total water withdrawals (Kenny et al., 2005).

Sector	**Description**	**Withdrawals (Million gallons per day)**	**Percentage**
Residential	Self-supplied	3,830	0.9%
	Public supply	25,636	6.3%
Commercial	Self-supplied	Not Reported	–
	Public supply	14,144	3.4%
Industrial	Self-supplied (non-irrigation)	33,140	8.1%
	Self-supplied (irrigation)	128,000	31.2%
	Public supply	4,420	1.1%
Power	Self-supplied	201,000	49.0%
	Public supply	Not Reported	–
Total	All withdrawals	410,170	100%

The energy intensity of a volume of water is influenced by factors such as source water quality, proximity to a water treatment facility and end use, intended end use and sanitation level, as well as conveyance to and treatment at a wastewater treatment facility. The energy intensity of a given water treatment technology correlates to the size, concentration, and nature of the contaminant to be removed. As source water becomes more degraded, more energy intensive water treatments are required to remove contaminants. Furthermore, water requiring a high end use quality typically requires more energy for treatment than water requiring a lesser end use quality. Since these requirements differ by geographic location, climate, season, and local water quality standards, the energy consumption of regional water systems vary significantly.

While public water supply withdrawals are considerably smaller than those of the thermoelectric power and irrigation sectors, these withdrawals typically have higher energy requirements per unit volume because this water must be treated to the potable drinking water standard specified by the US Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA). Water delivered in the public water supply is also typically pumped longer distances, since self-supplied industrial and agricultural users generally draw water in close proximity to where it will be used (EPA, 2013b; Roberson, 2011). Providing water at this quality and at these volumes requires significant amounts of energy to pump, treat, and distribute water to end users, who are likely to heat, chill, or pressurize this water to suit their needs on-site. After water is used, much of it is collected and sent to a wastewater treatment plant where it is reconditioned to a sufficient quality that it can be released back into a water reservoir. In some cases, water is recycled or reclaimed, that is, it is treated to an acceptable standard for use in non-potable applications (e.g. agricultural and landscape irrigation, groundwater recharge, industrial cooling/process water, toilet flushing, etc.). Depending on the circumstances, reclaimed water might require tertiary treatment following standard wastewater treatment to be suitable for its intended end use. However, in many regions of the US, wastewater is treated to a standard acceptable for non-potable reuse and requires no treatment in addition to standard practice. Thus, most of the current energy expenditures for recycled water are for pumping water from the wastewater treatment facility, to its end user (Stillwell and Webber, 2010). However, the use of reclaimed water for potable reuse in the US is limited, comprising only 0.1% of the total volume municipal wastewater treated annually (NAS, 2012).

The US public water supply serves several different end uses that are highlighted in Table 2.1. Over half of the public supply (58%) is delivered to residential users, while 12% is delivered for use in the industrial sector (Kenny et al., 2005). (Three-quarters of the total water used in the industrial sector is self-supplied.) Of the remaining 30% of the public water supply, about half is delivered to commercial users and the other half is used in public locations, such as municipal buildings and recreation spaces, and for public services such as street washing, fire hydrants, and fire fighting. A small percentage of the public use category includes water that is "lost" or unaccounted for. The USGS includes water used for public services and leaks in the same category, since a significant volume of this water is unmetered, so there is no way to distinguish this water use from losses in water systems (Kenny et al., 2005). Consequently, the actual volume of water that is lost through leakages is not known since this category is determined by calculating the difference between water released into the distribution system and the volume of water delivered to billed customers. Some of this category might also include errors in water metering. Statewide public use and losses have been reported anywhere in the range of 3 to 41 percent of the total public supply (Templin, William E. and Herbert, Richard A. and Stainaker, Claire B. and Horn, Marilee and Solley, 2010). Since the EIA includes municipal, public, and recreational energy use in its commercial sector category, all water delivered to commercial, municipal, and public users is included in the "Commercial" category of Table 2.1.

Self-supplied water collected by power generators, irrigators, and industrial facilities is not required to meet the sanitation standards defined by the SDWA and is not typically treated to potable quality. (However, some industrial users such as producers of semi-conductors require water of extremely high standards to prevent equipment fouling (Williams, 2004).) Although less rigorous water treatment uses less energy, other aspects of water use often cancel out any energy savings. For example, self-supplied water users often use less-efficient pumps than public utilities (due to reduced scales of pumping (Goldstein and Smith, 2002)) and might also pressurize, heat, or cool water according to their intended end use. Many of these users are also required to treat their wastewater before discharging it to a reservoir to remain in compliance with the EPA's Clean Water Act (EPA, 2002). Chemical and refining industries often require primary, secondary, and tertiary treatments before water is of sufficient quality to discharge to public water treatment facilities or water reservoirs. Additionally, these industries must often strip wastewater with hot steam or gas streams to remove chemicals and oil from wastewater prior to primary wastewater treatment (Pellegrino et al., 2007).

Previous analyses have concluded that over 3% of national electricity consumption is used for the production, conveyance, and treatment of water and wastewater in the US and much more when considering the additional energy required for on-site heating, cooling, pumping, and softening of water for end use (Cohen et al., 2004; Goldstein and Smith, 2002). Most of the estimates made to date regarding the energy intensity of water are based on work done by the Electric Power Research Institute (EPRI) over the past few decades. In 2002, EPRI published a report regarding the electricity consumed for providing water and wastewater treatment in the US. The report estimates the average electricity-intensity of the water supply by considering the energy to supply, treat, and recondition wastewater effluent. Electricity data from

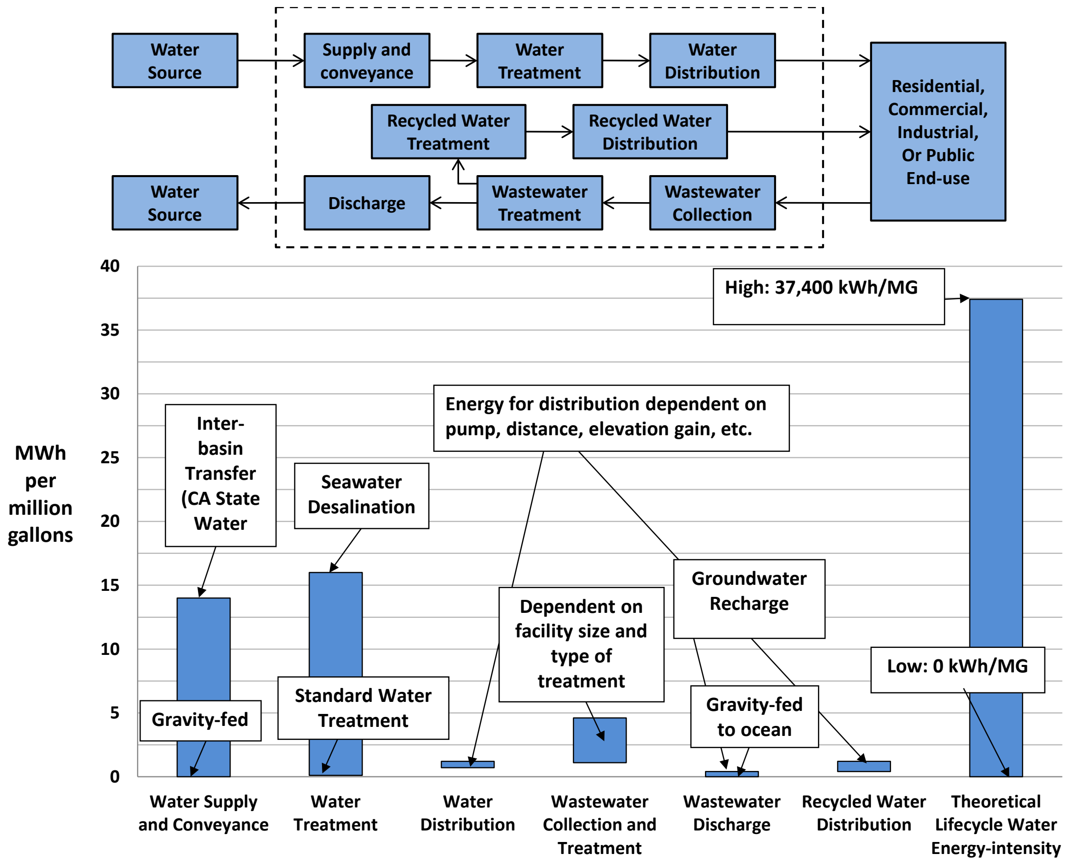

Figure 2.1: The energy intensity of each stage of the public water supply life-cycle varies according to regional topography, climate, and policy framework. The range in energy intensity of each stage included within the dotted region of the flowchart (top panel) is depicted in the bar graph (bottom panel). Water is not always discharged to the source that it was originally extracted from. (Data and flow-chart adapted from (Klein et al., 2005).)

public water supply agencies, publicly and privately owned wastewater facilities, and self-supplied sectors including domestic, commercial, industrial, mining, irrigation, livestock, and thermal power generating sectors were considered. The report does not, however, attempt to quantify the water-related energy needs of end use preparation such as heating, cooling, and pressurization (Goldstein and Smith, 2002).

A report released in 2009 by the River Network extends the 2002 EPRI analysis to quantify water-related energy for end use in the residential and commercial sectors, as well as the greenhouse gas emissions associated with this energy use (Griffiths-Sattenspiel and Wilson, 2009). While this report advances the state of understanding about water-related energy and carbon for all public and self-supplied water-users by including end use, its assumption that all end use consumption of energy for water is in the form of electricity fails to consider the likelihood of direct use of fuels on-site (for example, natural gas for water heating). Consequently, the assumptions for conversion efficiency are likely to yield an over-estimate for total energy consumption in context to the report's scope. The work in this chapter advances this prior work with more recent data, performing more detailed analysis at the component level, and refining the assumptions about conversion efficiencies at the power plant and in water heaters and treatment systems to account for direct and indirect uses of water.

While national studies have aggregated averages for the energy use and energy intensity of various stages of the US water system, these estimates do not capture the wide disparity between regional water systems. Several studies have been completed to estimate water-related energy use at the state level. California, a state that uses 19% of its electricity and 32% of its natural gas to withdraw, collect, convey, treat, distribute, and prepare water for end use, has been especially diligent in accounting its water-related energy use (Klein et al., 2005; Stokes and Horvath, 2009). While other states such as Massachusetts, Wisconsin, Iowa, and New York have also begun quantifying their water and wastewater utility energy consumption at the state-level, the data are sparse for most states (DOE, 2011).

Figure 2.1, adapted from a 2005 report from the California Energy Commission (CEC) (Sapudar et al., 2006), defines a range of energy intensities for each life-cycle stage included within the dotted boundaries of the flow diagram. These benchmarks are useful since several of California's public water supplies are among the most energy intensive in the world, while others require very little energy. Data reported by New York, Massachusetts, Wisconsin, and Iowa regarding the energy intensity of water supply segments fall well within the prescribed ranges defined in Figure 2.1 (DOE, 2011). The upper bound of each range represents an energy intensive scenario based on empirical data collected from Californian public water systems. High-energy scenarios usually include water systems that require extensive water pumping (e.g. the State Water Project and the Central Valley Project in California) and/or advanced water treatment. The lower bounds represent scenarios requiring very low energy inputs. Low-energy scenarios generally include situations in which gravity can be used to move water instead of pumping and/or raw water is of sufficient quality for its intended end use.

Considering the disparity across regional water systems, calculating water-related energy consumption in the US is not straight-forward, as it requires analysis with temporal and geographic fidelity. Furthermore, analysis is hindered by data gaps, the largest being outdated information on energy consumption by water and wastewater plants; incomplete data for water-related end uses, especially in non-residential sectors; and poor accounting for losses and leaks. The following manuscript will describe a first-order method of quantifying baseline water-related energy consumption in the US.

2.3 Methodology

This analysis builds on the work done by the CEC, using data from the US EIA, the US Department of Energy (DOE), EPRI, and private sources, to derive a first-order approximation for the primary energy embedded in water in the US. Water-related energy in the residential, commercial, industrial, and power sectors, were considered, which represent just over 70% of total US primary energy consumption (EIA, 2012). (Transportation, representing the remainder of energy use, was not included.) Results are reported for primary energy consumption in terms of british thermal units (BTUs) to be consistent with the notation of most authoritative energy agencies in the US. A flow diagram that illustrates the methodology employed in this chapter is provided in Figure 2.2.

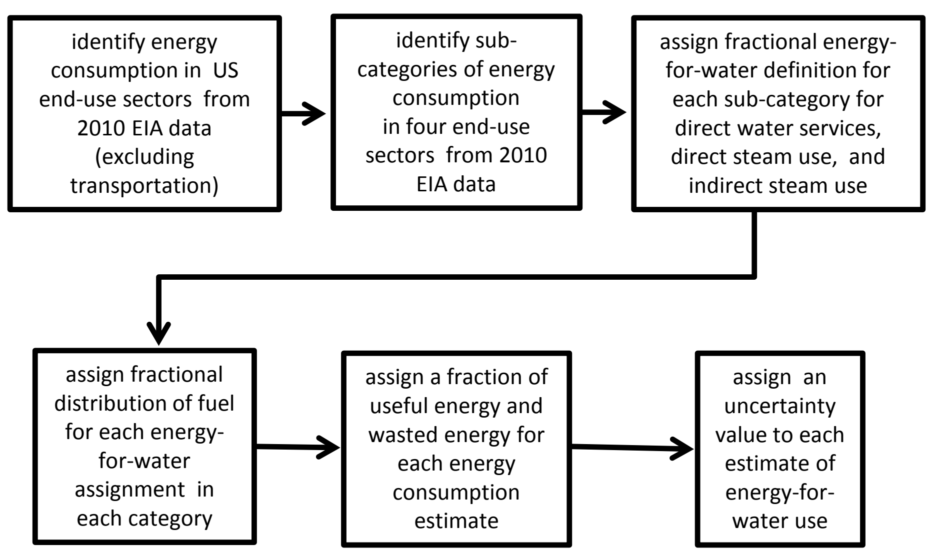

Figure 2.2: An illustrative overview of the methodology utilized in this chapter.

2.3.1 Data Sources

Residential and commercial sector energy consumption data reflect DOE's 2010 Buildings Energy Data Book (DOE, 2011), various sources from the EIA (EIA, 2011a,c, 2006), and EPRI's projections regarding 2010 water and wastewater utility energy use (Goldstein and Smith, 2002). Industrial data reflect energy consumption projections for 2010 published in EIA's Annual Energy Outlook 2011 (EIA, 2011a). (EIA projects industrial energy consumption on an annual basis based on the Manufacturing Energy Consumption Survey (MECS), which is only published every few years. The latest edition, as of early 2012, was the 2006 MECS, published in 2008.) Data regarding the power sector are from the 2010 DOE/EIA Form EIA-923 database, which characterizes combined heat and power (CHP) and electric power plants in terms of electric power generation, fuel consumption, operation cooling water use, primary mover type, location, etc. (EIA, 2011b).

Supplementary reports were used in addition to these large, aggregate datasets, to gain insight into the technology and/or fuel distribution across certain technologies (e.g. the fuel distribution across industrial boilers or commercial air-conditioners). Although energy consumption data from 2010 were used, fuel distribution estimates based on industry reports published prior to 2010 were not adjusted, assuming that the general distribution of technologies changed very little in the past decade. For example, if 40% of industrial boilers for energy refining were fueled by natural gas in 2005, this distribution was assumed to be the same in 2010, though it is possible that shifts had occurred.

2.3.2 Allocation Methods

Total primary energy consumption data from 2010 were aggregated and organized by sector and primary fuel consumption. Each sector included between 3 and 12 categories that were analyzed on a line-by-line basis to determine the fraction of energy, if any, that was attributable to water-related services. (Table 2.3.2 organizes these energy-consuming activities by category, j, and sector, i.)

Definition of Water-related Energy Classifications:

Three general classifications of water-related energy use were defined based on whether energy was used to prepare water to be delivered to an end user or as a secondary product used directly or indirectly to produce another good or service. These classifications are as follows:

1. *Direct Water Services*: Direct primary fuel consumption for water heating, cooling, pumping, pressurization, evaporation, softening, removal, and treatment. (Assigned a fraction, $\mathrm{F(DWS)}_{ij}$ of total energy use, E_{ij}. This direct energy for water is included in Figure 2.4.)

2. *Direct Steam Use*: Energy for on-site steam generation that is used directly (i.e. steam comes into direct contact with feedstocks) in processes. Examples would include steam used for sterilization and cleaning; boiling, steaming, and blanching for food preparation; steam stripping in chemical manufacturing and refining processes; and direct injection of steam in paper-pulp industry processes. (Assigned a fraction, $\mathrm{F(DSU)}_{ij}$ of total energy use, E_{ij}. This direct energy for water is also included in Figure 2.4.)

3. *Indirect Steam Use*: Energy for on-site steam production that is used for indirect process heating (i.e. steam does not come into direct contact with process

feedstocks), space heating, and electricity generation. (Assigned a fraction, $\mathrm{F(ISU)}_{ij}$ of total energy use, E_{ij}. This energy, considered indirect, is not included in Figure 2.4.) Although steam for electricity generation is commonly considered as an "energy-related water use" in energy-water nexus studies, it must also be considered as a "water-related energy use" in this analysis, since water is typically boiled for electricity generation. That is, without an initial conversion into steam, water cannot be used to generate power in conventional thermal plants.

Three definitions were used to allocate a fraction of energy to one, two, or all of these categories depending on the nature of the energy use of each energy-consuming category included in Table 2.3.2. Each fraction represented the ratio of water-related energy use to total energy use in a given category.

Equations 2.1–2.3 were used to determine total energy for *Direct Water Services* (E_{DWS}), *Direct Steam Use* (E_{DSU}), and *Indirect Steam use* (E_{ISU}), respectively. Total direct and indirect energy embedded in water is categorized in Equation 2.4 and Equation 2.5, respectively.

$$E_{DWS} = \sum \sum (F(DWS)_{ij} \cdot E_{ij}) \tag{2.1}$$

$$E_{DSU} = \sum \sum (F(DSU)_{ij} \cdot E_{ij}) \tag{2.2}$$

$$E_{ISU} = \sum \sum (F(ISU)_{ij} \cdot E_{ij}) \tag{2.3}$$

$$E_{W,Direct} = E_{DWS} + E_{DSU} \tag{2.4}$$

$$E_{W,Indirect} = E_{ISU} \tag{2.5}$$

Table 2.2: The sectors, i, and activities, j, that were aggregated in Equations 2.1-2.3(are listed here.

	Residential	**Commercial**	**Industrial**	**Power**
j	$i = 1$	$i = 2$	$i = 3$	$i = 4$
1	Space Heating	Space Heating	Chemical	Power Plant Use
2	Water Heating	Water Heating	Refining	Steam Driven Power
3	Air Conditioning	Public Water and Wastewater Utilities	Paper and Pulp	Pumped Storage
4	Wet Cleaning	Air Conditioning	Construction	
5	Ranges, Stoves, Ovens	Ventilation	Mining	
6	Hot Tubs, Pools, Spas	Refrigerators	Food	
7	Refrigerators and Freezers	Food Service Equipment	Iron, Steel, and Aluminum	
8	Separate Freezers	Cooking	Agriculture	
9	Televisions	Electronics and Computers	Other	
10	Personal Computers	Lighting		
11	Lighting	Other		
12	Other			

Included below are brief descriptions of the sectors that were analyzed. Full details regarding the assumptions made for all sectors and categories are detailed in Appendix A.

Water-related Energy in the Residential Sector

The residential sector was divided into 12 energy-consuming appliance categories based on classifications offered in the EIA's 2010 Buildings Energy Data Book

(DOE, 2011). Although the EIA defines total energy consumption in each category by fuel, it does not include any further data resolution. Thus, each category had to be rigorously analyzed to determine (1) the percentage of energy in each category, j, that was consumed exclusively for water-related purposes, (2) the fraction of water-related energy consumed for *Direct Water Services*, *Direct Steam Use*, and *Indirect Steam Use* in each category, j, and (3) the subset of fuels that were used for each energy consuming activity.

The EIA, for example, reports that 5.84 quads of primary energy was consumed for residential *Space Heating* in 2010 (DOE, 2011), but it does not split this category into smaller device-specific subsets. Since some space heating devices require water as a heat delivering medium (i.e. hydronic systems, including residential boilers, water-driven heat-pumps, hot water radiant floors, etc.) and others do not (e.g. central heating, ventilation and air conditioning systems), the distribution of water-driven space heating technologies across the US had to be estimated. Based on the literature, it was assumed that 11% of total energy for *Space Heating* was consumed by hydronic systems (EIA, 2011c; Lekov et al., 2004; Navigant Consulting Inc, 2007). Secondly, this water-related energy had to be classified. In this case, the entire fraction (i.e. 11% of 5.84 quads) of water-related energy was considered in the *Indirect Steam Use* category since hydronic systems use steam or hot water to deliver heat in a closed-loop system, and thus, the heat-carrying fluid does not come into direct contact with the air being heated. Thirdly, the distribution of fuels that made up this energy consumption was approximated based on EIA's 2009 Residential Energy Consumption Survey and other sources in the literature (DOE, 2011; EIA, 2012, 2011c). (When there were no data to indicate otherwise, the general fuel distribution across technologies was assumed consistent with earlier reports, as shifts in technology generally occur over many years.) Fossil-fuels were assumed to supply the majority of the energy consumed by these systems, primarily in boilers, but renewables such as wood and geothermal also contributed a small fraction of energy for hydronic space heating.

The remaining 11 residential sector categories were analyzed with similar rigor to determine total water-related energy for each. Most water-related energy in the residential sector was considered in the *Direct Water Services* category, with the aforementioned exception of energy consumed in residential space heaters. Categories such as *Water Heating*, *Hot Tubs*, and *Pools* were relatively straightforward to analyze, since most, if not all, of consumed energy was attributed to heating or pumping water. Categories such as *Lighting*, *Television*, and *Personal Computers* were also straightforward as they consume essentially no energy for water-related purposes. Other categories were less clear and, like the *Space Heating* category example, required device-specific interpretation. For example, the majority of the energy used to run clothes washers, dryers, and dishwashers was considered in the *Direct Water Services* category since water is the required medium for cleaning; in the case of clothes dryers, operation is dependent on effectively removing water from clothes. Cooking related activities were also difficult to estimate since steaming, blanching, boiling, and other water-related cooking processes vary widely across residences and are not well-documented. Categories that required more analysis or had less available data at the device or activity-specific level were assigned greater levels of uncertainty (See Appendix A for full details.)

Water-related Energy in the Commercial Sector

Eleven energy-consuming categories were defined and analyzed in the commercial sector with the same methodology discussed in the Space Heating example above. Activities such as public water and wastewater treatment, and distribution and water heating were assigned values of $F(DWS)_{ij}$=1, as all of the energy consumed in these categories was to move and treat water. Since the *Public Water and Wastewater Utility* category is not explicitly defined in EIA's 2010 Buildings Energy Data Book (DOE, 2011), energy use in this category was based on EPRI's projections for 2010 public water and wastewater utility energy consumption (Goldstein and Smith, 2002). (This primary energy use was subtracted from EIA's *Other* category, where it would otherwise be included.) EPRI's projection regarding energy use by public water and wastewater utilities in 2010 was based on data from 2000, and is therefore subject to error. However, more recent energy data on public water utilities at the national scale are unavailable. Other categories required more rigorous analysis based on detailed sources such as EIA's 2006 Commercial Building Energy Consumption Survey (EIA, 2006) and the 2005 Commercial Boiler Inventory (Energy and Environmtental Analysis, 2005).

Although category definitions were generally similar to those in the residential sector, results were generally very different, reflecting large sectoral differences. For example, central chillers and district chilled water systems are two common technologies that use water as a means to extract heat from large spaces; air-conditioners in the residential sector, on the other hand, generally use air to cool residences (an exception being swamp coolers that are only used in a very small percentage of homes). Large commercial computer and electronics facilities (such as data centers) were assumed to use some water-related energy for cooling devices. Commercial refrigerators, freezers, and ice-makers were also assumed to use an appreciable amount of energy for chilling water and freezing ice. Although freezers and refrigerators are also used for chilling drinking water and ice in the residential sector, this energy use was not explicitly considered. However, this omission is unlikely to affect results since this energy consumption is relatively small in comparison to other water-related, energy consuming activities.

The commercial and industrial sectors use a significant fraction of their energy for generating steam in boilers. This energy was generally assigned to the *Direct Steam Use* and/or the *Indirect Steam Use* categories, depending on the nature of the steam use. Process heating and boilers consume a large fraction of US industrial energy use to provide hot water (generally 250°F) and steam (generally 350-400°F). The DOE estimates that 34% of 1994 industrial sector energy was consumed to produce steam (Hart, 2002). This energy use was considered in the *Indirect Steam Use* category unless boiler steam or hot water was injected directly into a process (Energy and Environmtental Analysis, 2005). Twelve percent of the nation's 4.7 million commercial buildings are served by boilers that consume approximately 1.6 quads of primary energy in the sector, the majority of which are fueled by natural gas (Energy and Environmtental Analysis, 2005). While industrial boilers tend to drive large industrial applications such as power generation, industrial process, and district heating with steam, commercial boilers are used primarily to provide hot water for space heating (2/3 of commercial boilers) and domestic hot water (1/3 of commercial boilers) for buildings such as hospitals, food service, office buildings, and apartment buildings (Energy and Environmtental Analysis, 2005). Consequently, the majority of commercial boilers are used in colder regions of the US. Domestic hot water production by boilers is included in *Direct Water Services*, while space heating is considered in the *Indirect Steam Use* category.

Water-related Energy in the Industrial Sector

The EIA's Manufacturing Energy Consumption Survey (MECS), the authoritative data set on the manufacturing industry, was last published in 2006; thus, the nine 2010 energy consumption categories analyzed here are reference case estimates documented in the 2011 EIA Annual Energy Outlook (EIA, 2012). More detailed energy data for industrial processes are not generally available since most companies consider their energy consumption proprietary, so greater uncertainty was generally assigned to activities in this sector. Consequently, assignments made in the residential and commercial sectors tended to be more straightforward than those made in the industrial sector. Residential and commercial water heating energy data, for example, are explicitly reported by the EIA (DOE, 2011), whereas the energy consumed for on-site water treatment and pumping in manufacturing industries had to be estimated based on white papers, industry reports, boiler inventories, and correspondence with industry experts (BCS Incorporated, 2002; U.S. Environmental Protection Agency, 2010; Pellegrino et al., 2007; Klaas et al., 2009; Okos, 1998; Worrell, Ernst and Phylipsen, Dian and Einstein, Dan and Martin, 2000; Resource Dynamics Corporation, 2002; Hart, 2002; CCI, 2003).

Water-related Energy in the Power Generating Sector

The energy consumed by all steam-driven power generators contained in the 2010 DOE/EIA Form EIA-923 inventory was characterized as *Indirect Steam Use* since steam is used for electricity generation. Steam-driven power generation technologies represented 75.5% of approximately 40 quadrillion BTUs (1 quadrillion BTUs = 1 quad) of total primary energy consumed in the US power sector in 2010. These technologies include steam turbines, the steam portion of combined-cycle systems, and combined-cycle single-shaft combustion turbines and steam turbines that share a single generator, representing 74%, 0.8%, and 0.6% of total 2010 US primary energy consumption for electric generation, respectively (EIA, 2011b).

A small fraction of energy consumed by the power sector is allocated to the *Direct Water Services* category. This fraction includes energy for pumping and pressurizing cooling water, which is used to extract heat from steam after it exits the turbine. Based on interviews with industry experts, this amount was estimated to be less than half of a generator's internal plant energy use (Lee, 2012). (This energy use is included in the *Industrial Sector* of Figure 2.4, as opposed to the *Electricity Generation* portion of the figure since this quantity of energy is generated and consumed on-site, rather than sold as retail electricity. The figure reflects the general US electricity mix, which is why there is a small quantity of nuclear fuel consumed in the *Industrial Sector* of Figure 2.4.)

Electricity consumption for pumped storage systems was also considered since these systems move water from lower elevations to higher elevations when electricity demand and prices are low, and subsequently releasing it through turbines during periods of high demand to generate electricity. The US consumed 29.5 billion kWh for pumped storage in 2010 in order to generate 25.5 billion kWh, resulting in a net electricity consumption of 4.09 billion kWh (36 trillion BTUs of primary energy) (EIA, 2011b). (Although pumped storage systems are net-electricity consumers, they are valuable load balancers in times of high electricity demand.)

To avoid double-counting electricity generated in the power sector and sold to the residential, commercial, and industrial sectors, all of the electricity consumed for direct water-related services was summed across these four sectors (5,364 trillion BTU) and multiplied by 75.5% to determine what quantity of this retail electricity was generated in the power sector using steam-driven technologies (4,050 trillion BTU). This quantity was included as a negative value in Table 2.4 so that this energy would not be double counted in the tally of steam-driven power generation in the power sector. The remaining 1,314 trillion BTU was assumed to be provided by non steam-driven power such as hydropower, natural gas turbines, wind, and solar photovoltaics.

2.3.3 Uncertainty Assignments

To account for error, an uncertainty value was assigned to each water-related, energy-consuming activity. For example, 20% error was assigned to the estimate regarding the water-related energy consumption for residential space heating and repeated for every energy-consuming activity listed in Table 2.3.2. Uncertainty estimates only considered the anticipated error in the prescribed estimate of water-related energy and did not assign any value of error to the underlying, original data reported by EIA. Total uncertainty, U_{tot}, was calculated for the energy embedded in *Direct Water Services* and *Direct Steam Use* with the relationship $U_{tot}=(\sum\sum u_{ij}^2)^{1/2}$, where, u_{ij}, refers to the uncertainty in each energy-consuming category, j, of sector category, i. This methodology was repeated to calculate the uncertainty associated with the *Indirect Steam Use* category. Table 2.4 details the resulting uncertainty in each end use sector after all energy-consuming activities were considered, as well as the the total uncertainty embedded in the analysis. (Note: Since the equation for uncertainty is not additive, the total error embedded in the analysis is *not* the sum of the individual end use categories.) The uncertainty assignment for each energy-consuming activity can be found in Appendix A.

2.3.4 Reporting Results

Direct water-related energy included in the *Direct Water Services* and *Direct Steam Use* categories was summed across sectors and fuel types and incorporated into a flow diagram that considers energy conversion losses at the point of electricity generation, transmission and distribution, and end use (See Figure 2.4 and Equation 2.4) These calculations consider the average efficiency of US generation in 2010 based on average heat rates (EIA, 2012), average transmission and distribution losses across the grid (ABB Inc., 2007), and end use efficiencies of water-related devices and processes. The distribution of primary fuels for power generation in Figure 2.4 was assumed to mirror the average distribution of fuels consumed for US electricity generation in 2010 (EIA, 2012). (On a primary energy basis this distribution: coal 47%, natural gas 19%, petroleum 1%, nuclear 21%, and renewables 11%). These assumptions are discussed further in subsequent sections. Water-related energy consumption considered in the *Indirect Steam Use* category is not included in the figure.

2.4 Results

Our analysis indicates that direct water-related energy consumption (i.e. energy considered in the *Direct Water Services* and the *Direct Steam Use* categories) was 12.6% (12.3±0.346 quads) of 2010 US primary energy consumption. (Total primary energy consumption was 98.0 quads for all sectors (including transportation) in 2010 (EIA, 2012).) Approximately 8.2 quads of energy were consumed for *Direct Water Services* (See Equation 1) and about 4.1 quads were consumed in the *Direct Steam Use* category (See Equation 2). An additional 34.1 quads of energy were consumed for *Indirect Steam Use*. Figure 2.3 summarizes the energy used in each of these three categories.

Table 2.4 details the water-related energy consumption in each of the end use sectors analyzed. Water-related energy in the transportation sector was not included in the analysis because the majority of the energy consumed in this sector is for petroleum-based transportation fuels, which is not considered within the scope of this analysis. An exception would be fuel consumed for the transportation of water products, but this energy consumption is not likely to be large (other than for transportation within piped systems, which has already been included).

Figure 2.4 summarizes the 12.3 quads of water-related energy flows in the

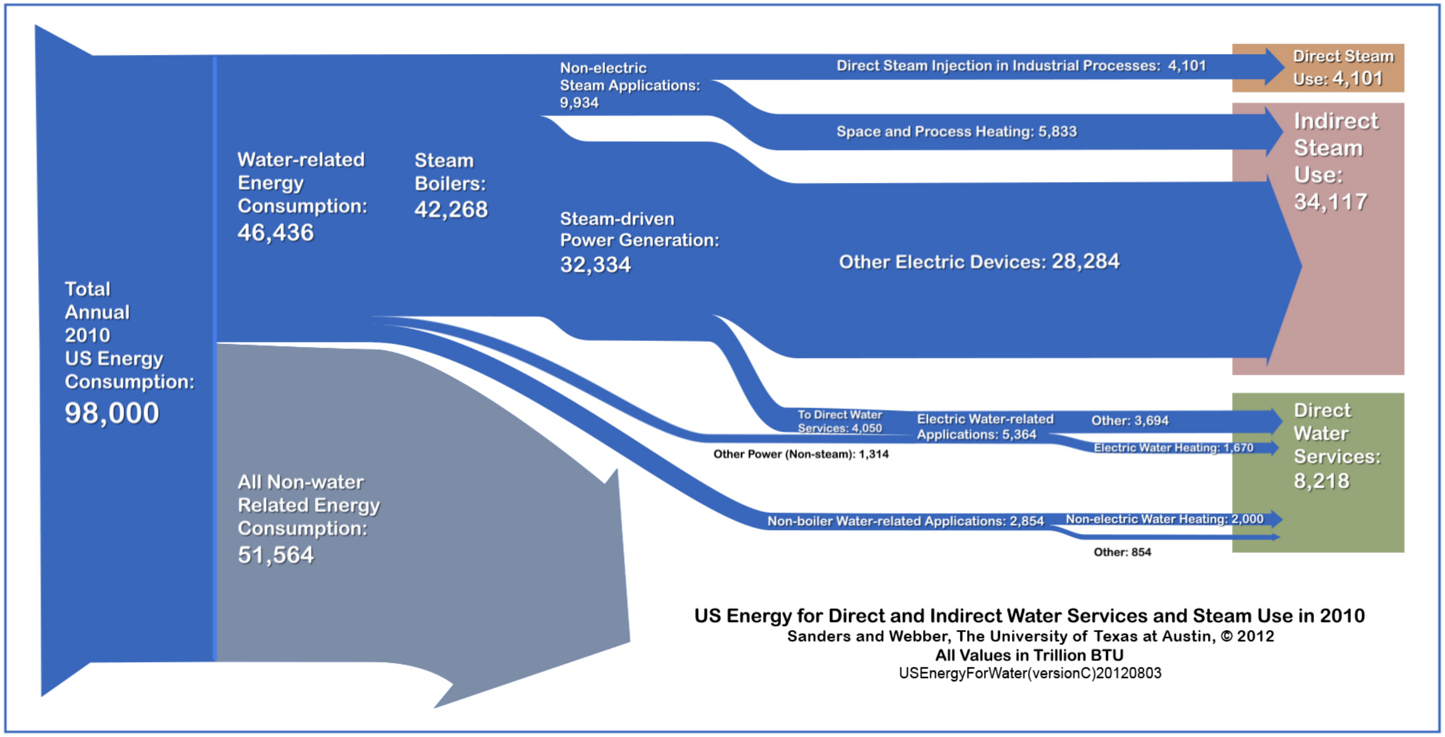

Figure 2.3: Approximately 46.4 quads of 2010 US annual energy consumption was used for water-related purposes. The majority of this energy (33.1 quads) was used to make steam for electricity, space heating, and industrial process use. Only 12.3 quads of energy was used for *Direct Water Services* (i.e. 8.2 quads for heating, chilling, treating, pressurizing, and pumping water) and *Direct Steam Use* (i.e. 4.1 quads for direct steam-injection, steam stripping, etc.).

Table 2.3: Total energy use in the *Direct Water Services* and *Direct Steam Use* categories was approximately 12.3 quadrillion BTUs in 2010. An additional 34.1 quads of energy was consumed in the *Indirect Steam Use* category for on-site electricity generation, indirect process heating, and space heating. Note: *Direct Water and Steam Services* is the sum of the *Direct Water Service* and the *Direct Steam Use* categories, individually listed in Appendix A.

		Water-related Energy Consumption By Primary Fuel [Trillion BTU]							
Category	**Description**	**Coal**	**Natural Gas**	**Oil**	**Renewable or Other**	**Subtotal**	**Primary Energy for Retail Power**	**Total Energy Use**	**Error**
Residential	Direct Water & Steam Services	0	1,472	191	5	**1,668**	2,802	**4,470**	±70
	Indirect Steam Use	20	395	231	22	**668**	0	**668**	±100
Commercial	Direct Water & Steam Services	0	737	283	9	**1029**	1,812	**2,841**	±96
	Indirect Steam Use	53	849	180	0	**1082**	0	**1082**	±162
Industrial	Direct Water & Steam Services	252	2,366	1,422	60	**4,100**	714	**4,814**	±324
	Indirect Steam Use	753	1,838	1,396	96	**4083**	0	**4083**	±373
Power	Direct Water & Steam Services	96	10	2	50	**158**	36	**194**	±19
	Indirect Steam Use	19,662	2,058	365	10,249	**32,334**	-4,050	**28,284**	±1,616
Total	Direct Water & Steam Services	**348**	**4,585**	**1,898**	**124**	**6,956**	**5,364**	**12,319**	±346
	Indirect Steam Use	**20,488**	**5,140**	**2,172**	**10,367**	**38,167**	**-4,050**	**34,117**	±1,670

US for the *Direct Water Services* and *Direct Steam Use* categories (note that the *Indirect Steam Use* category is not included in that figure). Primary fuels (on the left) are used directly and indirectly via retail electricity generation for the three end use sectors (on the middle-right). The thickness of the flows is proportional to the amount of energy consumed. In order to visualize primary retail electricity used in the residential, commercial and industrial (which includes power) sectors, primary electricity data from the EIA were proportioned to reflect the distribution of primary fuels consumed to generate net US electricity in 2010 as reported in the EIA's Annual Energy Review (EIA, 2012). Losses at the point of electricity generation were calculated using a normalized average national 2010 net heat rate of HR_{avg} = 8,830 BTU kWh^{-1} (EIA, 2012). (Heat rate is weighted based on 2010 heat rates for fossil-fuel, nuclear, and renewable energy generators; renewable generators have a heat rate of zero.) Approximately 56% (6,955 trillion BTUs) of primary energy was consumed directly for water; the remaining proportion (5,364 trillion BTUs) was converted into electricity for retail sale and then used for water. As Figure 2.4 indicates, much of the primary energy used in retail electricity production is lost as waste heat. National electricity production in 2010 was 38.5% efficient based on the aforementioned average national heat rate. Of the electricity generated, an additional 6–8% is lost during transmission and distribution (ABB Inc., 2007); these losses are considered in Figure 2.4 at the point of use, rather than at the point of generation.

Heating water consumed nearly three-fourths of the residential sector's and approximately one-third (35%) of the commercial sector's direct water-related energy, respectively. (Note that the proportions highlighted in the blue boxes of Figure 2.4 reflect energy consumption at the point-of-use and do not include energy losses at the power plant. See Appendix A for details regarding the total primary energy use for each energy-consuming activity). On-site water pumping was relatively low in the residential sector, in comparison to the industrial and commercial sectors, as residential structures tend to be smaller. Residential water systems often operate with the prevailing pressure of the water distribution network, which means pumps are generally not needed at all. Large industrial facilities and high-rise buildings, by contrast, tend to require large quantities of energy to move water on-site (for example, to pump water to rooftop storage tanks).

Determining the average efficiency of each end use sector required additional engineering assumptions as national data sets do not detail specific water-related processes and technologies when they report energy consumption data. Electric power losses between the point of power generation and final end use were assumed to average 18% when average electric device end use efficiencies are also considered. (This estimate assumes average transmission and distribution losses and 10%–12% losses at end use based on prior work by ABB Inc. (2007) and ACEEE (2013).)

For on-site primary energy consumption, efficiencies were estimated based on known, commercial-scale technologies. For example, according to the American Council for an Energy-Efficient Economy (ACEEE), average residential electric and natural gas water heaters are 90% and 60% efficient, respectively; those fueled by petroleum by-products (namely fuel oil and Liquid Petroleum Gas (LPG)) are about 55% efficient (ACEEE, 2013). The efficiency rating of a particular water heater varies based on the effective transfer of thermal energy from the heating element to the water, energy losses during storage, and the energy consumed by the device by switching between active and idle modes, and does not include power plant losses or distribution losses. Additional energy losses occur during the conveyance of water from the water heater to the point-of-use at a particular appliance within the home or facility. However, these losses vary a great deal depending on piping network characteristics

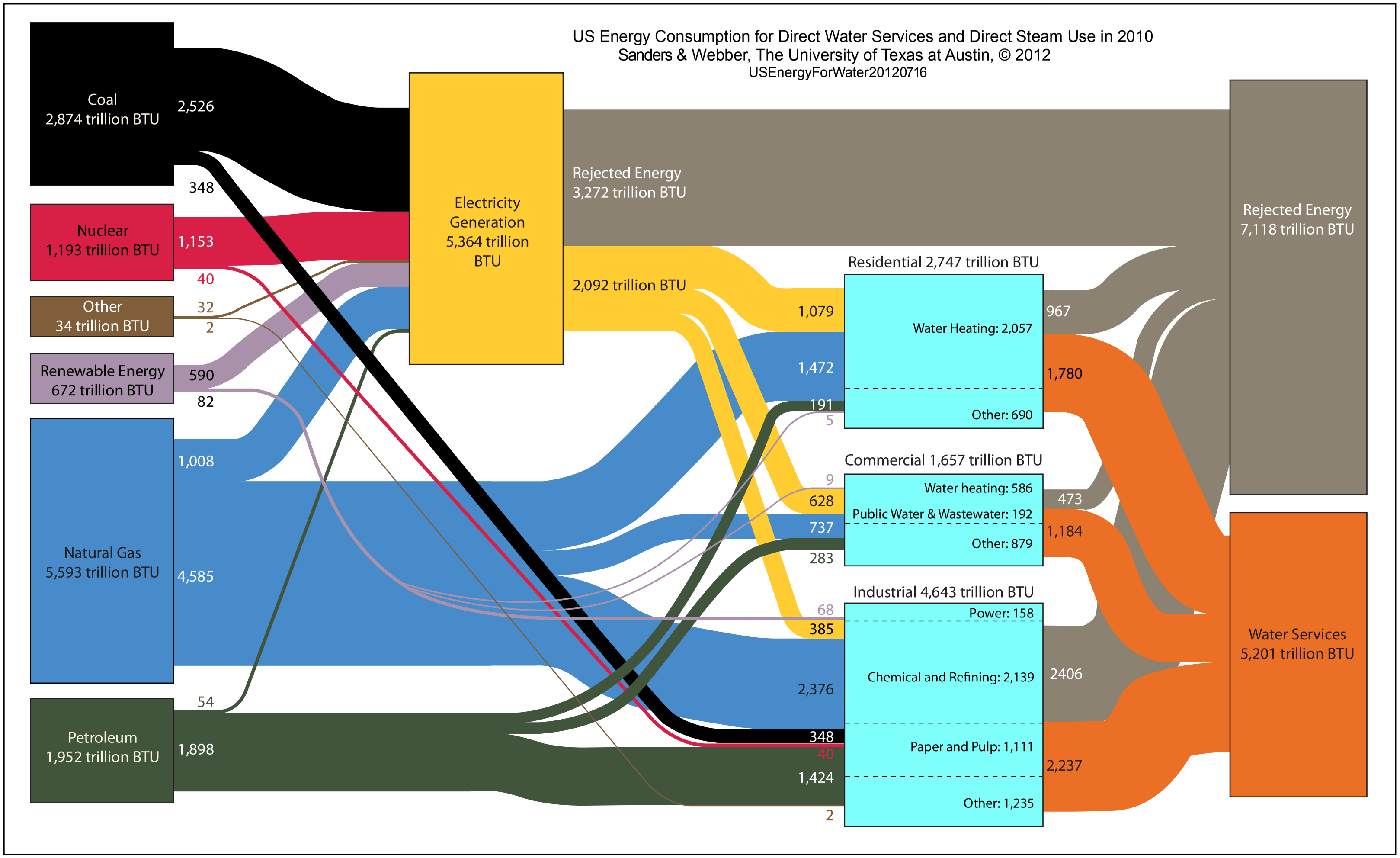

Figure 2.4: This diagram summarizes the water-related energy flows in the United States included in the *Direct Water Services* and *Direct Steam Use* categories. Primary fuels (on the left) are used directly and indirectly via electricity generation for different purposes (on the right). The thickness of the flows is proportional to the amount of energy consumed. About 58% of the total energy consumption is lost as waste heat. Note: The 5.4 quads used for electricity generation only includes retail electricity sold to residential, commercial, and industrial customers; the primary energy consumed for electricity generated and used on-site is included in the sector where it was generated.

such as total pipe length, geometry, and insulation properties, and the ambient temperature around the pipe. Commercial water heating efficiency varies considerably depending on the facility. Some highly-efficient commercial facilities have natural gas water heaters approaching 75%, while less efficient facilities are comparable to average residential water heaters.

For the purpose of this analysis, the average end use efficiency of non-electric energy consumption in the residential, commercial, and industrial/power sectors were assumed to be 55%, 65%, and 45%, respectively. These assumptions were based on the premise that residential and commercial sector water-related energy consumption is dominated by water heating, while the energy consumed in the industrial and power sectors is mainly in boilers to make steam and generate electricity. Although non-steam processes and devices in the industrial and power sectors tend to be more efficient than in the residential and commercial sectors due to economies of scale, these processes consume much less energy than industrial steam boilers.

The efficiency of any boiler is sensitive to its size, age, and fuel type. New boilers typically fall in the range of 60–85% efficient (CIBO, 1978; Hart, 2002); however, two-thirds of large, industrial boilers are greater than 30 years old and have much lower efficiencies (Energy and Environmtental Analysis, 2005). Efficiencies for electricity generation technologies in the industrial sector vary by technology but are generally in the range of 15% (for simple-cycle wood boilers) to 51% efficient for some combined-cycle applications (CIBO, 1978). Based on the literature (Energy and Environmtental Analysis, 2005; CIBO, 1978; Resource Dynamics Corporation, 2002; Hart, 2002), the average end use efficiency for the industrial/power sector was assigned to be 45% as a conservative estimate.

Energy losses at the point of electricity generation, transmission and distribution, and end use are represented by the quantity "Rejected Energy" in Figure 2.4. This quantity represents 58% of the total primary energy that was consumed for water-related purposes in 2010. It is important to note that this quantity reflects broad estimates about the average efficiency of each sector's water-related energy processes, which are extremely diverse and subject to uncertainty.

2.5 Discussion

Useful observations can be derived from these general trends. Firstly, economies of scale such as those achieved in the industrial sector and large commercial facilities typically enable more efficient systems than those that are smaller in scale, such as individual households. Secondly, because of the large conversion losses at power plants when considering end-to-end efficiency, it is much less energy intensive to heat water by direct use of natural gas on-site than to use that natural gas to make electricity that is then used to heat water (DOE, 2011). From the perspective of displacing fossil fuel use, solar thermal water heater systems are even more advantageous.

Although this analysis attempted to characterize the embedded energy in water from national aggregate averages, it is important to realize that water systems vary a great deal regionally. The following sections discuss the role of regional variations in the US public water supply and the sources of variability that can affect the regional energy intensity and CO_2-intensity of each individual life-cycle stage.

2.5.1 Regional Variation in the US Public Water Supply

The United States is a difficult country to generalize. It has diverse climates that affect factors such as annual precipitation and susceptibility to drought. These factors impact how much water is available in proximity to a water treatment facility.

It has a diverse topography that affects the permeability of soil and recharge rates and affects how high in elevation water must be pumped and across what distance it is distributed. A home owner in Southern California, for example, might receive water that has been pumped hundreds of miles, over two mountain ranges, from the San Joaquin Delta in Northern California. Before that water even reaches its intended customers or undergoes treatment, the water has an energy intensity of about 11,000 kWh per million gallons (Klein et al., 2005). By contrast, a customer in Massachusetts, where precipitation and water reservoirs are ample, receives water that has an intensity of about 1,500 kWh per million gallons before wastewater treatment, a mere 14% of the Californian counterpart, because it is relatively clean at the source and potentially gravity-fed.

Figure 2.5 illustrates the lifecycle electricity-intensity of several regional water supply systems in the United States. While the national average for the energy intensity of water delivered by the public supply is 1,960 kWh per million gallons for pumping, treatment and distribution (and 3,200–3,600 kWh per million gallons when the energy for wastewater pumping/treatment is considered), specific locations are higher or lower depending on regional characteristics such as topography, climate, seasonal temperature and rainfall variations, local policy regimes, etc. (DOE, 2011). Note that average energy intensities included in Figure 2.5 only consider water returned to the drain, that is, they only include water reconditioned in a wastewater treatment facility. Water lost to the environment at end use by means of irrigation or landscaping will have an energy intensity closer to 1,960 kWh per million gallons, on average.

The following sections describe factors that influence the energy intensity of each stage in the water life-cycle illustrated in Figure 2.1.

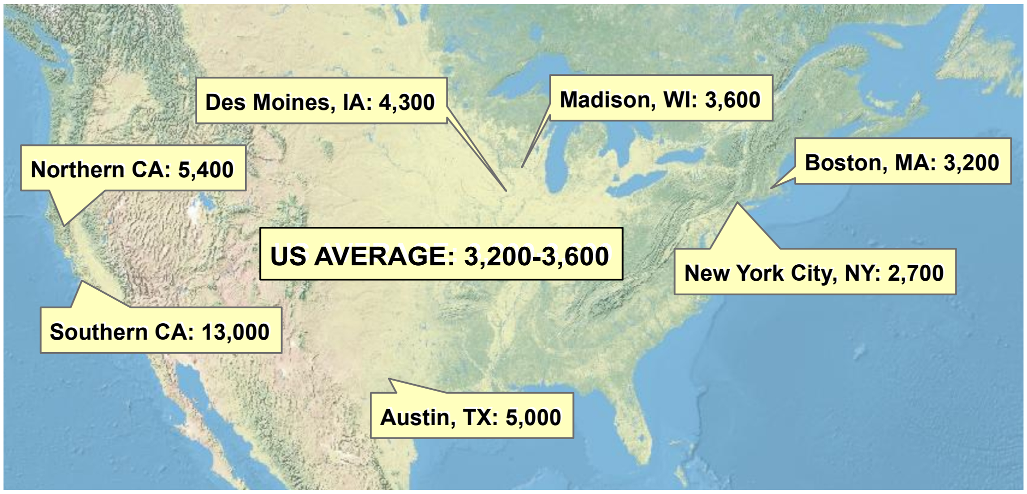

Figure 2.5: Large variations in life-cycle electricity-intensity exist across regions of the US (Klein et al., 2005; DOE, 2011; Green, 2011). (All units in figure are in kWh per million gallons of water)

2.5.2 Sourcing and Distribution

Table 2.4 includes several pumping scenarios for retrieving and delivering water from a reservoir to the water treatment facility. Groundwater treatment is typically more energy intensive than surface water treatment per unit water treated since energy is required to pump water from the reservoir below ground level. The energy requirement for groundwater pumping is largely correlated to reservoir depth; as the depth of the well increases, the pumping energy required to move the water from the well increases significantly (Goldstein and Smith, 2002). Although surface water pumping typically requires less energy than groundwater pumping, surface water pumping costs can become extremely energy intensive in cases when water is pumped long distances. For example, as described before, Southern California receives much of its water from the Central Valley or State Water projects, each of which carry water over hundreds of miles from water-rich Northern California, to the water-stressed, population-dense regions of the South (Cohen et al., 2004).

Inter-basin water transfers such as these systems in California are being considered in places such as the Southwestern US that are becomingly increasingly water stressed (Shrestha et al., 2011). Large expected population growth in these regions could exacerbate current water strains, which might increase the energy intensity of these water systems in the future.

Table 2.4: The energy required for pumping water varies by factors such as elevation change, distance pumped, and pump size (Twomey et al., 2010; Goldstein and Smith, 2002; Drbal et al., 1996).(Note: MG = million gallons)

Pumping Process	**Energy Intensity** kWh MG^{-1}
Groundwater (GW) Well-Pumping (120 ft)	540
GW Well-Pumping (Average)	602
GW Well-Pumping (400 ft)	2,000
GW Well-Pumping plus pumping to Utility (Average)	1,213
Surface Water (SW) withdrawal plus pumping to Utility (Average)	1,205
Pumping from Colorado River to Treatment in Southern CA	6,134
Pumping from San Joaquin Valley to Treatment in Southern CA	6,966

2.5.3 Water Treatment

Table 2.5 illustrates a very large range in energy intensity for water treatment processes. Raw water that is of high ambient quality only requires basic treatments to meet EPA's drinking water standards, while brackish water and seawater require very energy intensive treatments like desalination to remove small contaminants from the source water. Brackish and seawater desalination are alternatives to inter-basin transfers in water-scarce regions, but are also extremely energy intensive. Despite these costs, desalination projects have been built in states such as California, Florida, and Texas to meet growing water demand.

Table 2.5: Energy consumption of different water treatment technologies varies widely with level of treatment. Treating water to a cleaner standard requires more energy (Twomey et al., 2010; Goldstein and Smith, 2002; Drbal et al., 1996).

Treatment Process	**Energy Intensity**
	kWh MG^{-1}
Average groundwater treatment (chlorine disinfection)	10
Average surface water treatment	140–210
Chlorine disinfection	80
Electrodialysis	2,600–5,000
Multi-Effect Distillation	7,700–15,300
Reverse Osmosis (Brackish water)	3,900–9,700
Reverse Osmosis (Seawater)	13,200–26,500

2.5.4 End-use

The energy used to prepare water for end use is usually the highest of any stage. Even in areas that spend large amounts of energy desalinating or pumping water vast distances, more energy is consumed overall to prepare water for end use than in conveyance (Cohen et al., 2004). Table 2.6 and Figure 2.6, from a Natural Resources Defense Council (NRDC) report, show average energy trends in end use water activities in San Diego County. The general estimates for energy intensities of the given end use activities included in the table tend to be much higher than those energy intensities cited in Table 2.4 and Table 2.5 associated with pumping and treatment, respectively.

Table 2.7 details data collected from the American Water Works Association Research Foundation (AWWARF) about the energy use in single-family residential homes in the US. It illustrates how much water is used for common residential end uses, and how much of that water is heated, since water heating tends to be the most energy intensive aspect of the public water supply's lifecycle. Table 2.6 and

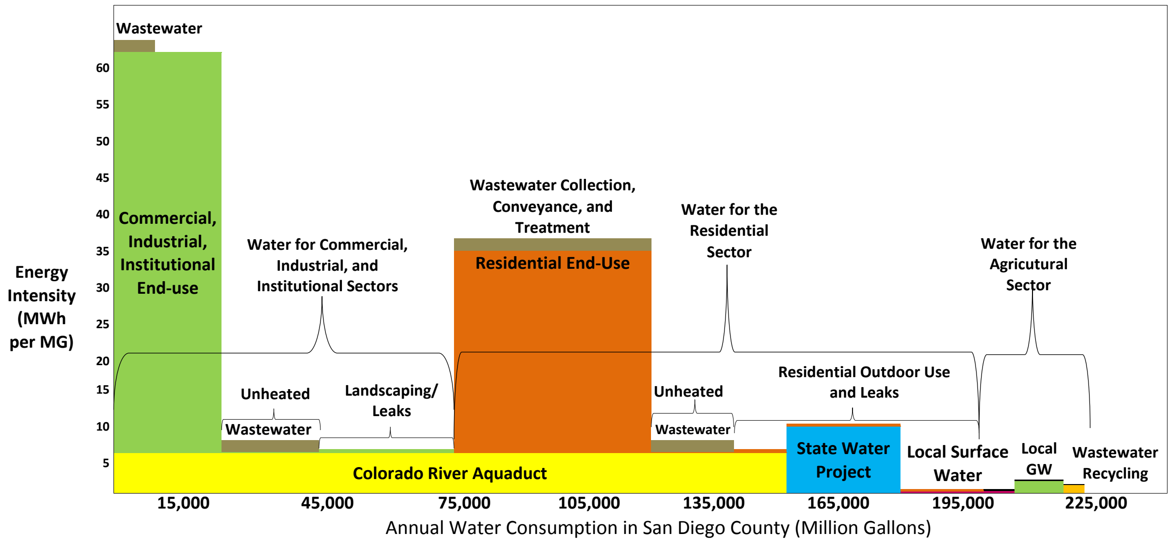

Figure 2.6: Water related energy use in San Diego County is very dependent on source water and end-preparation. The area within each colored box represents net energy per year consumed to deliver, treat, or prepare the respective volume of water. (Adapted from data in (Cohen et al., 2004).)

Table 2.6: Estimated water-related energy use for end use purposes in San Diego county, CA (Cohen et al., 2004).

	Percent of Total Use in 2010	**Energy Intensity kWh MG^{-1}**
Residential	58.0%	–
Toilets and Leaks	14.0%	0
Dishwashers	1.0%	83,474
Clothes Washers	8.0%	35,752
Showers, Faucets and Bathtubs	12.0%	20,562
Landscape Irrigation	23.0%	0
Commercial, Industrial and Institutional	**32.0%**	–
Kitchen Dishwashers	0.5%	83,474
Prerinse Nozzles	0.2%	20,562

Table 2.7: The average single-family US home uses approximately 70 gallons of water for indoor use, nearly 40% of which is heated (EIA, 2012).

Residential End-use	Average water for end use (gallons/home/day)	Hot water for end use (gallons/home/day)
Toilet	18.5	0.0
Clothes Washer	15.0	4.2
Shower	11.6	8.5
Faucet	10.9	7.9
Other Domestic	1.6	0.6
Bath	1.2	0.9
Dishwasher	1.0	1.0
Leaks	9.5	2.5
Total Indoor	**69.3**	**25.6**
Unknown	1.7	0.0
Outdoor	100.8	0.0
Total Indoor/Outdoor	**171.8**	**25.6**

Table 2.7 provide higher data resolution than the analysis described above. For the purposes of this first-order analysis, EIA water heating data for the commercial and residential sectors were used to avoid making broad assumptions regarding the behavioral characteristics of people across diverse regions did not have to be made.

2.5.5 Wastewater Collection and Treatment

Wastewater treatment is typically more energy intensive than treatment at the public water utility since wastewater is of much lower quality than the raw water that is extracted from surface water sources. Unlike water treatment, whose energy intensity only varies slightly with plant size, the energy intensity of wastewater treatment facilities is inversely correlated to the treatment capacity of the wastewater treatment facility.

Table 2.8: The energy intensity of wastewater treatment processes depends on incoming water quality and decreases with plant size (Goldstein and Smith, 2002).

Treatment Capacity MG Day^{-1}	Trickling Filter kWh MG^{-1}	Activated Sludge kWh MG^{-1}	Advanced kWh MG^{-1}	w/ Nitrification kWh MG^{-1}
1	1811	2236	2596	2951
5	978	1369	1573	1926
10	852	1203	1408	1791
20	750	1114	1303	1676
50	687	1051	1216	1588
100	673	1028	1188	1558

2.5.6 Wastewater Disposal and Reclamation

Depending on the circumstances, reclaimed water might require tertiary treatment following standard wastewater treatment to meet an end-quality level appropriate for its intended end use. However, in many regions of the US, wastewater is treated to a standard acceptable for non-potable reuse and requires no treatment in addition to standard practice. (In fact, wastewater discharged into a water reservoir after standard US treatment typically requires a final dechlorination process to mitigate ecosystem impacts, while reclaimed water does not require this step prior to reuse (Green, 2011).) Thus, most of the current energy expenditures for recycled water are those for pumping water from the wastewater treatment facility, to its end user (Stillwell et al., 2011a). Some reclaimed water projects, such as those for industrial cooling water and irrigation in Denver, Colorado and the West Basin Municipal Water District of Los Angeles County do incur additional treatment costs, but non-potable water reuse projects requiring additional treatment in the US are less common (NAS, 2012).

In the US, federal standards for water reuse do not exist, so criteria for water reclamation are determined at the state level (Asano, 2002). Thus, the intended sanitation level of reclaimed water might vary depending on its purpose. For instance, reclaimed water for crop irrigation requires a higher degree of sanitation than water reclaimed for landscaping use. In California, the most popular uses for reclaimed water in 2002 were for agricultural irrigation (46%), landscape irrigation (21%), ground water recharge (10%), and industrial uses (5%) (Klein et al., 2005).

The use of reclaimed water for potable reuse in the US is limited, comprising only 0.1 % of the total volume of municipal wastewater treated annually. The majority of this water is injected to recharge groundwater wells or a surface water supply reservoir, and is therefore an "indirect" potable reuse, since an environmental buffer exists between discharge from the water treatment plant and recollection for the potable water supply. No formal regulations currently exist for direct potable reuse (i.e. water to be used for potable purposes without the use of an environmental buffer) since these projects generally incite strong public resistance. However, the California Senate passed a bill in 2010 that requires the California Department of Public Health to assess the feasibility of developing uniform direct potable reuse projects into the state's water plan, indicating that this option might become more of an appreciable water supply for the state in the future. The assessment report is due in 2016 (NAS, 2012). Direct potable reclaimed water projects will require more energy intensive processes to ensure adequate compliance with accepted drinking water standards. The net energy savings or expenditures resulting from this energy use is non-obvious (Stillwell et al., 2011a).

2.6 Conclusion

Results presented in this chapter indicate that the energy embedded in the US water system represents 12.3±0.346 quads (12.6%) of national primary energy consumption in 2010. (To put this result in context, 12.3 quads of energy is the equivalent annual energy consumption of roughly 40 million Americans (EIA, 2010a).) Over five (5.4) quads of this primary energy was used to generate electricity (611 billion kWh delivered) for pumping, treating, heating, cooling, and pressurizing water in the US, which is approximately 25% more energy than is used for lighting in the residential and commercial sectors (EIA, 2010a). Despite this equivalency, much more policy attention has been invested in energy efficient for lighting, rather than reducing hot water consumption or investing in energy efficient water heating methods, even though the latter might have just as much impact. One of these options–water heating–is considered in the next chapter.

Chapter 3

Evaluating Energy and Emissions Reductions Through Shifts in Residential Water Heating

3.1 Introduction

The US dedicates nearly 13% of its annual primary energy consumption to providing water at the desired quality, temperature, pressure, location, and time that it is demanded (Sanders and Webber, 2012). Of the 12.3 quads consumed for water supplied to the residential, commercial, industrial, and power sectors in 2010, nearly 25% (2.86 quadrillion BTUs) was consumed for residential water heating (DOE, 2011). Accordingly, reducing the energy consumed for water heating offers an important opportunity for energy conservation in the residential sector (Sanders and Webber, 2012).

In addition to its large energy demand, water heating is a large source of residential greenhouse gas (GHG) emissions, since the majority of water heating units in the US consume natural gas (51.7%), electricity (41.3%), or oil-derived fuel sources (6.7%) such as fuel oil and liquid petroleum gas (LPG) (EIA, 2011c). Energy performance metrics assigned by the federal government are uniform across the US and only consider the energy efficiency of a water heating device at the point-of-use; however, the environmental performance of a water heating technology also depends on regional characteristics such as hot water demand and usage profiles, climate, and the GHG intensity of the local electricity mix.

To date, little analysis has been done to evaluate the regional effects of fuel switching on the energy consumption and carbon dioxide (CO_2) emissions associated with residential water heating in the US. This analysis fills that gap by quantifying the energetic and environmental trade-offs of water heating in 27 regions of the contiguous US. The potential for fuel switching is assessed based on technical, as well as economic, social, and political factors.

3.2 Background

Water heating is the second-largest consumer of end use residential energy after space heating (DOE, 2011). Since the residential sector represents nearly 25% of the energy consumed in the United States (EIA, 2012), energy savings realized on a small-scale through improved end use device decisions can result in significant overall energy savings. Today, the majority of US homes and commercial facilities use storage-type water heating units (95%) to produce hot water for activities such as cleaning, bathing, cooking, clothes washing, and dishwashing; tankless models represent the remaining units (Maguire et al., 2013).

Water heaters are labeled with efficiency ratings called Energy Factors, which are intended to represent the end use efficiency of a water heating device. This rating is assigned by the federal government based on a series of standardized testing procedures intended to increase consumer awareness about the energy performance of end use appliances. The Energy Factor (EF) is defined as the ratio of thermal energy embedded in a volume of hot water divided by the energy delivered to the water heating unit to produce that volume (Bohac et al., 2010). Conventional fossil-fueled water heating technologies represent over 99% of the water heating units in the US and typically have an EF ratings between 0 and 1 since a fraction of the energy provided to the system is lost as waste heat. EF values for natural gas and electric storage water heaters range from 0.58 to 0.65 and 0.90 to 0.98, respectively, based on insulating conditions and flue losses (Maguire et al., 2013; ACEEE, 2013).

Federal EF rating protocols have been criticized for not mimicking realistic usage patterns in terms of usage volumes, flow rates, draw durations, number of draws, and seasonal variation (Hoeschele and Weitzel, 2013; Hernandez and Kenny, 2012). Several *in situ* analyses assessing the validity of posted EF ratings have concluded that the actual energy efficiency of a water heating device is often 10–20% less than its posted EF value (Bohac et al., 2010; Dieckmann et al., 2009). Additionally, the EF rating only characterizes the "site-efficiency" of a device (i.e. the efficiency at the point-of-use); it does not consider the upstream losses of primary fuels, losses at the point of electricity generation, or electricity losses during transmission and distribution (Denholm, 2007).

The energetic trade-offs between conventional natural gas and electric storage tank water heating units reflect differences in the conversion of primary fuel into thermal energy. Site-energy losses in natural gas storage water heaters are larger than electric units due to the conversion of natural gas to heat, as well as thermal losses between the tank and the ambient environment when combustion products are vented at a high temperature through a central flue (Maguire et al., 2013). (Condensing storage natural gas water heaters that re-inject the heat from combustion gases into the tank rather than releasing it into the environment have EF ratings as high as 0.86 (ACEEE, 2013).)

In the case of electric water heaters, the conversion of primary energy into electrical energy occurs before the point-of-use. In 2010, 980 of the 1,380 trillion BTUs of primary energy consumed for residential electric water heating in the US was lost as waste heat. Approximately 95% of these energy losses occurred at the power plant (940 trillion BTU), indicating that the standard EF rating neglects the majority of energy losses in electric end use devices, as the thermal losses during power generation are roughly two-thirds of the total primary energy supplied to the electric power plant (EIA, 2010b). Consequently, EF ratings for conventional electric water heaters are typically higher than comparable natural gas water heaters, despite the fact that electric water heating is less efficient than burning fuels directly for water heating when upstream losses are considered (ACEEE, 2013; DOE, 2011). Thus, when only the site-efficiency is considered, electric water heaters appear advantageous to residential consumers since natural gas water heaters typically have more losses at the point-of-use. But when source-efficiency is considered, natural gas water heaters generally perform better than electric units since upstream losses of natural gas at the well-head and though pipelines are typically an order of magnitude lower than losses at the power plant (Denholm, 2007).

Table 3.1 includes characteristic ranges of “site-efficiency” ratings (i.e. EF) for various water heating technologies based on fuel consumed at the home, as well as “source efficiency” ratings, which account for both upstream and point-of-use losses for each device (Maguire et al., 2013; ACEEE, 2013). Source-efficiency ratings in Table 3.1 reflect upsteam losses of 8% and 70% for natural gas and electricity, respectively, based on estimates from Maguire et al. (2013). In reality, the source-efficiency of a device varies significantly according to its ambient environment, as well as spatial and temporal variability in regional energy systems. Additionally, the efficiency of a conventional storage water heater generally increases with the volume of water drawn from the device (Maguire et al., 2013).

Water heaters can impact the energy required for space heating or cooling in conditioned spaces (i.e. heated or cooled space within a building (ASHRAE, 2013)), since thermal losses can increase the temperature of the space, especially in the case of storage tank water heaters. Tank losses can increase or decrease depending on the temperature of unconditioned spaces; that is, in cold climates, thermal losses might increase, and in hot climates, losses might be reduced (Maguire et al., 2013). The energy consumed by a water heating device also varies with the incoming water temperature, which is influenced by climate and seasonal variations (Široký et al., 2011).

Table 3.1: Site-efficiency ratings vary from source-efficiency ratings due to upstream losses at the point of fuel extraction, energy conversion, and distribution. Efficiencies greater than one indicate that useful thermal energy leaving the system exceeds the amount of fuel delivered to the unit. (Efficiency, therefore, can exceed one if solar energy or heat from the ground is delivered to the unit in addition to fuel inputs.) Reproduced from Maguire et al. (2013) and ACEEE (2013).

Fuel Source	**Residential Water Heating Technology**	**Approximate Installed Cost (USD)**	**Average Lifetime (years)**	**Site Efficiency**	**Source Efficiency**
Natural Gas	Storage	700 – 1,900	13	0.58 – 0.65	0.53 – 0.59
Natural Gas	Non-condensing Tankless	1,900 – 2,900	20	0.82 – 0.98	0.75 – 0.90
Natural Gas	Condensing Storage	1,500 – 2,400	13	0.70 – 0.85	0.64 – 0.77
Solar/Nat. Gas	Storage	6,000 – 14,000	30	1.2 – 6.0	1.1 – 5.49
Electric	Storage	400 – 800	13	0.90 – 0.98	0.27 – 0.29
Ground source	Heat Pump	1,200 – 2,200	13	2.00 – 2.35	0.59 – 0.70
Solar/Electric	Storage	6,000 – 14,000	30	1.80 – 9.0	0.53 – 2.67

Figure 3.1 illustrates the energy flows and conversions for water heating technologies utilized in the US residential and commercial sectors in 2010 (DOE, 2011; Twomey and Webber, 2011). As described in Chapter 2, average losses at the point of electric power generation were calculated using a normalized average national 2010 net heat rate of 8,830 BTU kWh^{-1}. Losses at end use were assigned based on average federal EF ratings detailed by ACEEE (2013). Commercial electric and natural

gas water-heating devices were assigned a slightly higher average site-efficiency since commercial facilities are often more efficient than average residences due to economies of scale.

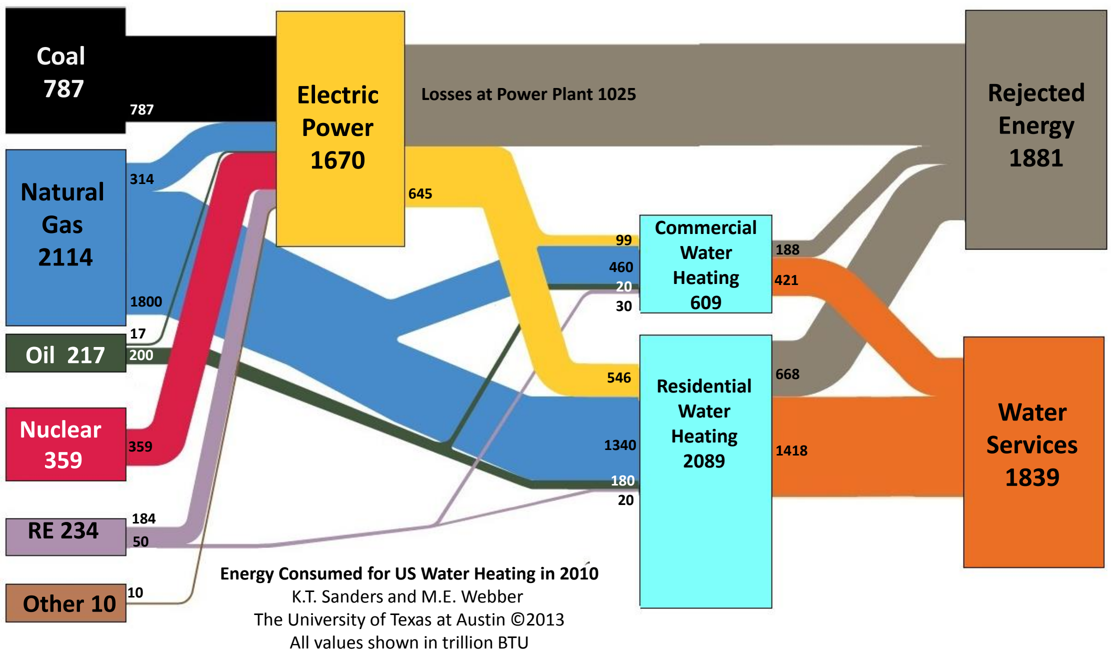

Figure 3.1: Energy flows for residential and commercial water heating in the US in 2010 are diagrammed. Primary fuels (on the left) are used directly and indirectly via electricity generation for water heating in end use sectors (on the right). The thickness of the flows is proportional to the amount of energy consumed. Approximately 50% of total energy consumption is lost as waste heat (Twomey and Webber, 2011).

Although Figure 3.1 is instructive for visualizing average losses across the US water heating fleet, regional energy use trends in water heating reflect climatic and demographic characteristics. Currently more households in the US use natural gas than electricity to heat water, but according to the EIA, from 2005 to 2009, US households installed more electric storage water heaters than natural gas storage water heaters, suggesting a trend towards electric water heaters (EIA, 2010b). It is unclear how recent decreases in the price of natural gas due to increases in domestic natural gas production will affect trends in natural gas end use appliances, since the lifespan of water heaters are generally between 10–30 years making technological transitions slow and unresponsive to short-term price fluctuations (EIA, 2012, 2011a; Hoffman et al., 2013).

Alternative water heating technologies exist that offer large energy and CO_2 savings, but currently represent less than 1% of the US water heating market (EIA, 2012). Solar Water Heaters (SWHs) typically provide upwards of half of the energy for water heating; the remaining energy must be provided by an auxiliary system (i.e. a back-up water heating system) to meet demand when solar resources are not sufficient (Maguire et al., 2013). (These units typically have site-efficiencies in the range of 1.2 to 9.0, indicating that more thermal energy is transferred to hot water than is consumed by a device's auxiliary system (ACEEE, 2013; Maguire et al., 2013).) A residential SWH installation in the US typically yields a reduction of 50–85% in water heating energy demand to the average residential consumer (Cassard et al., 2011). An average residential SWH system provides 7–10 kWh per day depending on the system and solar resource, while an average electric storage water heater typically consumes 12 kWh to meet hot water demand, depending on ground water temperature (SRCC, 2001). Thus, the energy savings associated with SWHs are moderated by the efficiency and operational requirements of the auxiliary system, especially in less sunny climates.

The efficiency of a SWH is calculated with:

$$\eta_{SWH} = \frac{E_{delivered}}{E_{consumed} + E_{auxiliary}} \tag{3.1}$$

where η_{SWH} is the SWH efficiency, $E_{delivered}$ is the thermal energy delivered to a volume of water, $E_{consumed}$ is the energy consumed (i.e. non-solar energy) by the water heater (zero for passive system designs), and $E_{auxiliary}$ is the energy consumed by the auxiliary system. Thus, in hot, sunny climates, the efficiency of SWH systems is higher than in cooler, overcast climates.

Unlike the efficiencies of natural gas and electric water heaters, which increase with volume drawn, the efficiency of SWHs decrease with draw volume, especially when solar resources are limited and water main temperatures are lower (Maguire et al., 2013). The site-efficiencies of SWHs with electric backup systems are generally higher than those with gas backups. A SWH with a gas auxiliary system requires two tanks, while an electric system requires one solar-electric integrated tank and experiences fewer stand-by losses (Maguire et al., 2013). However, the overall energy savings of SWH installations are dependent on the hot water system that is being replaced, as well as other climatic and dwelling-specific characteristics.

A report published in 2013 by NREL evaluated the source energy consumption of water heating systems including conventional gas storage, conventional electric resistance storage, tankless noncondensing gas, heat pump water heaters, condensing storage, and SWHs with both gas and electric backup. Energy consumption results differ by daily draw volumes and use profiles, pipe distribution networks in the house, climatic zone (i.e. cold, mixed-humid, hot-humid, hot-dry, marine- warm, and marine-cold), and use in a conditioned (i.e. heated or cooled) versus an unconditioned space (i.e. a basement or garage), indicating that the EF is not consistent across US homes (Maguire et al., 2013). The report concludes that SWHs are generally the most efficient system for homes with relatively low hot water usage, especially in unconditioned spaces. However, in the Pacific Northwest, SWHs are not an economical choice since hot water demand is high and there is a high percentage of overcast days throughout the year (Maguire et al., 2013).

The NREL report also concludes that SWHs result in net heating in spaces around the pipes, which is not advantageous in conditioned spaces in hot climates, where heat pumps, for example, might be more efficient by providing net cooling by removing heat from the ambient environment. (Conventional storage units also result in net heating in cooled spaces according to the length and geometry of the piping network (Hiller, 2005; Maguire et al., 2013).) Therefore, high SWH efficiencies in hot climates did not always result in the best performance because the systems compromise cooling in air-conditioned spaces. However, in unconditioned spaces, SWHs consumed the least annual primary energy in five of the six climate zones evaluated across all hot water usage profiles, with the exception of the marine-cold climate where heat pump water heaters performed better. The highest primary energy savings from the baseline scenario occurred in moderate climates such as Atlanta, GA and Los Angeles, CA, rather than Phoenix where hot pipes can increase cooling loads and water heating loads are relatively low. Source energy savings with solar–gas systems are not as large (Maguire et al., 2013).

Cassard, Denholm, and Ong estimated the potential for energy conservation through the diffusion of SWHs in the US to be approximately 1 quadrillion BTU (approximately 1% of 2012 energy consumption), which would correspond to an annual reduction of 50–75 million metric tons of CO_2 (Cassard et al., 2011; Denholm, 2007). Primary energy savings were quantified by assuming a national average heat rate for electricity production; however, scenarios based on a range of marginal fuel distributions for electricity demand were provided in an attempt to account for temporal fluctuations in the averaged heat rate across power generators (Denholm, 2007). National potential for solar water heating was assessed by quantifying the energy performance of a generic SWH assessed by NREL's Solar Advisor Model at thousands of locations based on typical meteorological year (TMY3) climate data at 1020 TMY3 stations. The analysis also calculated the average annual fraction of daily load met by SWHs (versus the load met by the auxiliary water heater) across the US based on the TMY3 stations (Cassard et al., 2011). Therefore, the report assesses total technical potential (i.e. roof availability and solar resource) under the assumption that all regions of the US would implement SWHs. Factors such as economics, aesthetics, local building codes, ordinances, ownership, and other non-technical barriers to diffusion were not considered (Cassard et al., 2011; Denholm, 2007).

Gadsden, Rylatt, and Lomas introduced a GIS-based decision support system to assess the SWH potential in urban environments in the UK based on dwelling characteristics (roof orientation, area, and inclination), socio-economic factors (i.e. ownership, income, number of occupants, and value of dwelling), baseline water heating energy demand, and solar potential (Rylatt et al., 2001; Gadsden et al., 2003). Other analysts have created GIS-based frameworks to quantify the rooftops suitable for residential solar PV and solar thermal installations in regions across the world (Wiginton et al., 2010; Karteris et al., 2013). Although these methodologies are useful for predicting energy savings over small areas when dwelling specific data are available, they are not feasible for assessing SWH potential across the US due to data availability constraints.

In addition to the technical considerations regarding SWHs, there are also non-technical factors, chiefly economic, that affect their proliferation. Most solar water heating analyses point to the critical role of policy incentives in the adoption of these technologies, which tend to trump solar resource and other demographic characteristics (Krasko and Doris, 2013; Timilsina et al., 2012; Coughlin and Cory, 2009; Yamaguchi et al., 2013; Ferrari et al., 2012; Kwan, 2012; Li et al., 2013; Fairey and Parker, 2012; Grieve et al., 2012; Maguire et al., 2013). With federal incentives alone, high installation costs inhibit the cost-competitiveness of SWHs in most regions compared to other technologies (Maguire et al., 2013; Cassard et al., 2011). But despite the economic viability of solar water heating in the many regions of the US where federal, state, and local incentives are combined, the diffusion of SWHs has been relatively low and is poorly documented (NREL, 2013a; Maguire et al., 2013; Shukla et al., 2013; Raisul Islam et al., 2013). Estimates of SWH sales in 2009 range from 7,000 to 40,000 units (less than 0.1% of annual water heater sales) (Maguire et al., 2013; Raisul Islam et al., 2013). And in terms of global installations, the US represented only 1.3% of SWHs (by capacity), lagging far behind China (70.5%), the European Union (12.3%), and Turkey (5.0%) in 2010. (Installations in Japan, Australia, Brazil, Israel, and India are comparable (in terms of total capacity) to the United States (Raisul Islam et al., 2013).)

Solar PV installations, on the other hand, averaged a 49% growth rate per year between 2000 and 2010 increasing from 1.4 to 40 GW of installed capacity, globally (Timilsina et al., 2012). Furthermore, there exists a comprehensive database of US solar PV installations curated by the National Renewable Energy Laboratory, but no analogue exists for SWHs (NREL, 2013d). Several recent analyses have utilized these data to investigate the role of non-technical factors on the adoption of solar PV installations, which lend useful insight into SWH markets. Kwan (2012) developed a regression model to evaluate the influence of various environmental, economic, political, and social characteristics on the dissemination of solar PV installations in the US at the zip-code level. Results indicated that number of solar PV installations are positively correlated to characteristics such as high solar radiation levels, electricity costs, policy incentives, median home values, educational attainment, and voting characteristics (Kwan, 2012).

Other analyses point to the role of peer effects in the adoption of new technologies. Bollinger and Gillingham (2012) conclude that every additional solar PV installation in a zip code in California increases the probability of another installation in that zip code by 0.78 percentage points. Rai and Robinson (2013) reach similar findings in Texas, concluding that the adoption of solar is influenced by the proximity of other solar PV installations by increasing confidence and motivation to invest in new technologies.

Some of the growth of solar PV as compared to SWHs is driven by public perception. Yamaguchi et al. (2013) predicted the diffusion of residential solar PV and SWHs in Japan through 2025 using a Bass diffusion model reflecting consumers preferences measured by means of 375 surveys. The analysis concludes that the willingness to pay index (defined as the utility value relative to the additional initial installation cost) for SWHs was very low compared to solar PV despite lower capital costs, indicating very poor public perception (Yamaguchi et al., 2013). Baskaran et al. (2013) also point to low consumer confidence in SWH suppliers and installers as a factor in the slow growth of SWHs in New Zealand. Although government incentives make SWHs cost competitive, low consumer awareness and lack of information regarding subsidies have limited the technology's diffusion (Baskaran et al., 2013).

3.3 Methodology

This work assesses the primary energy consumption and CO_2 emissions resulting from residential water heating in 27 regions that when aggregated, represent the entire contiguous United States. (It should be noted that Hawaii, while omitted here, has a relatively high fraction of SWHs because of building codes and high energy costs.) The analysis investigates the impact of regional characteristics on reducing energy demand and CO_2 emissions. A flow diagram that illustrates the methodology employed in this chapter is provided in Figure 3.2.

Baseline estimates of average primary energy consumption and associated CO_2 emissions for residential water heating were computed for an average household based on the average regional distribution of water heating units detailed in the EIA 2009 Residential Energy Consumption Survey (RECS). Once baseline quantities were established, changes to regional water heating fleets were assessed to quantify the influence of shifts in technology on the energy and CO_2 emissions derived from regional residential water heating practices.

Scenarios 1 and 2 assess the effects of switching technologies in 10% of all households across the US (i.e. all regions experience uniform shifts). Scenarios 3 and 4 assess the effect of switching in 10% of households nationally based on regional potential. Scenarios 1 and 3 assume switching from electric storage water heaters to natural gas storage water heaters; Scenarios 2 and 4 assess switching from electric storage water heaters to SWHs with electric back-up. Regional estimates of primary energy consumption and CO_2 emissions are resolved to consider local electricity mixes, heat rates, solar radiation profiles, heating degrees days, and water heating unit sales for each of the 27 regions. The four scenarios are as follows:

Scenario 1: 10% of total water heaters in region i switch from electric to natural gas storage water heaters.

Scenario 2: 10% of total water heaters in region i switch from electric to SWHs with electric storage water heating backup.

Scenario 3: 10% of total homes nationally switch from electric to natural gas storage water heaters based on regional potential.

Scenario 4: 10% of total homes nationally switch from electric to SWHs based on regional potential.

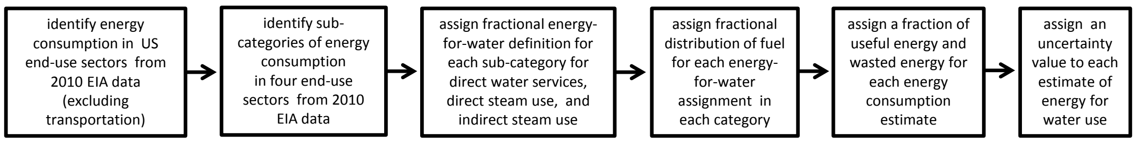

Figure 3.2: An illustrative overview of the methodology utilized in this chapter is provided here.

To aid in the quantification of primary energy and CO_2 emissions, several sets of indices are employed. These indices are summarized in Table 3.2.

3.3.1 Quantifying Regional 2010 Water Heating Trends

Regional trends in water heating characteristics were estimated using data from EIA 2009 RECS, which characterizes the total stock of water heating units in the US in terms of fuel type, size, and age for 27 regions of the contiguous United States (EIA, 2011c). (The analysis assumes that there is no change in the 2009 and 2010 US water heating stock since 2010 data were not available.) Clustered regions are illustrated in Figure 3.3 and consist of 5 clusters of two states, 2 clusters of three states, 3 clusters of four states, and 1 cluster of five states. The 16 states not pictured in Figure 3.3 are considered individually.

Quantifying 2010 Primary Energy Consumed by Electric, Natural Gas, and Oil Water Heaters for 27 regions of the Contiguous US

Once regional water heating unit distributions were established, the primary energy consumed for water heating in 2010 was estimated for each region. Since the 2009 RECS water heating data offered no information regarding energy consumption

Table 3.2: Definition of Indices for Water Heating Analysis

Index	Classification	Description
i = 1, 2, 3,..., 27	Regions	27 US regions
$j = 1$	WH type	Electric
$j = 2$	WH type	Natural Gas
$j = 3$	WH type	Fuel oil
$j = 4$	WH type	Liquid Petroleum Gas
$j = 5$	WH type	Solar Water Heater
$k = 1$	Life-Cycle	Upstream Losses & Conversions
$k = 2$	Life-Cycle	Fuel Distribution
$k = 3$	Life-Cycle	End use (i.e. Efficiency of Appliance)
$k = 4$	Life-Cycle	Pipe losses
m = 1, 2, 3,..., n	US County	3109 US Counties; variable n within region i
$n = 1$	Primary Fuel	Coal
$n = 2$	Primary Fuel	Natural Gas
$n = 3$	Primary Fuel	Petroleum liquids (incl. fuel oil)
$n = 4$	Primary Fuel	Petroleum gases (incl. LPG)
$n = 5$	Primary Fuel	Solar or non-biomass renewable
$n = 6$	Primary Fuel	Biomass
$n = 7$	Primary Fuel	Nuclear

(only a physical inventory of water heating units per region), total annual primary residential energy consumption in each region was aggregated by region according to the EIA State Energy Data System (SEDS) (EIA, 2013b). Water heating in the US represented 12.9% of total annual primary residential energy consumption in 2010 (DOE, 2011); however, since the energy required for regional water heating is dependent on the temperature of incoming water, more energy is required for water heating in states with higher heating loads (Široký et al., 2011; Maguire et al., 2013). The Heating Degree Day (HDD) index, reported by NOAA, indicates the demand for energy needed to heat a home or building based on regional climatic variables (Široký et al., 2011). Equation 3.2 is used to accommodate for regional differences in

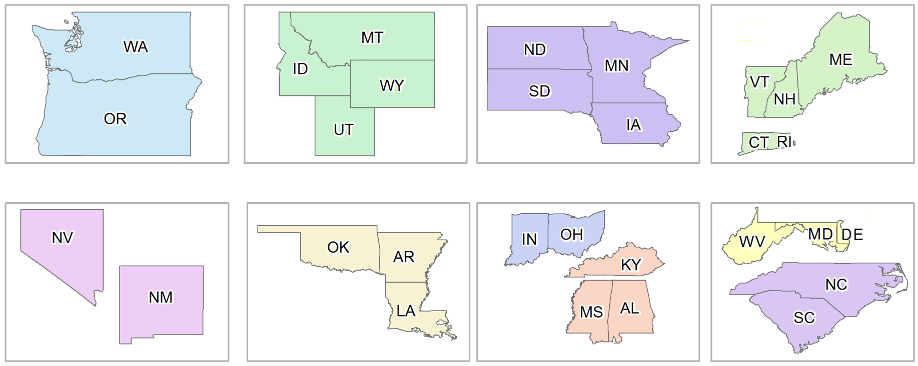

Figure 3.3: Regional trends in water heating were summarized for 27 regions of the US. Similarly colored states were considered as clusters. States that are not pictured were considered individually.

the relative magnitude of residential water heating energy demand across each region. PE_i is the weighted estimate of primary energy for water heating in region i defined as:

$$PE_i = PE_{res,i} \times F_{res,wh} \times W_i \tag{3.2}$$

where $PE_{res,i}$ is annual residential primary energy consumption in region i; $F_{res,wh} = 0.129$, which is the average annual fraction of residential primary energy consumed for residential water heating in the US in 2010; and W_i is a weight based on the annual HDD index in region i reported by NOAA (NOAA, 2013).

W_i was assigned based on the percentile distribution when HDD index values were ranked across all 27 regions from lowest heating load (low HDD) to highest heating load (high HDD). Figure 3.4 shows the percentile rank for each region based on its HDD index. Thus, a region in the lowest 20% of heating degree days, was assumed to use a lesser fraction of its regional residential energy for water heating than a region in a higher quintile. These definitions were as follows:

- Very Low HDD_i, (0-20%): $W_i = 0.8$;

- Low HDD_i, (20-40%): $W_i = 0.9$;
- Average HDD_i, (40-60%): $W_i = 1.0$;
- High HDD_i, (60-80%): $W_i = 1.1$; and
- Very High HDD_i, (80-100%): $W_i = 1.2$.

Next, an average source efficiency, η_j, was computed for each water heating technology j, with Equation 3.3 using the assumptions listed in Table 3.3. (Note that estimating pipe heat losses was beyond the scope of the analysis due to the wide variability in residential piping networks.)

$$\eta_j = \prod_{k=0}^{4} \eta_{j,k} \tag{3.3}$$

The averaged heat rate and fuel distribution of electricity generation for each region was calculated and the thermal efficiency of electricity generation, $\eta_{j=1,k=1}$, in region i was determined with Equation 3.4:

$$\eta_{j=1,i} = \frac{E_{out,i}}{PE_{in,i}} \times 3412 \frac{MMBTU}{MWh} \tag{3.4}$$

where $E_{out,i}$ was the power generated (MWh) in region i in 2010; and $PE_{in,i}$ was the primary energy consumption by electricity producers (MMBTU) to generate $E_{out,i}$.

Total annual primary energy consumption, $PE_{i,j}$, was calculated for water heating technology j across each region i with Equation 3.5:

$$PE_{i,j} = PE_i \times \frac{N_{i,j} \times N_i^{-1} \times \eta_j{}^{-1}}{\sum_{j=1}^{5} (N_{i,j} \times N_i^{-1} \times \eta_j{}^{-1})} \tag{3.5}$$

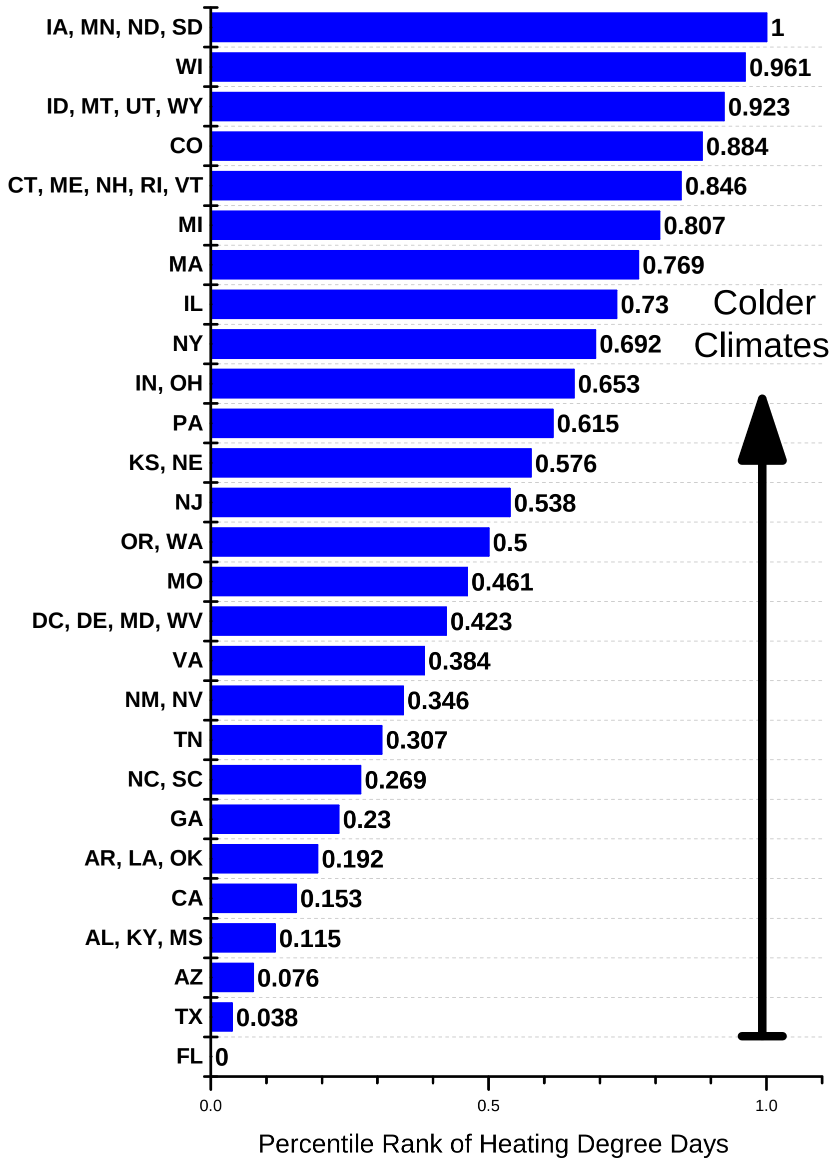

Figure 3.4: A percentile rank was assigned to each region based on its Heating Degree Day (HDD) index. Regions with the coldest climates have very high heating loads (percentile rank close to 1), while warmer regions have very low heating loads (percentile rank closer to zero).

Table 3.3: Source efficiencies were calculated by multiplying upstream and site efficiencies listed here for each technology. End use Energy Factors reflect values from the American Council for an Energy-Efficient Economy (ACEEE, 2013).

k	$\eta_{j=1,k}$	**Electric Storage**	$\eta_{j=2,k}$	**Natural Gas Storage**	$\eta_{j=3/4,k}$	**LPG/ Fuel Oil Storage**
1	$\eta_{gen,i}$	Power Generation	0.95	Extraction & conversion	0.95	Extraction & conversion
2	0.93	Transmission & Distribution	0.95	Distribution	0.95	Distribution
3	0.90	End use	0.60	End use	0.55	End use
4	NA	Pipe Losses	NA	Pipe Losses	NA	Pipe Losses

where $N_{i,j}$ was the number water heating units of type j in region i, and N_i was the total water heating units in region i. (The index j was summed from $j = 1$ to $j = 5$ to include electric (j=1), natural gas (j=2), fuel oil (j=3), LPG (j=4), and solar water heaters (j=5).) In the baseline case, solar water heaters represented a negligible proportion of water heaters.) Figure 3.5 summarizes the fractional distribution of water heating units by fuel type in 27 regions. The 15 uppermost regions in Figure 3.5 had more natural gas storage water heaters than electric storage water heaters in 2009; the 12 remaining regions lean more on electric storage water heating technologies.

$$PE_i = \sum_{j=1}^{5} PE_{i,j} \tag{3.6}$$

$$PE = \sum_{i=1}^{27} \sum_{j=1}^{5} PE_{i,j} \tag{3.7}$$

Equation 3.6 represents the total annual primary energy consumed for water heating in region i across all technologies. Equation 3.7 represents the annual primary energy consumed for water heating across the whole contiguous US. (If calculations have been done correctly, PE_i in Equation 3.7 will equal PE_i calculated in

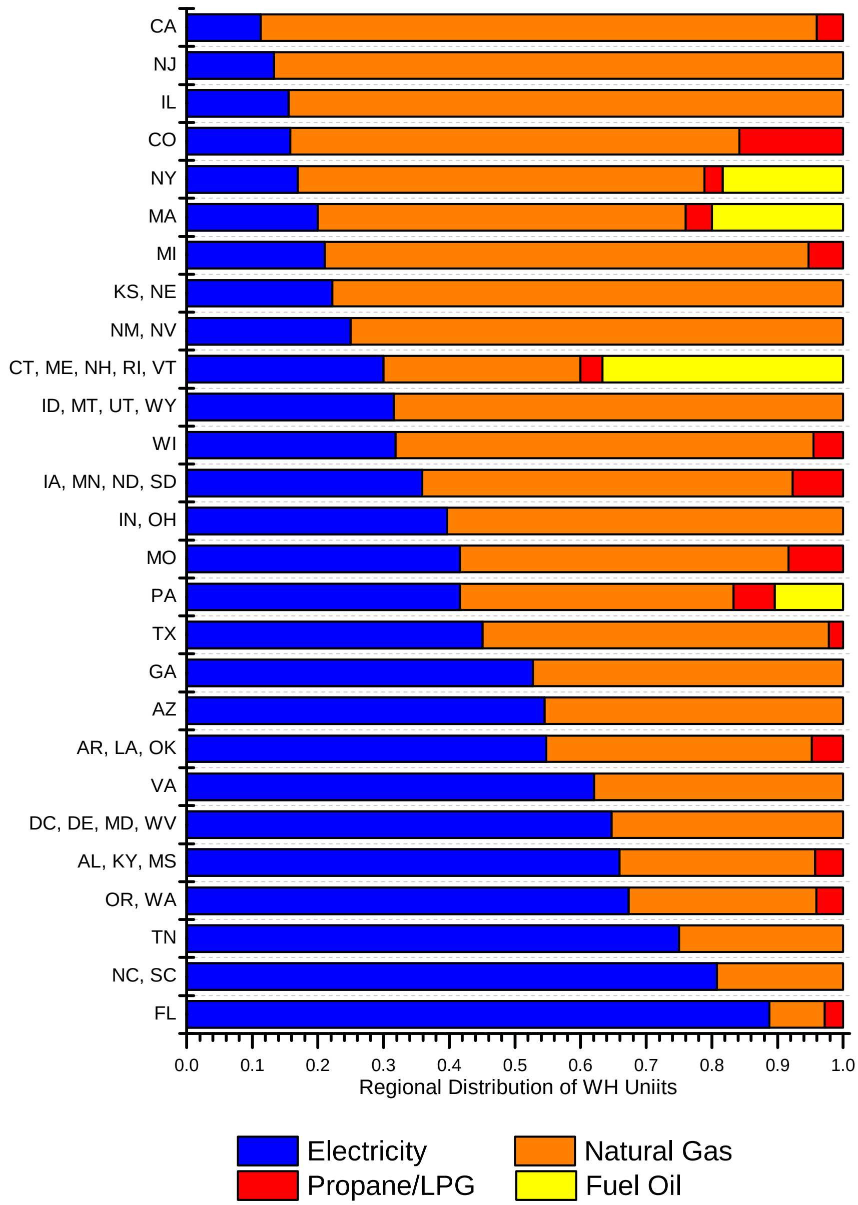

Figure 3.5: The distribution of water heating units by fuel type in 2009 varied across the 27 regions of interest (EIA, 2011c). Regions are sorted by increasing fraction of electric water heaters. Solar water heating systems are negligible.

Equation 3.2. Likewise, PE should equal the value for primary energy consumed for US water heating reported in the DOE's 2010 Building Energy Book (DOE, 2011).) Average annual primary energy per household in region i was calculated by normalizing PE_i by number of households in region i, HH_i (Equation 3.8). Figure 3.16 summarizes these results.

$$PE_{HH,i} = \frac{PE_i}{HH_i} \tag{3.8}$$

Quantifying 2010 CO_2 Emissions derived from Electric, Natural Gas, LPG, and Fuel oil Water Heating in 27 regions of the Contiguous US

Each primary energy consumption estimate, $PE_{i,j}$, was used to compute a CO_2 emissions estimate, $CE_{i,j}$, for regional water heating technology. Emission factors defined by the US EPA were used to reflect the CO_2 emissions intensity, ϵ_n, of each primary fuel consumed for water heating in terms of kg CO_2 per MMBTU (EPA, 2013a). (Index n refers to the primary fuels detailed in Table 3.2, which are consumed for water heating technologies j = 1,...,5 in the United States.) Table 3.4 details an emissions intensity value, (ϵ_n), for each primary fuel consumed at the point of water heating or electricity generation.

Table 3.4: EPA emission factors were used to calculate CO_2 emissions for water heating in 27 regions of the contiguous US.

n	Fuel	**Emission Intensity Factor, ϵ_n kg CO_2 per MMBTU**
1	Coal	94.4
2	Natural Gas	53.0
3	Petroleum liquids (incl. fuel oil)	74.0
4	Petroleum gases (incl. LPG	63.0
5	Solar or other non-biomass renewable	0.0
6	Biomass	93.8
7	Nuclear	0.0

Equation 3.9 was used to compute the total annual CO_2 emissions, $CE_{i,j=1}$, for electric storage water heaters in region i. In this calculation, PE_j had to be multiplied by the fractional electricity mix (composed of $F_{elec,n}$ for primary fuels n = 1,...,7) in order to capture the CO_2 intensity of each region's power sector. (Regional electricity mixes are summarized in Figure 3.6.) Carbon free fuels, nuclear and renewables, are summarized in shades of green and blue, respectively. In the case of natural gas ($j = 2$), fuel oil ($j = 3$), and LPG ($j = 4$) consuming water heating technologies, Equation 3.10 was sufficient to quantify total annual emissions, $CE_{i,j}$.

For $j = 1$:

$$CE_{i,j} = PE_{i,j=1} \times \sum_{n=1}^{7}(F_{elec,n} \times \epsilon_n) \tag{3.9}$$

For $j > 1$:

$$CE_{i,j} = PE_{i,j} \times \epsilon_{n=j} \tag{3.10}$$

Equation 3.11 represents total annual CO_2 for water heating in region i. Equation 3.12 represents the annual CO_2 for water heating across the whole contiguous US. Average CO_2 per household in region i was calculated by normalizing CE_i by number of households in region i, HH_i (See Equation 3.13). Figure 3.16 summarizes these results.

$$CE_i = \sum_{j=1}^{5} CE_{i,j} \tag{3.11}$$

$$CE = \sum_{i=1}^{27}\sum_{j=1}^{5} CE_{i,j} \tag{3.12}$$

$$CE_{HH,i} = \frac{CE_i}{HH_i} \tag{3.13}$$

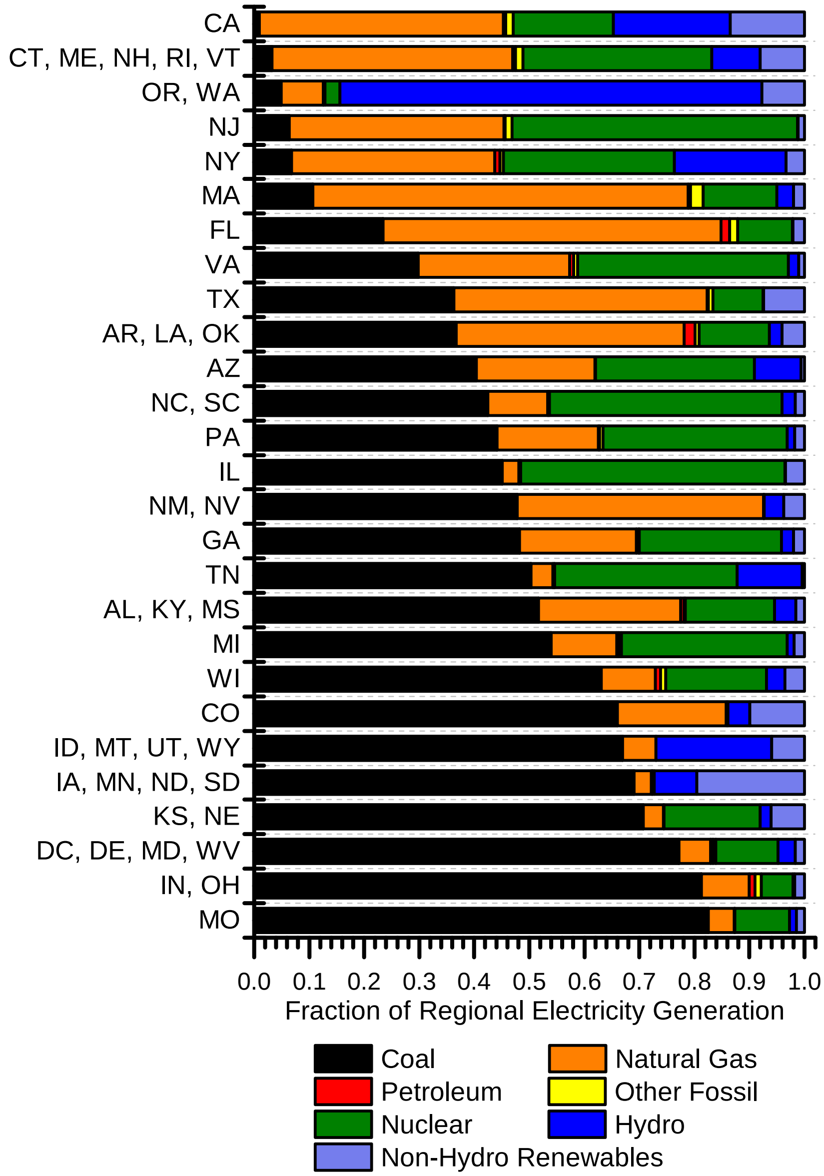

Figure 3.6: Regional electricity fuel generation distributions vary by region. States with large fractions of renewables (blue) and nuclear (green) generally have a less CO_2 intensive power sector than states with fossil-fuel heavy electricity generation. This chart does not include power imports from one region to another (i.e. it considers production, not consumption).

3.3.2 Assessing Energy Impacts from Uniform Shifts in Water Heating Technologies

Once baseline energy consumption and CO_2 emissions were established, the effects of shifting 10% of the water heaters in each respective region were evaluated in Scenarios 1–4. Here, scenario-specific calculations use the notation **(S:1)**, **(S:2)**, **(S:3)**, and **(S:4)** for Scenarios 1, 2, 3, and 4, respectively. Switching in these scenarios from electric water heaters ($j = 1$) to natural gas water heaters ($j = 2$) and electric water heaters to SWHs ($j = 5$) is represented by the notation j=1→2 and j=1→5, respectively.

Scenario 1: Electric to Natural Gas Water Heating Units

Scenario 1 assesses the energy consumption and CO_2 emissions that follow technology shifts in 10% of the water heating fleet in each region. All shifting is assumed to be from electric storage water heating to natural gas storage water heating units. The number of units subject to switching between electric ($j = 1$) and natural gas units ($j = 2$), $N(S:1)_{i,j=1\rightarrow 2}$, was determined by Equation 3.14.

$$N(S:1)_{i,j=1\rightarrow 2} = 0.1N_i \tag{3.14}$$

Equations 3.15 and 3.16 were used to compute the total number of electric storage units and natural gas storage units, respectively, in Scenario 1.

$$N(S:1)_{i,j=1} = N_{i,j=1} - N(S:1)_{i,j=1\rightarrow 2} \tag{3.15}$$

$$N(S:1)_{i,j=2} = N_{i,j=2} + N(S:1)_{i,j=1\rightarrow 2} \tag{3.16}$$

Equations 3.2 through 3.5 were used to assess the effects of uniform shifts in water heating technologies across the 27 regions of the US by inserting new values of $N_{i,j}$ (i.e. $N_{i,j=1} = N(S:1)_{i,j=1}$ and $N_{i,j=2} = N(S:1)_{i,j=2}$). The *total* number of water heating units across the US is assumed to be consistent with the baseline scenario; the numbers of fuel oil, LPG, and solar water heating water units are also assumed to be equal the number of each in the baseline scenario.

Since the total primary energy consumed for Scenario 1 is not equal to the primary energy consumed in the baseline scenario, the primary energy results had to be multiplied by a weighted factor, $W(S:1)_i$, computed in Equation 3.17 which is specific to region i and technology j. This factor is unrelated to the weighted factor in Equation 3.2 and serves in scaling Scenario 1 results so that primary energy is not overpredicted. (Note: $PE(S:1)_{i,j}$ is the value computed with Equation 3.5 based on the new values of $N(S:1)_{i,j=1}$ and $N(S:1)_{i,j=2}$, while $PE_{i,j}$ is the value computed with baseline values of $N_{i,j=1}$ and $N_{i,j=2}$.)

$$W(S:1)_i = \frac{\sum_{j=1}^{5} PE(S:1)_{i,j}}{\sum_{j=1}^{5} PE_{i,j}} = \frac{PE(S:1)_i}{PE_i} \tag{3.17}$$

$$PE(S:1)_{w,i,j} = W(S:1)_i \times PE(S:1)_{i,j} \tag{3.18}$$

$PE(S:1)_{w,i,j}$ represents the final, weighted value of primary energy consumed for Scenario 1. The new value of $PE(S:1)_{w,i,j}$ was used to replace $PE_{i,j}$ in Equations 3.6 through 3.13 to calculate CO_2 emissions values.

Scenario 2: Electric to Solar Water Heating Units

Scenario 2 assesses the energy consumption and CO_2 emissions that are associated with shifting 10% of all of water heating units in region i from electric storage water heating to SWH units with electric storage backup. The number of units subject to switching between electric ($j = 1$) and SWHs ($j = 5$), $N(S:2)_{i,j=1\rightarrow 5}$, is equal to the value calculated in Equation 3.14.

$$N(S:2)_{i,j=1\rightarrow 5} = N(S:1)_{i,j=1\rightarrow 2} \tag{3.19}$$

In this scenario, values of $N(S:2)_{i,j=1}$ reflect the net decrease in electric storage water heaters, which is equal to the number of conventional electric storage water heaters subject to switching less the incremental increase in electric storage water heating units used as back-up for new solar water heating units. These relationships are illustrated in Equations 3.20 and 3.21.

$$N_{aux,i} = N(S:2)_{i,j=1\rightarrow 5} \times (1 - F_{solar,i}) = N(S:2)_{i,j=1\rightarrow 5} \times F_{aux,i} \tag{3.20}$$

$$N(S:2)_{i,j=1} = N_{i,j=1} - N(S:2)_{i,j=1\rightarrow 5} + N_{aux,i} \tag{3.21}$$

The annual water heating demand satisfied by a SWH unit varies by region according to average annual solar radiation. Here, the fraction $F_{solar,i}$ is defined as the fraction of annual water heating demand met by solar radiation in region i as reported by Maguire et al. (2013). Accordingly, $F_{aux,i}$ is the fraction of annual water heating demand met by the back-up auxiliary units in region i defined in Equation 3.22.

$$F_{aux,i} = 1 - F_{solar,i} \tag{3.22}$$

Since the fraction of annual water heating demand satisfied by the solar collector requires no fossil fuel input, only the net change in the amount of electricity demand in region i was pertinent to computing annual primary energy demand and CO_2 emissions from water heating. Once the new value for electric storage water heating units in region i was calculated ($N(S:2)_{i,j=1}$), the methodology outlined in Scenario 1 was repeated with the weighted value $W(S:2)_i$ defined in Equation 3.23. Again, this weighted factor is used to scale primary energy from a value equal to the baseline to a value that reflects the energy consumption of the redistributed water heating fleet. The total number of water heating units across the US is assumed to be consistent with the baseline scenario; the number of fuel oil, LPG, and natural gas storage water heating units are assumed to be equal to the baseline scenario.

$$W(S:2)_i = \frac{\sum_{j=1}^{5} PE(S:2)_{i,j}}{\sum_{j=1}^{5} PE_{i,j}} = \frac{PE(S:2)_i}{PE_i} \tag{3.23}$$

$$PE(S:2)_{w,i,j} = W(S:2)_i \times PE(S:2)_{i,j} \tag{3.24}$$

$PE(S:2)_{w,i,j}$ represents the weighted value of primary energy consumed for Scenario 2 and was used in place of $PE_{i,j}$ in Equations 3.6 through 3.13.

3.3.3 Assessing Regional Potential for Shifts in Water Heating Technologies

While Scenarios 1 and 2 assessed uniform shifts in water heating technologies across each of the 27 defined regions, Scenarios 3 and 4 assess shifts in water heating technologies according to potential by identifying the regions that would be most inclined to switch water heating technologies.

Scenario 3: Electric Storage to Natural Gas Water Heating Units

Scenario 3 assessed the effect of switching 10% of the national water heating fleet from electric storage water heaters to natural gas storage water heaters based on potential. The ratio of natural gas storage tank water heaters to electric is approximately 5:4 in the United States, and together they comprise approximately 94% of total US water heating units (EIA, 2011c; Maguire et al., 2013). Thus, it is assumed that the decision to buy an electric or natural gas water heater is largely economic, since both technologies are widely implemented, and therefore, exhibit high consumer awareness and trust.

Assessment of the potential for switching from electric to natural gas water heating was done by comparing statewide average electricity prices and natural gas prices reported by the EIA for the year 2011 (EIA, 2012).

- States that had average 2010 natural gas prices lower than the national mean price were assigned a fraction, $F_{NG,i} = 0.05$.
- States that had average 2010 electricity prices higher than the national mean price were assigned a fraction of $F_{NG,i} = 0.05$.
- States that met both of these criteria were assigned a fraction of $F_{NG,i} = 0.10$.

These fractional assignments are arbitrary, though logically deduced, and the methodology could be repeated for other values. These state assignments were averaged by region i (for regions with multiple states) to determine $F_{NG,i}$ and scaled such that 10% of national water heating units were switched using a scaling constant. This scaling constant, C, was determined with Equation 3.25:

$$C = \frac{0.10 \times \sum_{i=1}^{27} N_i}{\sum_{i=1}^{27} (F_{NG,i} \times N_i)} \tag{3.25}$$

The scaling constant was used to ensure that every region had an equal fraction of technology switching since the original $F_{NG,i}$ were arbitrary.

All values of $F_{NG,i}$ were scaled with C to compute, $N(S:3)_{j=1\rightarrow 2}$:

$$N(S:3)_{j=1\rightarrow 2} = C \times F_{NG,i} \times N_i \tag{3.26}$$

New values of electric storage and natural gas storage water heaters are quantified with Equations 3.27 and 3.28, respectively:

$$N(S:3)_{i,j=1} = N_{i,j=1} - N(S:3)_{j=1\rightarrow 2} \tag{3.27}$$

$$N(S:3)_{i,j=2} = N_{i,j=2} + N(S:3)_{j=1\rightarrow 2} \tag{3.28}$$

The methodology presented in Scenario 1 was repeated for new values of $N(S:3)_{i,j=1}$ and $N(S:3)_{i,j=2}$ to compute primary energy consumption and CO_2 emissions associated with Scenario 3.

Scenario 4: Electric Storage to SWH Units

Regression analysis is used to identify the potential for fuel switching from an conventional electric storage tank water heater to a SWH based on selected technical and non-technical variables to characterize regions that might be prone to fuel switching. Regression analysis is used to assess SWH diffusion since a consumer's decision to switch to a distributed renewable energy source (such as solar PV or solar thermal) is multivariable in nature (i.e. based on environmental, economic, political, and social characteristics). Data regarding PV installations are used to build a regression model to predict future SWH installations since they require similar siting considerations, are likely appeal to a similar population demographic, and have a robust centralized dataset regarding US installations.

The following sections describe the regression model, which is used characterize the potential scale of SWH installations per county based on factors such as solar radiation levels, fuel costs, policy incentives, median home values, educational attainment, and voting characteristics.

Model Overview

A regression model is built to characterize residential PV installations per county based on a number of explanatory variables. The fitted model is then used to predict county-level SWH diffusion replacing PV-specific policy incentives with SWH-specific policy incentives. A general weighted model is presented that considers the regression model, as well as two economic metrics, to predict the diffusion of SWHs across the US. The general model is proposed such that any of the three metrics can be valued less or more based on preferences, since the decision to switch to a SWH is more complex than conventional technologies.

For the purposes of this analysis, results of the weighted model are scaled such that 10% of the national water heating fleet ultimately switches from conventional electric storage water heaters to SWHs with electric storage back-up systems so that the results are readily comparable with the other scenarios. Details regarding the dependent (i.e. PV installations) and explanatory variables are described briefly below.

PV Installation Data

Data from NREL's OpenPV database were used to derive county-level solar PV installation data for the lower 48 states. This database represents a comprehensive national repository of PV installation data, voluntarily contributed by sources such as utilities, installers, and the general public (NREL, 2013d).

Since the focus of this analysis was residential-scale solar PV, installations exceeding 10 kW in size were eliminated from the dataset, as many solar PV financing policies use 10 kW as a cutoff for inclusion in residential PV rebate and tax credit policy incentives (Coughlin and Cory, 2009). This definition of residential-scale solar is also consistent with definitions prescribed in the literature (Kwan, 2012; Leloux et al., 2012). Residential installations were also filtered such that any installations built before January 2005 were excluded, as this was when the Energy Policy Act of 2005 implemented a tax credit (applicable for 30% of the total purchase amount of a qualified SWH) for residential scale solar installations (Kwan, 2012; 109th Congress, 2005; Raisul Islam et al., 2013).

The filtered database included approximately 164,000 residential solar PV installation records representing 837 MW of capacity nationwide. Solar PV installations ranged in size from 1 W to 10 kW, with an average installation size of 5 kW. Installations were plotted according to latitude and longitude coordinates and spatially aggregated to county-level data using the Spatial Join tool available in ESRI's ArcGIS 10.1 in order to be readily comparable to other county-level datasets. Figure 3.7 illustrates these data.

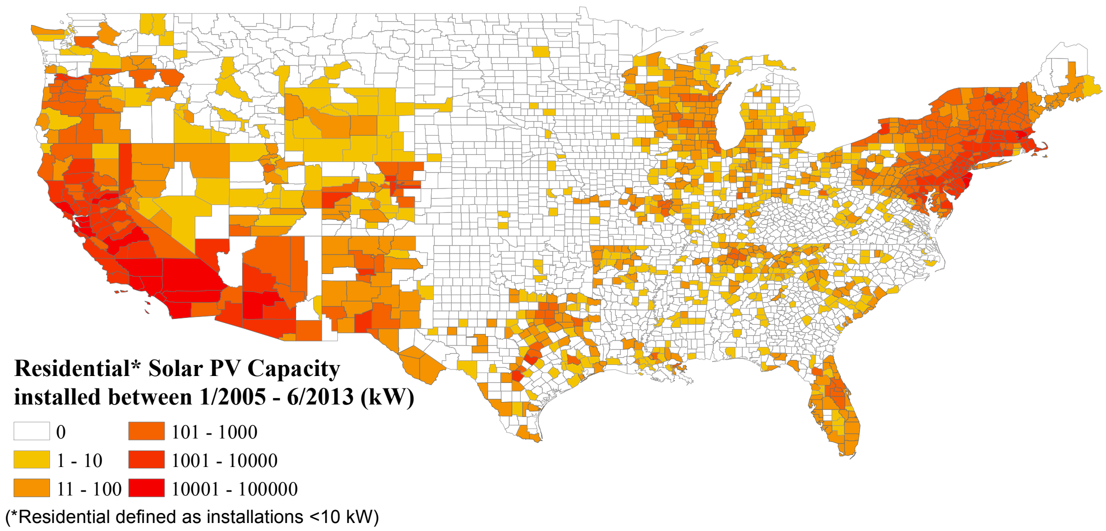

Figure 3.7: County-level solar PV data were derived from the National Renewable Energy Laboratory's OpenPV database. Data represent aggregated residential PV installations as of June 2013 (NREL, 2013d).

Direct Normal Irradiance Data

County-level Direct Normal Irradiance (DNI) values were derived from 10 kilometer resolution solar data published by NREL using the ArcGIS Zonal Statistics tool. (DNI is the quantity of solar radiation received per unit area by a surface held perpendicular to the direction of incoming radiation from the sun at its current position in the sky.) Data in Figures 3.8 and 3.9 represent mean DNI in July and January over the years of 1998 - 2009 (NREL, 2013c).

Solar PV Incentives Data

Data regarding state-level incentives (including rebates and tax credits) for solar PV and SWHs were collected from the *Database of State Incentives for Renewables and Efficiency* (DSIRE). The DSIRE portal, funded by the DOE and maintained by

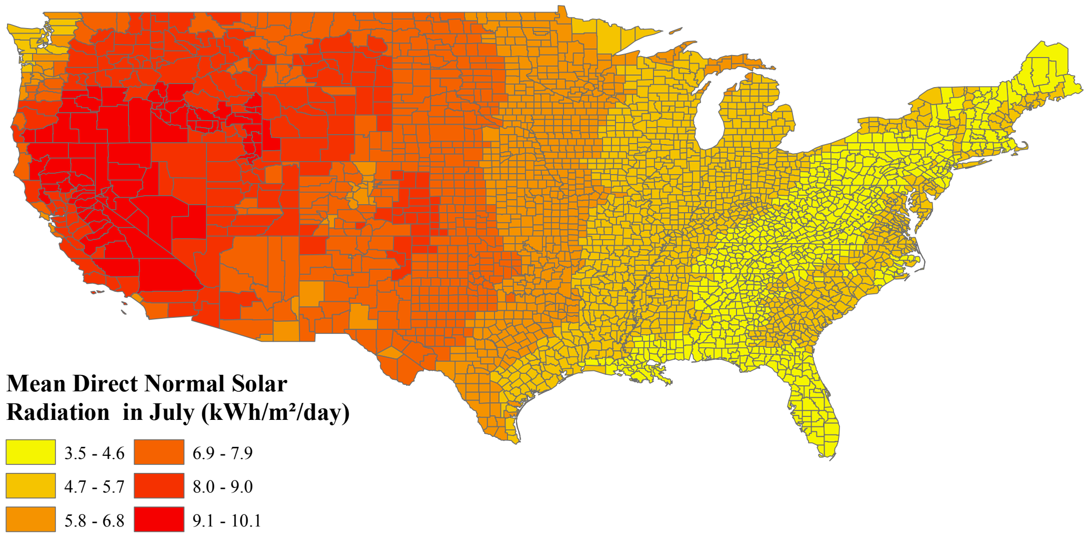

Figure 3.8: Average Direct Normal Irradiance values in July exceed 10 kwh per square meter per day in many counties in the US (NREL, 2013c).

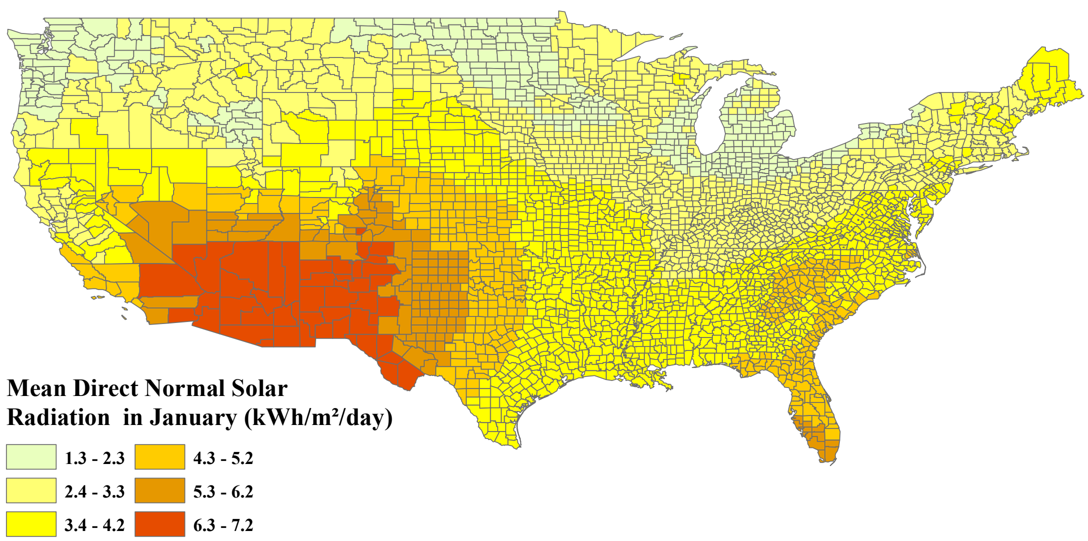

Figure 3.9: Mean values of Direct Normal Irradiance in January are considerably lower during winter months than in summer months, decreasing the cost-effectiveness of solar technologies in many regions of the US (NREL, 2013c).

the North Carolina Solar Center at North Carolina State University, contains aggregated information on incentives and policies that support renewables and energy efficiency (N.C. State University, 2013). Although additional incentives might be available for some residents from their utility or municipality, including local incentives were beyond the scope of this analysis.

Other Demographic Data

Other county-level data, including education, economic, and land use characteristics, were obtained from the US Department of Agriculture Economic Research Service data portal (USDA, 2013).

Summary of County-level Variables Evaluated for Regression Model

The following is a list of the explanatory variables evaluated in the regression model. The sections to follow detail regression model performance and identifies the most significant subset of explanatory variables in predicting solar installations.

- Solar resources: Average direct normal irradiation in January and July
- Poverty: Estimate of people of all ages in poverty in 2011
- Education: The fraction of adults that completed a 4-year degree or higher
- Affluence: Cost of living (COL) index, household mean income
- Energy costs: Average retail electricity price in 2011 and natural gas price (delivered) in 2011
- Urbanization: Population density

- Political Affiliation: Fraction of population who voted Democratic in the 2012 presidential election

- Renewable Energy Policy Incentives: Magnitude of statewide rebates, statewide tax credits, and renewable fuel standards

Regression Model Performance

The open-source software package R was used to complete the statistical analysis (R Development Core Team, 2013). Of the 3109 US counties evaluated in the regression analysis, 1953 counties had zero recorded solar PV installations during the time period of interest. The excessive occurrence of zeros (See Figure 3.10) subjected the model to biased parameters due to zero-inflation in the dependent variable (Zuur et al., 2010). Furthermore, the non-linearity in PV installations required transformation in order to apply linear regression. Although taking the log-transform of the dependent variable resulted in a near-normal distribution, it excluded the 1953 occurrence of zero values, which compromised the efficacy of the model since counties with zero solar installations were ignored.

Likewise, shifting the value of the dependent variable, PV capacity, by an arbitrary value (see Equation 3.29) was also ineffective, as the set of residuals from the transformed model was not normally distributed and exhibited heterogeneity in its variance. The large number of values at the low end of the logarithmic plot also caused a non-linear relationship between the covariate and the expected value, and biased the model. Thus, no transformation of the response variable was adequate to achieve both linearity of the response variable and homoscedasticity (i.e. homogeneity in the variance), which are critical to using a linear regression model (O'Hara and Kotze, 2010). Figure 3.11 illustrates the county-level PV data for a logarithmic transformation (all zeros are ignored) and a shifted logarithmic transformation that demonstrated a large number of values arbitrarily located at the value of the shift (i.e. $\log(0.01) = -2$).

$$Y_{transformed} = \log(Y_{observed} + 0.01) \tag{3.29}$$

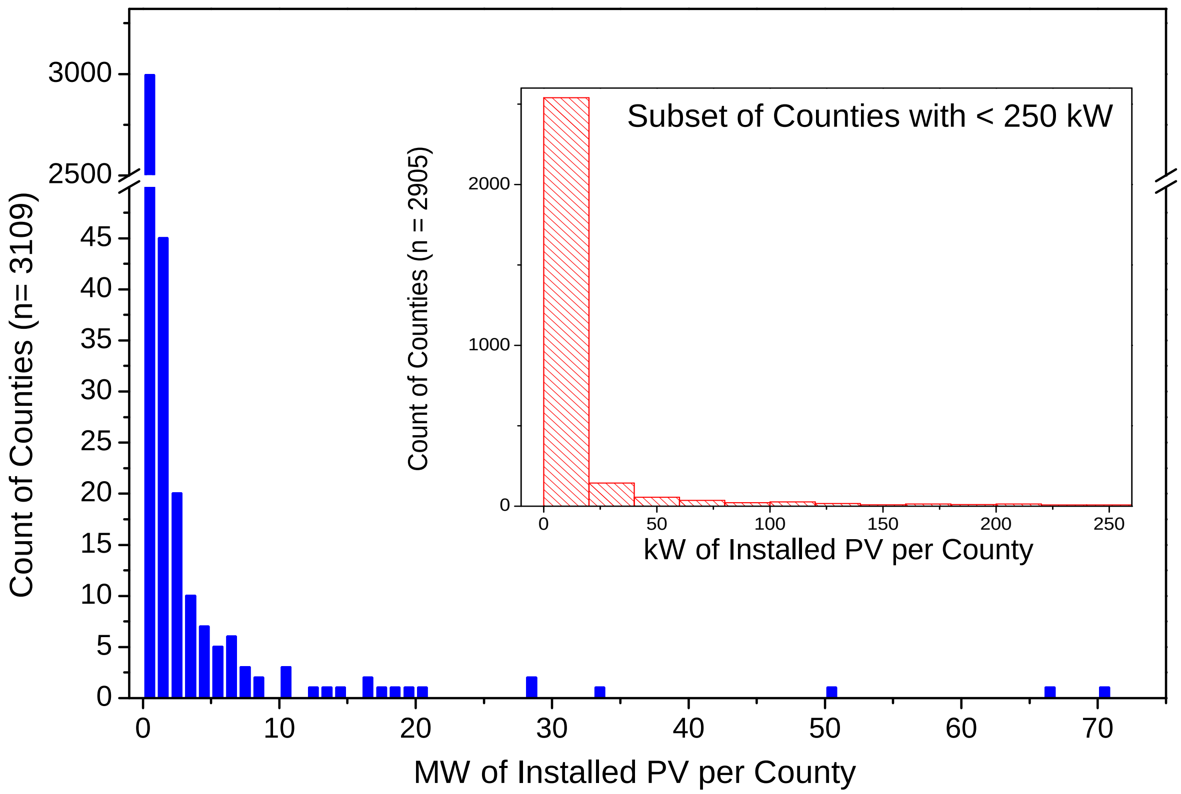

Figure 3.10: Over 90% of US counties in the US have less than 250 kW of installed residential solar PV; 1953 counties (64%) have no installed solar PV.

In general, O'Hara and Kotze (2010) warn that transformations perform poorly for datasets that have a large dispersion. While negative binomial and Poisson models capture large dispersion well, they tend to be inadequate for datasets containing large

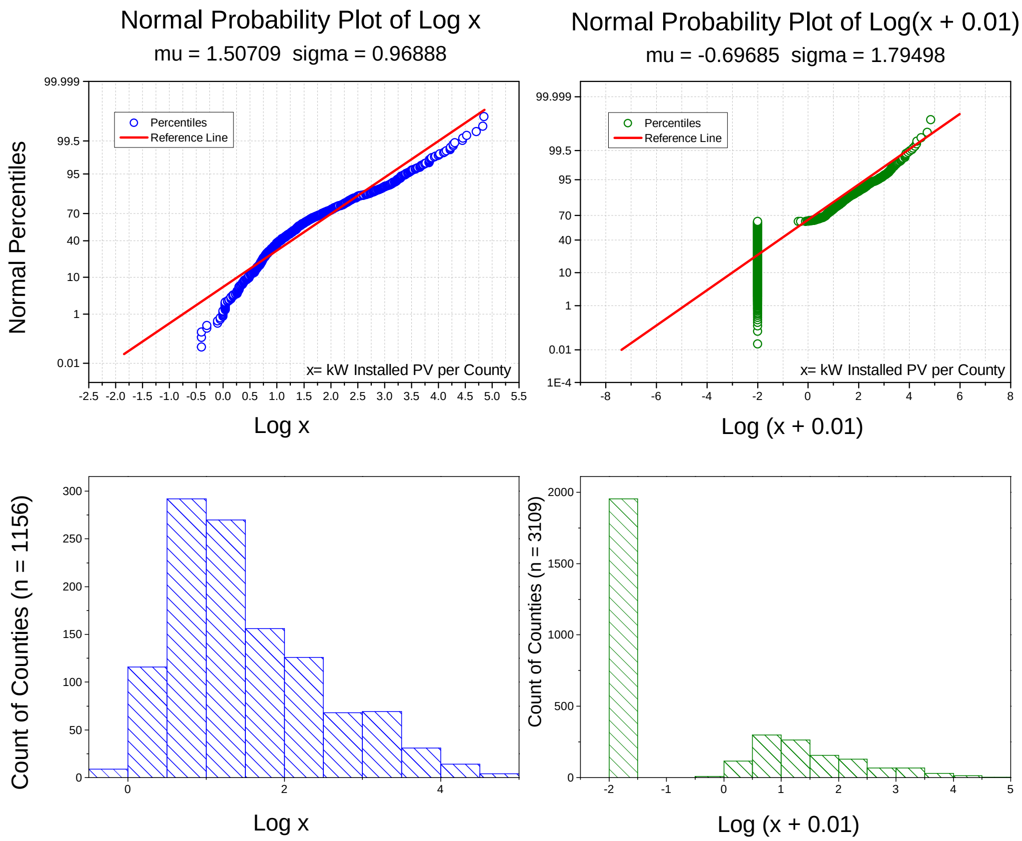

Figure 3.11: A logarithmic transformation of county-level installed residential PV data resulted in a near-normal distribution, but excluded 1953 counties with zero installed capacity. Shifting the data and performing the logarithmic transformation resulted in a model that was insufficient for use in a linear regression model.

counts of zero (O'Hara and Kotze, 2010; Gelman and Hill, 2007). Thus, a zero-inflated generalized linear model (GLM) was applied to the data to effectively accommodate for both over-dispersion and the large counts of zero in the dataset (Jackman et al., 2013; O'Hara and Kotze, 2010; Gelman and Hill, 2007). The model extends the log-linear mean function that characterizes GLMs but adjusts the likelihood for increased counts of zero (Zeileis et al., 2008). Thus, the zero-inflated model is a mixture model that combines a count distribution component and a point mass at zero, as represented in Equation 3.30 (Jackman et al., 2013; Zeileis et al., 2008). (Full documentation of zero-inflated model implementation in R available from Jackman et al. (2013)). The basic zero-inflated model presented by Zeileis et al. (2008) can be represented as:

$$f_{zinf}(y;\chi,\zeta,\beta,\gamma) = \underbrace{f_{zero}(0;\zeta,\gamma)}_{\substack{\text{Zero probability}\\ \text{inflation term}}} \cdot \underbrace{I_0(y)}_{\substack{\text{Point}\\ \text{mass}\\ \text{at zero}}} + (1 - f_{zero}(0;\zeta,\gamma)) \cdot \underbrace{f_{count}(y;\chi,\beta)}_{\substack{\text{Count distribution}\\ \text{term (i.e. Poisson,}\\ \text{Negative Binomial,}\\ \text{Geometric, etc.)}}} \tag{3.30}$$

Here, several zero-inflated models were used to identify a set of statistically significant explanatory variables that influence county-level PV installations. Two count distributions, specifically a generic negative binomial distribution (ZINB) and a geometric negative binomial distribution (ZIGEO), were selected to characterize the residential solar PV data. Although a zero-inflated Poisson (ZIP) regression model was evaluated, it predicted the data poorly. This outcome was expected as negative binomial distributions generally perform better than Poisson regression models for overly-dispersed data, since Poisson models tend to underestimate variance (Zeileis et al., 2008).

The fitted model was run over many iterations to identify the best-performing subset of the listed explanatory variables identified in Section 3.3.3. (A subset of these models are detailed in Figure 3.12.) Mean household income, the fraction of adults that completed a 4-year degree or higher, and the COL index all expressed co-dependence on one another, so only the COL index was considered in the final fitted model, as it was of higher statistical significance than the other two variables. A logarithmic transformation was applied to each explanatory variable that varied over several orders of magnitude, namely population density and the sum of statewide policy incentives. The performance of the fitted models were compared with the Wald Test and Likelihood Ratio Test of Nested Models, which evaluate the performance of estimated parameters and the ratio of likelihood functions, respectively (Hothorn et al., 2013). Additionally, each ZINB model was compared with its respective GLM (without the zero-inflation term) with the Vuong's non-nested hypothesis test (Vuong, 1989). The ZINB model performed better than its corresponding GLM in each case.

Table 3.5 details the performance of one well-fitted model. The output is divided into two sets: Count Model Coefficients and Zero-Inflation Model Coefficients. The Count Model Coefficients include the negative binomial regression coefficients that characterize GLMs, while the Zero-Inflation Model Coefficients characterize the inflation model to account for the high occurrence of zeros in the data set. (Note: "Highly Significant" is defined as a P-value < 0.001 and denoted with "***" in Table 3.5.) Results indicate that the explanatory variables that are most significant in characterizing the negative binomial distribution are not always the most significant in characterizing the inflation term. For example, the magnitude of incentives for solar PV is highly significant in prediciting the Count Model Coefficients, but insignificant in predicting counties with zero-installed PV. (Full details of a sample of six fitted models are provided in Appendix B, including model coefficients, standard error, P-values, and boxplots of residuals.)

In general, the fitted model performed well in predicting the scale of residential

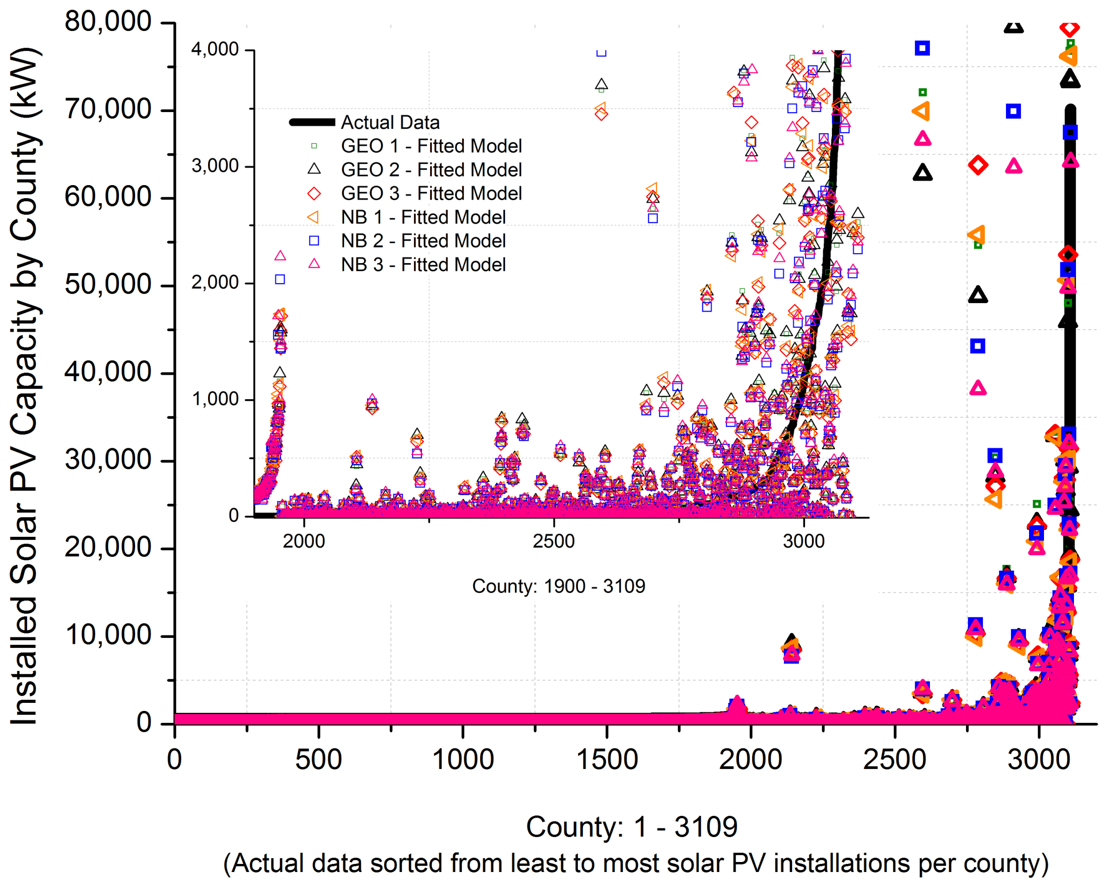

Figure 3.12: Data for 3109 counties were sorted in order of least to greatest solar PV installations. Six predicted values for each respective county are plotted based on the results of six fitted zero-inflated regression models. A sub-set of counties 1900 - 3109 is provided for to provide a more detailed look of the fitted models.

Table 3.5: The zero-inflated negative binomial model detailed here performed well in characterizing county-level residential PV capacity data.

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-8.226	0.395	-20.812	$<2\times10^{-16}$	***
Population Density	1.641	0.054	30.500	$<2\times10^{-16}$	***
Mean July DNI	0.738	0.026	28.456	$<2\times10^{-16}$	***
Avg. Electricity Price	0.373	0.016	24.067	$<2\times10^{-16}$	***
Policy Incentives	0.167	0.013	12.864	$<2\times10^{-16}$	***
Cost of Living Index	0.042	0.004	9.638	$<2\times10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	8.345	0.689	12.118	$< 2\times10^{-16}$	***
Population Density	-1.341	0.085	-15.751	$< 2\times10^{-16}$	***
Avg. Electricity Price	-0.576	0.035	-16.300	$< 2\times10^{-16}$	***
Mean July DNI	-0.462	0.045	-10.198	$< 2\times10^{-16}$	***
Policy Incentives	-0.030	0.019	-1.569	0.12	
Cost of Living Index	0.001	0.006	0.159	0.87	

PV installations. Of the 3109 US counties fitted, 60% of the counties were predicted within 10 kW of their actual installation capacity. Nearly 80% of the counties were fitted within 100 kW of their actual installation capacity. Approximately 10% of the data deviated from their actual installed capacity by more than 1 MW, suggesting that the model was not good at predicting the capacity in counties that had very high solar installation capacity. Considering that the actual installation data included installations that spanned from 0 to 70,000 kW of residential PV capacity, the model predicted installations sufficiently well for the purposes of this analysis. (Overall the mean installation capacity across all counties was 266 kW; the mean for counties with non-zero PV capacity was 714 kW.) Figure 3.13 details the residuals (i.e. the predicted minus the actual value of PV capacity) associated with the fitted model detailed in Table 3.5.

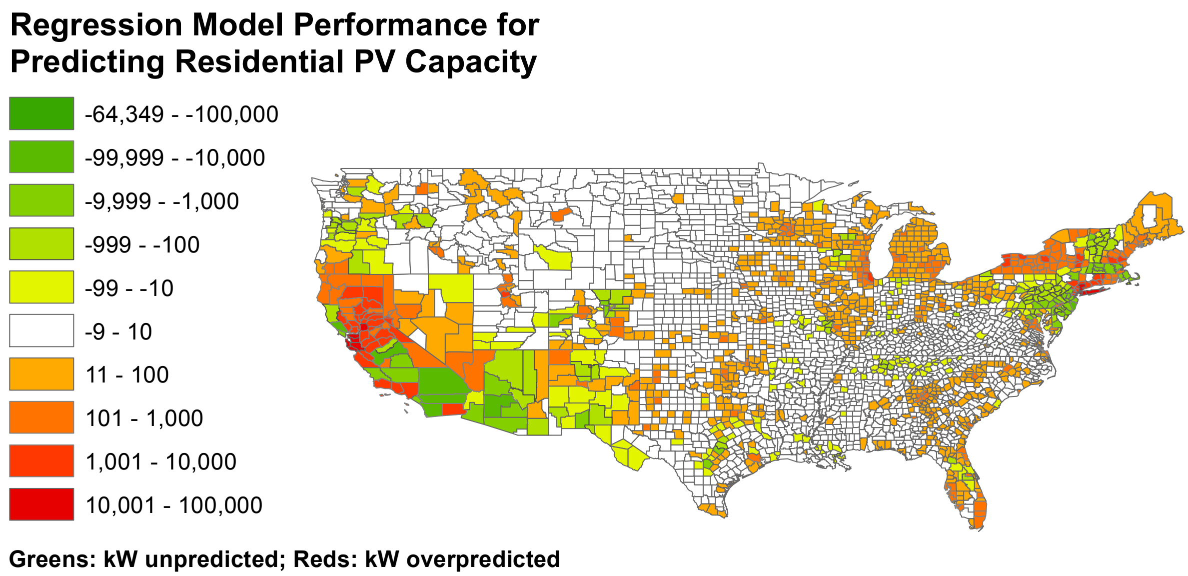

Figure 3.13: The regression model predicted approximately 90% of 3,109 counties within 100 kW of true residential PV capacity. Twenty-four counties were over-predicted or under-predicted by 100 MW or more.

The highest performing ZINB model, summarized in Table 3.5, was executed to predict counties that might be prone to switching to SWH using the same count model and zero-inflation model coefficients. To modify the solar PV prediction model to be applicable to SWH, the logarithmic sum of policy incentives (i.e. state level rebates and tax credits) for residential solar PV systems in each county was replaced with the logarithmic sum of policy incentives for SWH. Since the original model was created such that it predicted solar PV capacity in kW, the model with SWH-specific data was used only to derive to relative magnitude of SWH uptake as a metric to compare potential amongst counties; that is, the scale of the output was important, not the unit. The structure of these models are summarized in Table 3.6.

Table 3.6: Summary of the regressors included in the ZINB solar PV and solar hot water heating models

	Regressor Description	Regressors Used in Count Model	Regressors Used in Count Model
ZINB Solar PV Model	log(Population Density)	X	X
	Mean July DNI	X	X
	Avg. Electricity Price	X	X
	Cost of Living Index	X	
	log(solar PV Policy Incentives)	X	
ZINB Solar Water Heating Model	log(Population Density)	X	X
	Mean July DNI	X	X
	Avg. Electricity Price	X	X
	Cost of Living Index	X	
	log(SWH Policy Incentives)	X	

The log of the predicted values for each county m was calculated with Equation 3.31. Values for $Y_{SWH,m}$ ranged from -1.6 to 5.9 and are illustrated in Figure 3.14. However, values less than zero were assigned a zero value; thus, the final dataset of 3109 county values ranged from 0 to 5.9.

$$Y_{SWH,m} = \log(Y_{fit,m}) \tag{3.31}$$

Savings-to-Investment Ratio Calculations

In addition to the predictive regression model that effectively weights county-level demographic considerations, an average savings-to-investment ratio (SIR) was calculated for each county m based on mean solar DNI in January and July, respectively. The SIR is considered in addition to the regression model to weight new SWH dissemination by county, as the adoption of SWH has shown a stronger correlation to economic considerations than PV installations (Yamaguchi et al., 2013). The SIR is

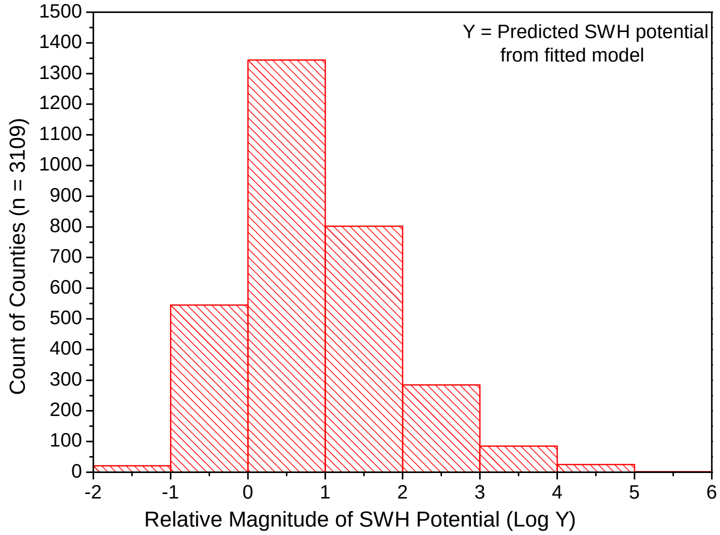

Figure 3.14: The logarithmic transformations of fitted ZINB model predictions for 3109 US counties were used to assess the relative magnitude of SWH potential by county.

used as a metric to assess the economic performance of a SWH investment. It is defined as the present value of total lifetime energy cost savings ($C_{savings,m,i}$) divided by the investment cost (C_{SWH}), as illustrated in Equation 3.32 (Gorgolewski, 1995). The numerator and denominator, $C_{savings,m}$ and $C_{SWH,m}$, are defined in Equations 3.33 and 3.34, respectively. (These costs are both in units of USD ft^{-2}.)

$$SIR_{m,i} = \frac{C_{savings,m,i}}{C_{SWH}} \tag{3.32}$$

In Equation 3.33, S_m is the mean solar radiation in kWh m$^{-2} \cdot day^{-1}$ in county i, η_{SWH} is SWH efficiency, $C_{elec,m}$ is the cost of a unit of electricity in USD kWh^{-1} in county m, r is the discount rate, and t is the SWH system lifetime in years.

$$C_{savings,m,i} = S_{m,i} \times \eta_{SWH} \times C_{elec,m,i} \times \frac{1-(1+r)^{-t}}{r} \times \frac{1m^2}{10.76ft^2} \times \frac{365d}{1yr} \tag{3.33}$$

Equation 3.34 represents the initial cost of the system in terms of C_{cap}, the SWH cost in USD ft^{-2}, and $F_{O\&M}$, the fraction of operation and maintenance (O&M) in relation to C_{SWH}.

$$C_{SWH} = C_{cap} \times (1 + F_{O\&M}) \tag{3.34}$$

To derive a conservative estimate of the SIR for switching from an electric water heater to a SWH, we assign $n = 20$ years and $C_{cap} = 150$ USD ft^{-2}. O&M costs were assumed to be 0.5% (based on NREL (2013b)) of the system cost, C_{cap}. The discount rate was assigned a value of 3.0%, which is consistent with the definitions assigned by the National Institute of Standards and Technology (Rushing et al., 2010). Average installed costs for SWH in the US market range from 100 to 200 USD per ft^{-2} and an average service lifetime of 15–25 years (Raisul Islam et al., 2013; Ong, 2011; Hernandez and Kenny, 2012). The average efficiency of a SWH is assumed to be $\eta_{SWH} = 0.40$. An average SIR_i value was calculated for July and January mean solar DNI values.

A weighting algorithm was created to value the contribution of the regression model, the mean January SIR metric, and mean July SIR metric. Since the ZINB regression model was used to determine relative magnitude of solar SWH potential from one county to another, the logarithmic transformation of the 3109 county-level predicted values for the SWH-specific ZINB model were computed. The 3109 logarithmic transformations are summarized in Figure 3.14. Next, a value was assigned to each county based on its mean January SIR and mean July SIR values, respectively. SIR values greater than one were assigned a weighted value of 1 and SIR values less than one were assigned a weighted value of 0.

Equation 3.35 offers a generic model to assess the potential number of households viable that would switch to SWH from a conventional storage system. β_a, β_b, and β_c scale the contribution of the SWH regression statistic (Equation 3.31), January SIR value, and July SIR value, respectively. The selected fractional values of β_a, β_b, and β_c are assigned to each of the three metrics depending on the preferential weight each should have on $N(S:4)_{j=1\to5}$. (Assigning a value of zero to any of these β values eliminates the dependence of $N_{SWH,m,j=1\to5}$ on that respective metric.)

For illustrative purposes, Figure 3.15 shows the sum of $Y_{SWH,m}$, $SIR_{jan,m}$, and $SIR_{jul,m}$ to show the relative potential for switching among 3109 US counties before aggregation by region i for cases when $\beta_a = \beta_b = \beta_c$.

$$N_{SWH,m,j=1\to5} = HH_i \times (\beta_a \underbrace{\log Y_{SWH,m}}_{\substack{\text{Regression}\\ \text{Model}\\ \text{Predictor}\\ <0-5.9>}} + \beta_b \underbrace{SIR_{jan,m}}_{\substack{\text{January}\\ \text{SIR term}\\ <0-1>}} + \beta_c \underbrace{SIR_{jul,m}}_{\substack{\text{July}\\ \text{SIR term}\\ <0-1>}}) \tag{3.35}$$

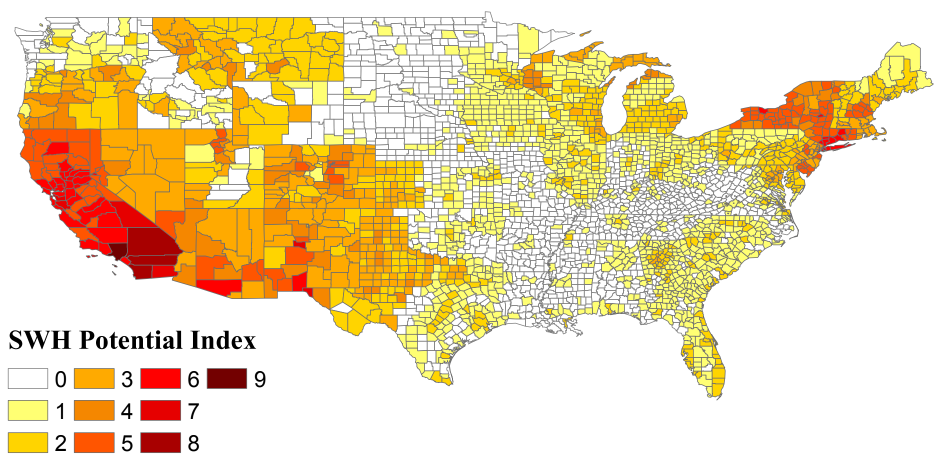

Figure 3.15: The sum of $Y_{SWH,m}$, $SIR_{jan,m}$, and $SIR_{jul,m}$ is shown to illustrate relative potential across 3109 counties of the US. Counties with a "0" index have very low potential for SWH dissemination; counties with a value greater than "5" are very prone to switching.

To ensure that these results are comparable to other scenarios, β_a, β_b, and β_c are assigned values of 0.01 and scaled such that 10% of national water heating units are switched. The scaling constant, C, is determined with Equation 3.36:

$$C = \frac{0.10 \times \sum_{i=1}^{27} N_i}{\sum_{m=1}^{3109} N(SWH)_{m,j=1\to 2}} \tag{3.36}$$

All values of $N(SWH)_{m,j=1\to 5}$ are scaled with C to compute, $N(S:4)_{m,j=1\to 5}$, which represents the number of households subject to switching from an electric storage water heater to a SWH in county m:

$$N(S:4)_{m,j=1\to 5} = C \times N_{SWH,m,j=1\to 5} \tag{3.37}$$

Then all values for $N(S:4)_{m,j=1\to 5}$ are summed in Equation 3.38 to determine a region-specific estimate, $N(S:4)_{i,j=1\to 5}$. (That is, all county-specific values are aggregated according to their region i.)

$$N(S:4)_{i,j=1\to 5} = \sum_{m=1}^{n} N(S:4)_{i,m,j=1\to 5} \tag{3.38}$$

Now, the methodology presented in Scenario 1 is repeated to derive values of primary energy consumption and CO_2 emissions associated with Scenario 4.

3.4 Results

Figures 3.16 and 3.17 illustrate the annual primary energy consumption and average household CO_2 emissions resulting from water heating in the 27 US regions considered in the analysis. While the two figures illustrate the same information, Figure 3.16 aggregates the primary energy consumed for residential electric water heaters into one value, and details each primary fuel consumed on-site for water heating by region. Conversely, Figure 3.17 details the primary fuels consumed to

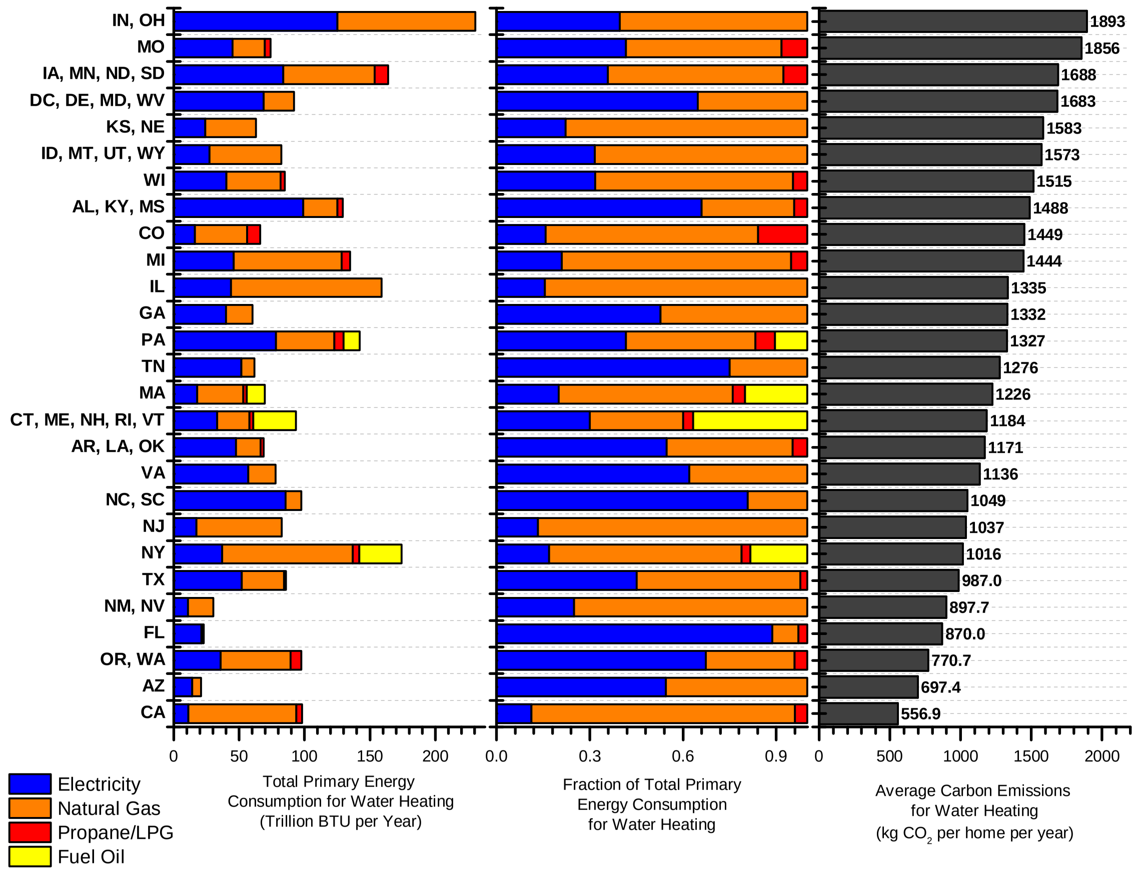

Figure 3.16: The primary energy and CO_2 emissions resulting from the average water heating practices in the baseline 2010 case vary for each region. The magnitude of CO_2 emissions varied according to regional electricity mixes (detailed in Figure 3.17), water heating technology distributions, and total primary energy consumption for water heating.

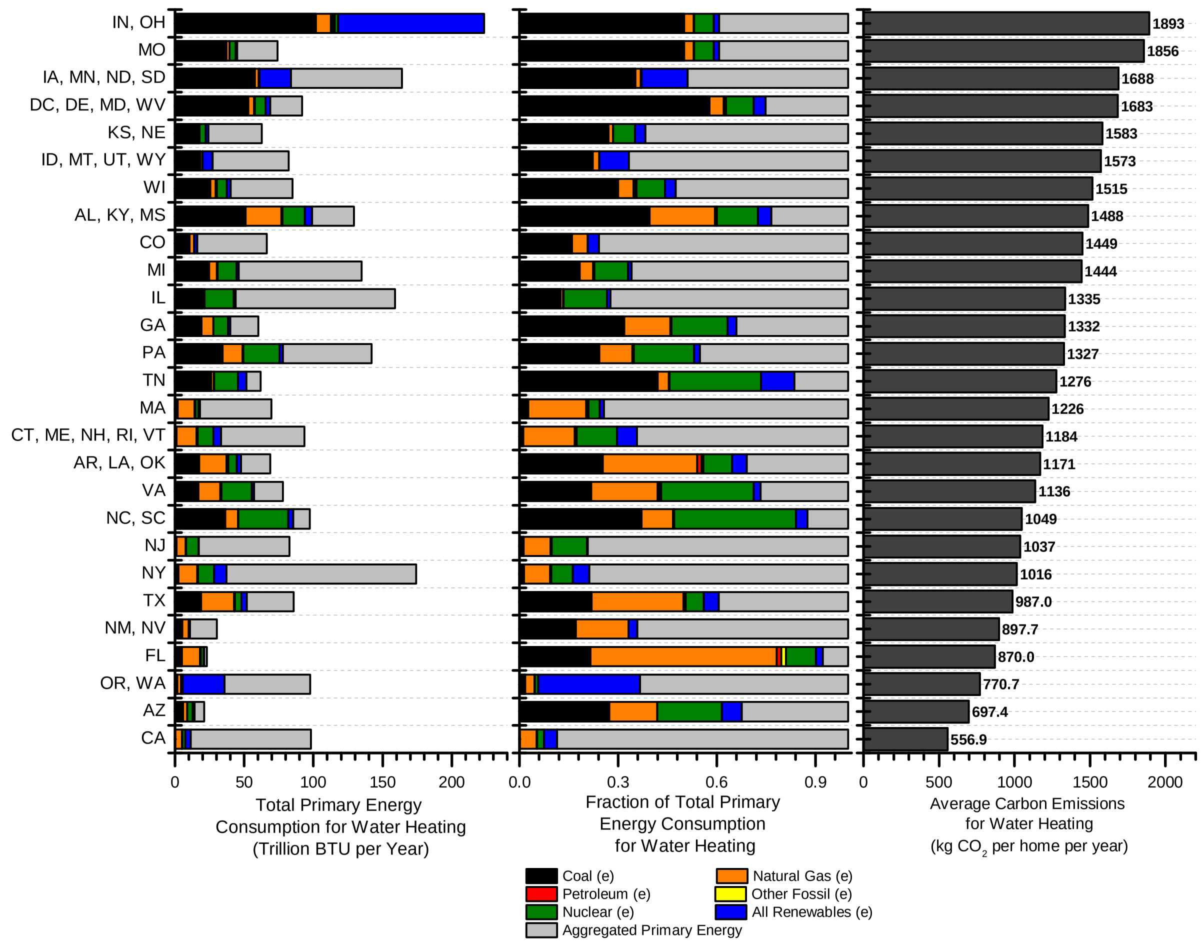

Figure 3.17: The CO_2 intensity of regional electricity mixes impacted the CO_2 emissions resulting from water heating, especially in regions with large numbers of electric water heaters. Here the primary energy consumed for electric water heating in the baseline 2010 case is detailed, while on-site energy consumption for water heating is aggregated.

provide retail electricity for electric water heating and aggregates all primary fuels consumed on-site for regional water heating.

Scenarios 1 and 2 quantified the impact of shifting 10% of each region's baseline water heating fleet on the CO_2 emissions associated with residential water heating. Scenario 1 assessed regional shifting from electric storage to natural gas storage. Generally, states with large fractions of coal generation saw the largest emissions reductions in this scenario. Four regions had net increases in CO_2 emissions in Scenario 1, as their average electricity generation mix was more CO_2 lean than burning natural gas on-site. Scenario 2 assessed regional shifting between conventional electric storage water heating units and SWH with electric storage auxiliary systems. Every region in this scenario experienced a net reduction in water heating-derived CO_2 emissions, since net electricity consumption was reduced in every region. The regions that experienced the largest CO_2 emissions reductions had coal heavy electricity mixes.

Scenarios 3 and 4 evaluated the CO_2 emissions derived from switching 10% of the nation's baseline water heating fleet. Switching was based on regional potential, rather than the uniform regional shifts investigated in Scenarios 1 and 2. Scenario 3 evaluated switching 10% of the national water heating fleet from electric storage to natural gas storage water heating units. On average, more CO_2 emissions were reduced in Scenario 1 than Scenario 3, but results varied depending on the level of switching in each region. Scenario 4 evaluated the effect of changing 10% of the national water heating fleet from electric storage water heaters to SWH units with electric storage back-up. In general, overall CO_2 emissions reductions were less in this scenario than in Scenario 2.

Results for each scenario are summarized for average household and total regional CO_2 emissions in Tables 3.11 and 3.12, respectively.

Table 3.7: The change in CO_2 emissions resulting from regional shifts in 10% of total water heating units from electric storage to natural gas storage in Scenario 1 are detailed in order from highest regional CO_2 reductions to lowest.

Region Definition	Average Household Emissions (kg CO_2 per home per year)	Change from Baseline (kg CO_2 per home per year)	Relative Change from Baseline (±%)
MO	1640	-191	-12%
IN, OH	1692	-179	-11%
KS, NE	1378	-178	-13%
IA, MN, ND, SD	1531	-142	-9%
CO	1291	-141	-11%
WI	1363	-137	-10%
MI	1312	-120	-9%
DC, DE, MD, WV	1561	-113	-7%
AL, KY, MS	1395	-87	-6%
IL	1245	-83	-7%
GA	1248	-79	-6%
AR, LA, OK	1090	-75	-7%
NM, NV	816	-74	-9%
PA	1256	-68	-5%
TX	914	-68	-7%
TN	1221	-53	-4%
ID, MT, UT, WY	1523	-48	-3%
VA	1094	-41	-4%
NC, SC	1010	-37	-4%
MA	1188	-37	-3%
FL	832	-36	-4%
AZ	664	-31	-5%
NJ	1044	7	1%
CT, ME, NH, RI, VT	1196	12	1%
NY	1041	26	3%
CA	583	27	5%
OR, WA	965	243	25%

Table 3.8: The change in CO_2 emissions resulting from regional shifts in 10% of total water heating units from electric storage to SWH with electric backup in Scenario 2 are detailed in order from highest regional CO_2 reductions to lowest.

Region Definition	Average Household Emissions (kg CO_2 per home per year)	Change from Baseline (kg CO_2 per home per year)	Relative Change from Baseline (±%)
KS, NE	1376	-180	-13%
MO	1664	-172	-10%
CO	1258	-166	-13%
IN, OH	1722	-155	-9%
IA, MN, ND, SD	1541	-134	-9%
DC, DE, MD, WV	1546	-126	-8%
MI	1308	-123	-9%
AL, KY, MS	1353	-122	-9%
GA	1202	-117	-10%
WI	1388	-116	-8%
ID, MT, UT, WY	1449	-114	-8%
IL	1214	-110	-9%
NM, NV	769	-110	-14%
TX	876	-98	-11%
AR, LA, OK	1064	-97	-9%
PA	1235	-86	-7%
TN	1184	-85	-7%
VA	1049	-80	-8%
NC, SC	965	-78	-8%
FL	793	-70	-9%
MA	1152	-69	-6%
AZ	621	-68	-11%
NJ	980	-54	-5%
CT, ME, NH, RI, VT	1141	-41	-4%
NY	978	-36	-4%
CA	527	-28	-5%
OR, WA	765	-6	-1%

Table 3.9: Scenario 3 quantifies the change in CO_2 emissions resulting from a national shift in 10% of total US water heating units (electric storage to natural gas storage) based on regional potential. Results are listed in order from highest regional CO_2 reductions to lowest.

Region Definition	Average Household Emissions (kg CO_2 per home per year)	Change from Baseline (kg CO_2 per home per year)	Relative Change from Baseline (±%)
WI	1294	-189	-15%
IA, MN, ND, SD	1478	-184	-12%
CO	1249	-173	-14%
IN, OH	1734	-146	-8%
MI	1305	-126	-10%
TX	849	-119	-14%
DC, DE, MD, WV	1560	-114	-7%
KS, NE	1492	-86	-6%
GA	1243	-83	-7%
AL, KY, MS	1404	-79	-6%
PA	1244	-78	-6%
TN	1194	-77	-6%
NM, NV	816	-74	-9%
FL	801	-63	-8%
IL	1279	-53	-4%
AR, LA, OK	1133	-37	-3%
AZ	661	-34	-5%
MA	1192	-33	-3%
ID, MT, UT, WY	1542	-31	-2%
NC, SC	1028	-20	-2%
MO	1856	0	0%
VA	1136	0	0%
NJ	1041	4	0%
CA	573	17	3%
CT, ME, NH, RI, VT	1201	17	1%
NY	1035	20	2%
OR, WA	1048	377	36%

Table 3.10: Scenario 4 quantifies the change in CO_2 emissions resulting from a national shift in 10% of total US water heating units (electric storage to SWH units) based on regional potential. Results are listed in order from highest regional CO_2 reductions to lowest.

Region Definition	Average Household Emissions (kg CO_2 per home per year)	Change from Baseline (kg CO_2 per home per year)	Relative Change from Baseline (±%)
GA	1166	-145	-12%
NM, NV	720	-143	-20%
CO	1291	-141	-11%
KS, NE	1449	-123	-8%
MO	1724	-123	-7%
DC, DE, MD, WV	1550	-122	-8%
PA	1214	-104	-9%
IL	1227	-99	-8%
AZ	580	-98	-17%
MA	1134	-85	-8%
AR, LA, OK	1080	-84	-8%
IA, MN, ND, SD	1599	-84	-5%
ID, MT, UT, WY	1486	-82	-6%
WI	1429	-81	-6%
NC, SC	964	-78	-8%
TX	903	-77	-9%
AL, KY, MS	1410	-74	-5%
MI	1376	-65	-5%
IN, OH	1829	-61	-3%
FL	806	-59	-7%
VA	1076	-57	-5%
NJ	982	-52	-5%
CT, ME, NH, RI, VT	1133	-49	-4%
CA	509	-44	-9%
NY	971	-43	-4%
TN	1232	-42	-3%
OR, WA	767	-4	-1%

Table 3.11: Scenario 2 (uniform switching from electric water heaters to SWHs) offered the largest reduction in average household CO_2 emissions for water heating. The magnitude of reduction varied by region.

Region Definition	Baseline (kg CO_2 per home) per year)	S:1 (kg CO_2 per home) per year)	S:2 (kg CO_2 per home) per year)	S:3 (kg CO_2 per home) per year)	S:4 (kg CO_2 per home) per year)
AL, KY, MS	1488	1395	1353	1404	1410
AR, LA, OK	1171	1090	1064	1133	1080
AZ	697	664	621	661	580
CA	557	583	527	573	509
CO	1449	1291	1258	1249	1291
CT, ME, NH, RI, VT	1184	1196	1141	1201	1133
DC, DE, MD, WV	1683	1561	1546	1560	1550
FL	870	832	793	801	806
GA	1332	1248	1202	1243	1166
IA, MN, ND, SD	1688	1531	1541	1478	1599
ID, MT, UT, WY	1573	1523	1449	1542	1486
IL	1335	1245	1214	1279	1227
IN, OH	1893	1692	1722	1734	1829
KS, NE	1583	1378	1376	1492	1449
MA	1226	1188	1152	1192	1134
MI	1444	1312	1308	1305	1376
MO	1856	1640	1664	1856	1724
NC, SC	1049	1010	965	1028	964
NJ	1037	1044	980	1041	982
NM, NV	898	816	769	816	720
NY	1016	1041	978	1035	971
OR, WA	771	965	765	1048	767
PA	1327	1256	1235	1244	1214
TN	1276	1221	1184	1194	1232
TX	987	914	876	849	903
VA	1136	1094	1049	1136	1076
WI	1515	1363	1388	1294	1429
Average	1261	1189	1153	1200	1171

Table 3.12: Scenario 2 (uniform switching from electric water heaters to SWHs) resulted in the greatest reduction in total CO_2 emissions for water heating. The magnitude of reduction varied by region.

Region Definition	Baseline (million kg CO_2 per year)	S:1 (million kg CO_2 per year)	S:2 (million kg CO_2 per year)	S:3 (million kg CO_2 per year)	S:4 (million kg CO_2 per year)
AL, KY, MS	4.2	-0.3	-0.4	-0.2	-0.2
AR, LA, OK	4.2	-0.3	-0.4	-0.1	-0.3
AZ	5.7	-0.3	-0.6	-0.3	-1.0
CA	3.1	0.1	-0.2	0.1	-0.3
CO	5.2	-0.6	-0.7	-0.7	-0.6
CT, ME, NH, RI, VT	6.3	0.1	-0.2	0.1	-0.3
DC, DE, MD, WV	7.6	-0.6	-0.6	-0.6	-0.6
FL	2.3	-0.1	-0.2	-0.2	-0.2
GA	10.6	-0.7	-1.0	-0.7	-1.3
IA, MN, ND, SD	4.6	-0.4	-0.4	-0.6	-0.2
ID, MT, UT, WY	6.9	-0.2	-0.5	-0.1	-0.4
IL	2.7	-0.2	-0.2	-0.1	-0.2
IN, OH	6.4	-0.7	-0.6	-0.5	-0.2
KS, NE	6.5	-0.8	-0.8	-0.4	-0.6
MA	11.1	-0.3	-0.7	-0.3	-0.8
MI	5.8	-0.5	-0.5	-0.6	-0.3
MO	12.1	-1.4	-1.3	0.0	-0.9
NC, SC	3.0	-0.1	-0.2	-0.1	-0.2
NJ	5.6	0.0	-0.3	0.0	-0.3
NM, NV	9.1	-0.8	-1.3	-0.8	-1.8
NY	5.1	0.1	-0.2	0.1	-0.2
OR, WA	1.7	0.4	0.0	0.6	0.0
PA	3.2	-0.2	-0.2	-0.2	-0.3
TN	3.7	-0.2	-0.3	-0.2	-0.1
TX	2.1	-0.2	-0.2	-0.3	-0.2
VA	15.6	-0.6	-1.2	0.0	-0.8
WI	7.0	-0.7	-0.6	-1.0	-0.4
Total	161.0	-9.2	-13.9	-7.1	-12.6

3.5 Discussion

This analysis uses regression and other methods to help illuminate the role of regional differences in the primary energy consumption and CO_2 emissions associated with water heating across the US.

There are several factors that characterize regional trends, including:

- Hot water demand (influenced by climactic and social factors),
- Water heating technology trends (influenced by economics, fuel availability, and customer preferences),
- Electricity generation mix, and
- Fuel Prices.

Although the relative fraction of shifts in water heating technologies was uniform across the nation in Scenarios 1 through 4, the resulting shifts in primary energy consumption and CO_2 emissions varied due to regional differences. For example, over 80% of Washington State's annual electricity generation in 2011 was derived from carbon-free sources including hydroelectric, nuclear, wind, solar PV, and solar thermal (EIA, 2012). By contrast, in West Virginia, 97% of 2011 electricity generation was coal based (EIA, 2012). Thus, the effect of switching from an electric water heater to a SWH in Washington would have less of an effect in reducing CO_2 emissions than fuel switching in West Virginia, where the electricity mix is more CO_2 intensive.

Table 3.13 summarizes the elasticity of CO_2 emissions reductions to changes in the regional baseline water heating fleet based on the technology shifts evaluated in Scenarios 1 and 2. Results are reported in changes in million kg CO_2 per percentage shift in technology. These results indicate that 14.1 million kg of CO_2 are abated for every percentage shift in the total water heating fleet from electric to natural gas storage water heaters. By contrast, the same relative change in the water heating fleet in the Washington-Oregon region will result in a 4.3 million kg of CO_2 increase.

Switching to a SWH in New Mexico and Nevada resulted in the largest reduction in CO_2 emissions, as they are coal-dominated, solar-resource intensive states. The Washington-Oregon region was least sensitive to SWH switching because it is a solar resource-poor region with high levels of carbon-free hydroelectricity in its electricity mix.

This analysis assumes that the CO_2 intensity of the electricity generated within a region reflects the CO_2 intensity of the electricity consumed within it. In reality, many states import and export electricity across state lines, so the actual emissions associated with electricity consumption might be underestimated or overestimated in some cases. California, for example, has CO_2-lean electricity generation, but imports electricity from coal-fired plants in neighboring states. However, due to the nature of transmission and distribution networks, in most cases it is reasonable to assume that local power generation reflects local power consumption.

Results of all scenarios evaluated in this analysis are detailed in the following sections. Of the four scenarios evaluated, Scenario 2 offered the greatest total reduction in regional CO_2 emissions from water heating.

Discussion of Scenarios 1 and 2

Scenarios 1 and 2 are comparable since they evaluate the effect of switching 10% of the water heating fleet in each region. In most regions, switching from an electric storage solar water heater to a SWH results in the largest reduction of CO_2 emissions. However, in four regions, switching to a natural gas storage water heater

Table 3.13: The elasticity of changes in CO_2 emissions to changes in regional water heating fleets varies by region.

Region Definition	CO_2 Elasticity Switching j=1→2 $\frac{\Delta\, 10^6\, kg\, of\, CO_2}{\Delta F_{j=1\rightarrow 2}}$	CO_2 Elasticity Switching j=1→5 $\frac{\Delta\, 10^6\, kg\, of\, CO_2}{\Delta\, F_{j=1\rightarrow 5}}$
AL, KY, MS	-2.63	-3.79
AR, LA, OK	-2.93	-3.87
AZ	-2.67	-6.19
CA	1.46	-1.67
CO	-5.65	-6.81
CT, ME, NH, RI, VT	0.65	-2.27
DC, DE, MD, WV	-5.50	-6.21
FL	-0.99	-2.03
GA	-6.70	-10.30
IA, MN, ND, SD	-4.27	-4.00
ID, MT, UT, WY	-2.18	-5.45
IL	-1.82	-2.47
IN, OH	-6.79	-5.78
KS, NE	-8.41	-8.47
MA	-3.45	-6.63
MI	-5.27	-5.41
MO	-14.13	-12.52
NC, SC	-1.10	-2.38
NJ	0.36	-3.06
NM, NV	-8.25	-12.97
NY	1.28	-1.85
OR, WA	4.32	-0.14
PA	-1.74	-2.23
TN	-1.58	-2.63
TX	-1.53	-2.32
VA	-5.82	-11.92
WI	-6.97	-5.82
Average	-3.42	-5.16

is the lowest CO_2 option. These regions include:

- Missouri
- Indiana and Ohio
- Iowa, Minnesota, North Dakota, and South Dakota
- Wisconsin

These regions are similar in that their regional electricity mix is primarily coal-fired and they have relatively limited solar resources, so any SWH heating unit would require its auxiliary backup to operate a significant fraction of the year. Thus, the incremental fraction of energy required to run a region's auxiliary water heating systems in the SWH switching scenario would result in more emissions than switching to natural gas storage water heaters.

Discussion of Scenarios 3 and 4

Scenarios 3 and 4 presented methodologies for assessing regional potential for technology switching among water heating technologies. Therefore, changes in CO_2 per region are more difficult to compare since varying levels of switching occurs across regions. However, these scenarios are useful because they anticipate the regions that are most likely to adopt new technologies and identify the regional characteristics that incentivize switching.

In Scenario 3, regions with low electricity prices were prone to less switching from electric to natural gas heaters. In the region including Washington and Oregon, this trend was environmentally advantageous, since the baseline electricity mix is primarily renewables. In regions with cheap and coal-dominated electricity mixes, this trend was not advantageous, since those regions were less prone to switching to natural gas water heaters.

In Scenario 4, the regression model used to assess regional fuel switching affirmed the role of incentives in the dissemination of renewable energy technologies. Regions with more state rebates and tax incentives were more likely to switch to SWHs. Since these states were also more likely to incentivize grid-scale renewables, more switching occurred in states with low-CO_2 electricity mixes, thereby reducing the net benefit of switching compared to switching in regions with more fossil-fueled generation. Accordingly, states with coal-dominated electricity generation were less likely to switch, resulting in lower CO_2 emissions reductions than in Scenario 2.

The nature of the regression model employed here does not consider siting considerations such as favorable roof alignment (i.e. south-facing installations are optimal), roof inclination, roof area, and shading effects. (SWH require roofs that do not face north (Maguire et al., 2013; Rylatt et al., 2001). It has been proposed that SWHs might be better assessed by the number of "effective days" for SWH, instead of using total annual solar radiation (which might overestimate SWH potential). This metric considers tap water temperature and daily solar radiation in a region (Pan et al., 2012). However, obtaining regional tap water temperature data was beyond the scope of the current analysis, so this metric was not explored.

Regional Water Heating Characteristics

Trends in regional water heating purchases reflect a number of factors, the most significant being fuel availability and prices. In the South, electric water heaters are dominant, since limited space heating requirements provide little incentive to expand natural gas pipeline infrastructure (Denholm, 2007). Fuel oil and LPG still represent a significant fraction of fuels used for water heating in the Northeast, where 2/3 of homes were built before 1960 (Denholm, 2007). Although access to natural gas has been limited in regional markets in the past, access has increased substantially since the 1970s through a series of regulatory changes including:

- wellhead price deregulation through the Natural Gas Policy Act in 1978,
- interstate market deregulation in the 1980s to mid-1990s through FERC Order No. 436 and 636, and The Natural Gas Wellhead Decontrol Act of 1989, and
- retail unbundling at the state level through "customer choice" programs (Arano and Velikova, 2010, 2012; Natural Gas Supply Association, 2011; EIA, 2013a).

Today expansive intrastate and interstate natural gas pipelines permit nearly ubiquitous access to natural gas in the US (Arano and Velikova, 2012); however, proximity to major transportation corridors still impact regional prices due to transmission and distribution costs. The trend towards converging gas prices is expected to continue as stronger cointegration, that is, more integrated transportation networks that minimize transportation cost, of the natural gas market persists (Arano and Velikova, 2010, 2012). Additionally, increased domestic production is expected to curb historic volatility in natural gas prices (EIA, 2010b; Hoffman et al., 2013). Thus, the transition towards natural gas end use appliances, such as water heaters, might become an attractive option for many consumers in the US (Hoffman et al., 2013). For these reasons, we assume that the technology shifts evaluated in this analysis are feasible in terms of access to fuel.

3.6 Conclusion

This analysis investigated the role of regional energy and climate variability on the environmental performance of various water heating trends. Results indicate that federal EF metrics aimed to inform consumers about the environmental performance of residential end use appliances are often insufficient in leading consumers towards the least energy and CO_2 intensive technology. This phenomenon is especially true in comparing natural gas and electric appliances, since EFs do not capture large energy losses upstream of the point of use. Developing metrics that reflect the *source* efficiency of an appliance would provide more useful information regarding the energy use characteristics of common household technologies.

Overall, reducing electric water heating prompted large CO_2 reductions in regions with coal-intensive electricity mixes. Whether these states benefited more by switching to natural gas or SWHs depended on the solar resources in the region. States with low solar resources and CO_2-intensive power generation generally had smaller relative CO_2 reductions by shifting to SWHs since the electric backup had to run a large fraction of the year.

Another interesting trend indicated that regions that promoted renewable electric power generation were more likely to switch to SWHs than states without renewable electricity incentives. However, regions without incentives generally benefited more from transitioning to SWHs than states that were likely to adopt the technology. This trend was due to the fact that states without renewable energy incentives often had coal-intensive electricity mixes.

Although this analysis considered the effects of switching among three technologies, there are other high-performing water heating technologies that were not analyzed here. For example, heat pumps that draw heat from the ambient air or ground to produce hot water have an EF of 2.2 and are also a valuable technology for reducing residential energy use. Condensing natural gas water heaters also have higher EFs than conventional technologies. Future work will analyze the tradeoffs among other technologies.

Chapter 4

Evaluating Water Reductions Through Changes in the Power Sector

4.1 Introduction

While Chapters 3 and 3 focused on the large opportunities for energy reductions through changes in water use, this chapter focuses on the potential for water reductions through changes in energy use. Here, the scope of the analysis shifts from a national assessment to a regional electric grid-level assessment. The Electric Reliability Council of Texas (ERCOT) was selected as a case-study due to its location in Texas, a state that has vast regional and climatic variability, a growing population, and scarce water resources.

The state of Texas experienced significant economic and social impacts from scarce water supplies in 2011. Future population growth, economic growth, and climate change are expected to reduce per capita water availability across much of the state (US GCRP, 2009). The Texas Water Development Board (TWDB) administers a comprehensive state water plan every five years that recommends water supply projects intended to meet 50 years of demand. In its latest State Water Plan, published in 2012, the TWDB recommended investing more than $53 billion in water management strategies including traditional water supply projects (e.g. transmission, treatment, and new groundwater and surface water supplies), unconventional supplies (e.g. reuse, desalination, and conservation), and the reallocation of existing supplies in order to secure adequate volumes of water through the year 2060 (TWDB, 2012).

Despite the large water use requirements of the power sector, water conservation by Texas' electricity generators is not addressed in the state's water plan. This analysis investigates potential reductions in water consumption and withdrawals by the power sector that would follow an increase in the water cost paid by power generators.

4.2 Background

Water use for electricity production in Texas is estimated to be responsible for 2.5–4.2% of its annual water consumption (Stillwell et al., 2011b; Scanlon et al., 2013) and 40–65% of its annual water withdrawals (Kenny et al., 2005; Scanlon et al., 2013). While Texas' population is projected to grow from approximately 25 to 46 million between 2010 and 2060, water withdrawals for thermoelectric power generation are expected to grow an average of 2.4% per year through 2060, outpacing average population and economic growth (TWDB, 2012). Figure 4.1 illustrates 2010 county-level water consumption and withdrawals by end-use sector.

ERCOT is responsible for managing and operating the electric grid across the majority of Texas. Power plants within ERCOT vary in their water use requirements. Furthermore, the water used by power producers has different implications for downstream users depending on whether the water is returned to a river basin or lost to evaporation. The water required for electric power generation can thus be separated into classifications of water use: withdrawals and consumption. Withdrawn water is defined as the volume of water removed from a groundwater or surface water reservoir that might or might not be returned after use. Consumed water refers to the subset of withdrawn water that is lost through evaporation, transpiration, or any other means

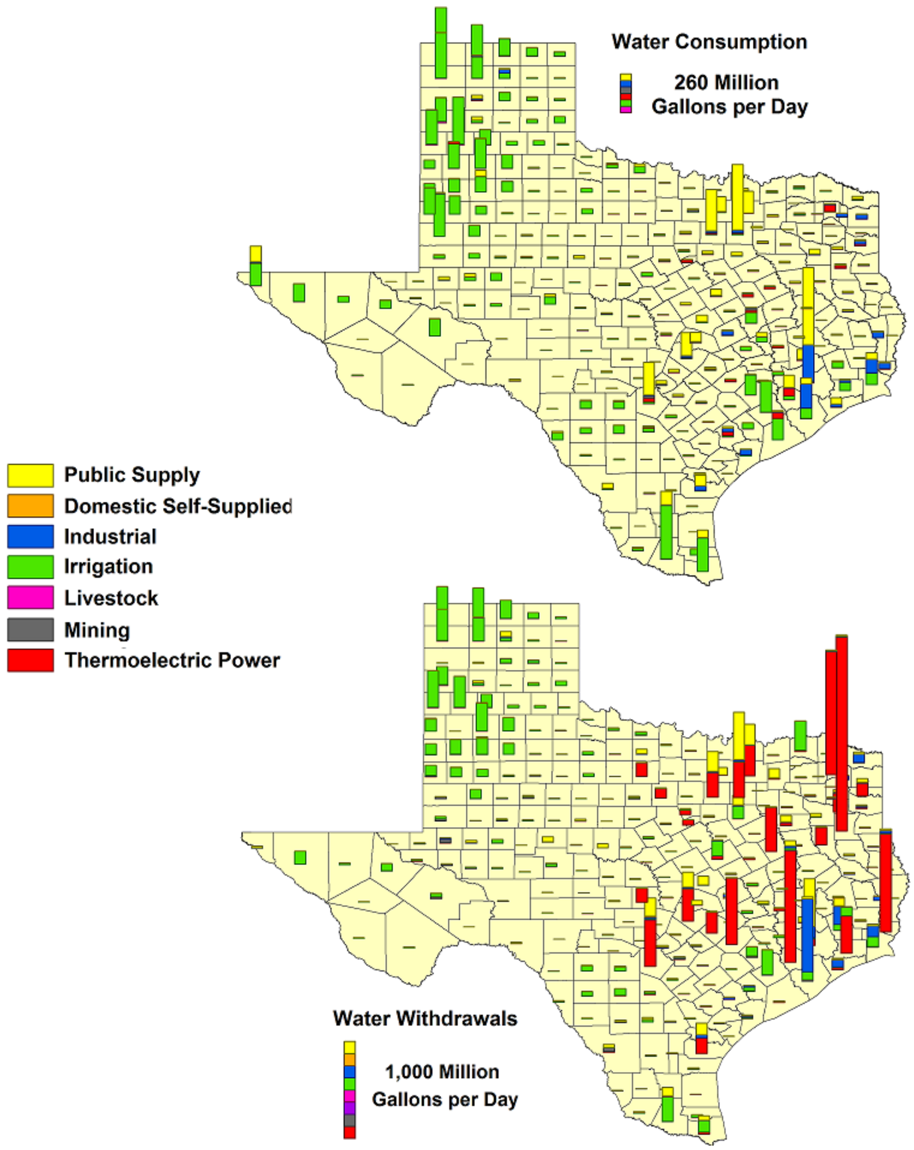

Figure 4.1: The water consumed for cooling thermoelectric power plants is a small fraction of that withdrawn. Irrigation and the public supply represent the majority of water consumption across the state, while thermoelectric power production only represents 2.5–4.2% . However, thermoelectric power production represents approximately half of state-wide withdrawals (Stillwell et al., 2011b; Scanlon et al., 2013).

such that the water is not returned to its original source. The volume of water withdrawn or consumed for power generation varies according to cooling technology, fuel type, prime mover (i.e. the technology responsible for converting thermal energy to mechanical work), and prevailing meteorological conditions. (Macknick et al., 2011, 2012b,a; Feeley III et al., 2008; Stillwell et al., 2011b; Förster and Lilliestam, 2009; Sovacool and Sovacool, 2009; Scanlon et al., 2013).

The water requirements of thermoelectric power generators, which include fossil-fuel (i.e. coal, natural gas, and in limited cases, petroleum), biomass, and nuclear generators, vary by orders of magnitude. Open-loop cooled or once-through cooled power plants withdraw large volumes of water from rivers, lakes, ponds, or storage reservoirs but typically return the majority back to the original reservoir. Closed-loop or recirculating cooled power plants, on the other hand, recycle cooling water via a cooling tower, and therefore withdraw much less water than open-loop cooling systems (Macknick et al., 2011; Feeley III et al., 2008). Accordingly, generation units with recirculating cooling systems withdraw relatively small volumes of water compared to similar once-through cooled power plants, but the majority of the withdrawn water is ultimately lost to evaporation. Once-through cooled plants lose relatively less water to the environment through forced evaporation, but large volumes of withdrawn water can negatively affect water availability for environmental flows, aquatic ecosystems, and in some cases, downstream users depending on whether water is from a multi-purpose reservoir or a river (Stillwell et al., 2011b; Stillwell and Webber, 2013).

Power plants affect water availability for other water users in Texas due to their large water requirements. Surface water rights in Texas are granted according to a hybrid water management system of prior appropriation and riparian rights.

Prior appropriation (i.e. the assignment of water rights in order of seniority) governs municipal, industrial, commercial, irrigation, mining, hydroelectric power, navigation, and recreational water uses. Water users that do not own a water right might buy or lease water from a municipality or river authority that owns the right to water in a particular water reservoir (Wurbs, 1995). When the legal allocation of water rights exceeds the physical availability of water, junior water right holders might not have access to water (Stillwell et al., 2011b). (In limited cases, municipalities or power plants might be granted precedent over more senior water rights holders (Stillwell et al., 2011b; Wurbs, 1995).) For power generators, a water shortage might cause (1) interruptions to power production in the case that a power plant does not have sufficient access to cooling water or (2) interruptions to the water availability to downstream users in the case that sufficient water is not present in a river basin (Stillwell et al., 2011b).

Previous studies cite varying impacts of once-through cooled plants on water availability to downstream users. Scanlon et al. (2013) suggest that the presence of a once-through cooled plant increases water availability to downsteam users by means of lower net consumption in the reservoir in comparison to a recirculating cooled plant of similar nameplate capacity, while Stillwell and Webber (2012) demonstrate that retrofitting once-through cooling systems with recirculating cooling towers can markedly reduce water withdrawals from water-stressed river basins in Texas and improve reliability for some water rights holders. Therefore, there are tradeoffs between once-through and recirculating cooling systems; recirculating cooled plants increase water consumption from a river basin, thereby undermining water supply reliability; once-through cooled plants are vulnerable to water shortages if sufficient volumes of water are not available for cooling, thereby undermining power reliability.

Power generation technologies exist that require very little water. Combustion-turbine and open-cycle natural gas generation units often require no cooling water, although newer units use a small amount of water to pre-chill air at the inlet of the turbine (Scanlon et al., 2013). These units are typically smaller in scale and are more expensive to operate than typical thermoelectric power plants but have faster ramp times, and are, therefore, usually procured for ancillary services. (Ancillary services provide regulation, spinning, and non-spinning reserves to ensure the reliability of the grid (Townsend, 2013)). Combined-cycle plants generally combine two combustion turbines with one steam turbine, reducing cooling water requirements by two-thirds in comparison to plants using steam turbines alone. Although dry cooling systems (i.e. cooling systems that use air rather than water to cool hot steam) exist, these systems typically have large capital costs and reduce power plant efficiency (Stillwell et al., 2011b). Wind and solar photovoltaic systems require no water for cooling but are constrained by the availability of wind and solar resources (Macknick et al., 2011).

Previous studies have investigated various energy and water management strategies to reduce the water intensity of power production. Stillwell and Webber (2013) conclude that increasing water storage at the site of power production increases the reliability of the power plant but has detrimental effects on downstream water users. Pacsi et al. (2013) analyze the potential for environmental dispatching (i.e. dispatching power plants according to water availability) to reduce water competition between power producers and other users in water scarce regions during times of drought. They conclude that shifting electricity production from power plants in drought-stricken regions of South Texas during the 2006 drought would have been feasible in the context of ERCOT's transmission and distribution constraints. Others have evaluated the use of alternative cooling technologies or water sources (Stillwell et al., 2011b); however, increased valuation of water through market levers as a mechanism to induce water savings in the power sector has not been analyzed.

The generation and dispatching of electricity within ERCOT is governed by a unit commitment and dispatch (UC&D) system. Such a system minimizes the marginal operating cost while meeting the electricity demands in ERCOT's service area by dispatching power production according to the least marginal cost producer. Plants with the lowest marginal costs are dispatched first, while plants with the highest marginal cost are dispatched last, and thus, only operate a few hours throughout the year during times of very high demand. Although operation and maintenance costs reflect some portion of the cost of cooling water supplies, these costs are near negligible given Texas' historical water lease rate (Stillwell et al., 2011b). Under current operating conditions, the majority of water withdrawn and consumed for power generation across ERCOT is associated with lower-cost generators, while the majority of the least water intensive generators are more expensive to operate and are utilized with low capacity factors under current grid operations (i.e. least marginal cost basis) (ERCOT, 2013). However, if the water withdrawn or consumed by a power plant had a higher cost, the order in which power generators are dispatched in ERCOT might shift towards more water-lean generators.

4.3 Methodology

This analysis presents a methodology for investigating that effect by imposing an increased cost on water used by power producers in ERCOT. A UC&D model is used to simulate grid-scale power plant operations based on 2011 fuel prices and load characteristics. A flow diagram that illustrates the methodology employed in this chapter is provided in Figure 4.2.

Water withdrawal and consumption characteristics were collected for 310 elec-

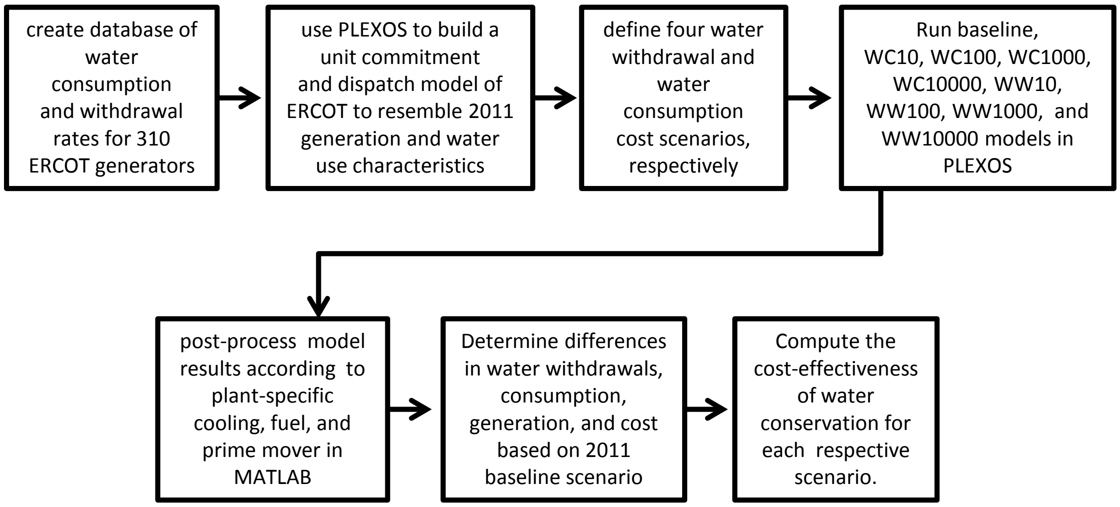

Figure 4.2: An illustrative overview of the methodology utilized in this chapter.

tric generation units (EGUs) in ERCOT based on data reported in the EIA-923 forms from 2010 and 2011 (EIA, 2011b), the Union of Concerned Scientists' EW3 Energy-Water database documented by Averyt et al. (2013), and the ERCOT water use report prepared by King et al. (2008) for the TWDB. (All wind generation was aggregated into two respective units for the purposes of modeling.)

Water consumption rates from King et al. (2008) were used in the model since the majority of consumption values available in the EIA databases were deemed too high based on a series of thermodynamic assessments completed on a selected sample of ERCOT EGUs. Withdrawal estimates from the 2010 and 2011 EIA-923 forms were used in the model for cases when the reported values were within the range prescribed by Macknick et al. (2011) based on fuel, cooling technology, and generation technology. However, since EGU-specific water use values reported in the EIA-923 form are self-reported, values were often unrealistic or missing (Averyt et al., 2013; Scanlon et al., 2013; US Government Accountability Office, 2009). In cases that reported EIA values were not with this reasonable range, withdrawal estimates from

Union of Concerned Scientists (2012) and King et al. (2008) were considered.

In limited cases, no value for a specific EGU was available across any of the datasets. Generally combined heat and power units were not listed included in the data, so generic values were assigned to these units based on fuel, cooling technology, and prime mover. In other cases, the estimates reported for the water use across a set of EGUs were consistently outside of the bounds identified by Macknick et al. (2011). The estimates regarding the water withdrawal rates of nuclear generators were consistently 1-2 orders of magnitude higher than average US facilities. Thus, for nuclear generators, a water withdrawal factor of 120,000 gallons per MWh was applied to all nuclear EGUs. While this factor was higher than the characteristic range identified by Macknick et al. (2011) (i.e. 25,000 to 60,000 gallons per MWh), it was much lower than the withdrawal factors contained in the 2010 and 2011 EIA-923 forms, the UCS database, and the TWDB report (EIA, 2011b; Union of Concerned Scientists, 2012; King et al., 2008).

Tables 4.1, 4.2, and 4.3 detail 310 EGUs in ERCOT by primary fuel type, cooling technology, and prime mover technology, respectively. Wind turbines are not included in these tables and are assumed to require no water for use. Hydroelectric facilities were assumed to have no water consumption and no withdrawals for power production, although in reality the presence of a dam increases the evaporation of water in comparison to the natural run of the river (i.e. without a dam). Overall, nuclear generators withdrew and consumed the most water of any type of generator.

Generally, pond-cooled and once-through cooled EGUs had the highest withdrawal rates across any cooling technology. EGUs with recirculating cooling averaged higher water consumption rates when compared against EGUs with once-through cooling within the same fuel and prime mover technology categories. In Table 4.2, dry-cooled plants include steam-cycle units cooled by air rather than water. Plants with no cooling technology refer to combustion turbines or hydroelectric facilities.

Table 4.4 details the water withdrawals and water consumption of 310 EGUs in ERCOT by fuel type, cooling technology, and prime mover technology combination (excluding wind turbines). Full assumptions regarding the water intensity of EGUs in ERCOT are included in Appendix C.

Table 4.1: The water intensity of electric generation units in ERCOT varies by several orders of magnitude when considering water withdrawals. Nuclear units are the most water intensive when averaged by fuel type.

Fuel Type	Unit Count	Average Consumption (gal/MWh)	Average Withdrawals (gal/MWh)
Nuclear (NU)	4	585	120,000
Coal (CL)	33	437	23,127
Natural Gas (NG)	236	223	3,370
Biomass (BM)	7	109	1,188
Hydro (HY)	30	0	0

Table 4.2: Electric generation units in ERCOT using pond and once-through cooling systems generally withdraw more (but consume less) water than recirculating cooled units per MWh of electricity generated.

Cooling Technology	Unit Count	Average Consumption (gal/MWh)	Average Withdrawals (gal/MWh)
Once-through and Pond (OT)	75	438	55,702
Recirculating (RC)	88	330	644
Dry Cooling (DC)	10	50	50
No Cooling (NA)	137	9	9

The unit commitment and dispatch (UC&D) model of ERCOT developed and detailed by Townsend (2013) was modified to consider water use characteristics for 310

Table 4.3: Electricity generation units using steam turbines generally use more water than units with other types of prime mover technologies.

Prime Mover Technology	Unit Count	Average Consumption (gal/MWh)	Average Withdrawals (gal/MWh)
Steam Turbine (ST)	91	470	44,846
Combined-Cycle (CC)	72	226	2,510
Combustion Turbine (CT)	117	50	50
Hydro Turbine (HY)	30	0	0

Table 4.4: The water requirements of 310 ERCOT power plants are characterized into 12 categories according to fuel type, cooling technology, and prime mover.

Technology Code	Unit Count	Average Consumption (gal/MWh)	Average Withdrawals (gal/MWh)
NU-OT-ST	4	585	120,000
NG-OT-CC	3	230	43,623
NG-OT-ST	46	432	37,836
CL-OT-ST	22	388	31,178
NG-RC-ST	10	502	1,402
BM	7	109	1,188
CL-RC-ST	11	576	706
NG-RC-CC	57	226	616
NG-DR-CC	10	100	100
OCGT-NA-CT	79	50	50
NGIC-NA-CT	31	50	50
HY-NA-HY	30	0	0

EGUs in ERCOT in 2011. The UC&D model was implemented in Energy Exemplar's PLEXOS for Power Systems (PLEXOS) version 6.208. This commercial software package simulates competitive power markets by means of linear, mixed integer, and quadratic optimization that serves to minimize the cost of serving electricity demand and providing ancillary services.

The order that generation is dispatched in ERCOT is determined according to least short run marginal cost (SRMC). Each EGU within ERCOT offers its SRMC of generation and these offers are sorted from least to most expensive. Units are then dispatched in order of least SRMC cost until load is met. (The electricity price is set by the highest offer price known as the marginal clearing price of energy.) The SRMC of each EGU is a function of the incremental cost of fuel and the EGU's variable operation and maintenance (VO&M) costs (Energy Exemplar, 2013). The cost of fuel is determined by a unit's marginal heat rate (MHR) in MMBTU per MWh, the incremental cost of fuel (C_{fuel}) in USD per MMBTU, and electricity production (E_{MWh}) in MWh, as illustrated in Equation 4.1. Equation 4.1 also includes an incremental emissions or environmental cost term (C_{enviro}) in USD per pollutant quantity, which is zero under baseline operating conditions, but can be incorporated in resource management regimes that consider an incremental cost for pollutants. Q_{enviro} is the rate of emissions (or water use) per MWh subject to an environmental cost. In this case, the environmental cost term is used to assess the impact of increased water costs in ERCOT.

$$SRMC_{EGU} = E_{MWh} \times (C_{VO\&M} + C_{fuel} \times MHR + C_{enviro} \times Q_{enviro}) \tag{4.1}$$

The UC&D model considered here optimizes the merit order of power generators by considering the short-term time horizon of one hour intervals to determine the dispatch order of the generation fleet that minimizes generation cost while meeting the given 2011 ERCOT load profile. Additionally, the model employs a one day look-ahead feature to optimize the ramping up and down of generators according to the next day's load forecast. That is, the look-ahead function prevents the model from decommiting generators that are not needed for the remainder of the short-term interval, but are needed to meet the next day's operation (Townsend, 2013).

The ERCOT model was run to simulate power generation in the year 2011 using 2011 fuel prices and ERCOT load profiles. The 310 EGUs (plus aggregated wind generators) reflect the generation fleet modeled by Cohen (2012) and Townsend (2013) based on ERCOT's 2012 Long Term Study (ERCOT, 2012). The model employs marginal heat rates to accurately represent fuel consumption to compute SRMC. Full details regarding the baseline UC&D model are documented by Townsend (2013).

Unit specific water characteristics were added for each of the 310 EGUs detailed in the model. A baseline scenario was run to verify that water use characteristics in the 2011 baseline simulation were consistent with historical water use. Generation fleet characteristics and total wholesale generation costs were consistent with 2011 ERCOT operations. Annual water withdrawals in the final calibrated 2011 baseline model were estimated to be 9.3 trillion gallons per year; of that total, approximately 118 billion gallons were consumed in the simulation. Since water withdrawals vary five orders of magnitude across ERCOT generation units, the model was particularly sensitive to estimations of withdrawal rates, especially for high generation units.

A recent estimate by Scanlon et al. (2013) suggests that withdrawals in Texas for thermoelectric power generation exceeded 8.5 trillion gallons in 2010, which is within 10% of the 2011 baseline estimated for this model. (The simulation likely overestimated water withdrawals because of the high withdrawal rate assumed for nuclear generators.)

Scanlon et al. (2013) estimate 2010 water consumptionin ERCOT to be 140 billion gallons, approximately 19% higher than the simulation. Two other datasets of water consumption rates were evaluated, including (1) 2010 and 2011 EIA-923 form consumption rates and (2) the UCS dataset of consumption rates. Total annual water consumption using the EIA-923 values was 134 billion gallons in the ERCOT simulation, which was closer to the estimate by Scanlon et al. (2013). However, when evaluating these water consumption rates on an individual generator basis, the rates were systemically high based on a series of thermodynamic evaluations. Using the consumption rates prescribed by the UCS database resulted in a consumption estimate that was nearly 30% lower than the estimate from Scanlon et al. Based on these three baseline simulations (i.e. from the TWDB, EIA-923, and UCS databases), the consumption rates specified in the TWDB dataset were considered the most reasonable.

After the baseline model was calibrated using historical 2011 data from ERCOT and the TWDB, scenarios were developed to evaluate changes to the unit commitment and dispatch of EGUs in ERCOT in the presence of higher water costs. Although the water consumed for power generation is a subset of water withdrawals, these criteria were defined separately for each EGU considered in the model in terms of a water use rate (i.e. the volume of water consumed or withdrawn per MWh of electricity generated) so that each could be accounted for separately. Therefore, the first set of water pricing scenarios considered the effect of increasing the cost of water to EGUs based only on the volume of water *consumed* for power generation in 2011; the second set of scenarios applied the increased water cost to total volume of water *withdrawn* for power generation. Water cost scenarios of \$10, \$100, \$1,000, and

\$10,000 per acre-foot (acre-ft), respectively, were applied for the water consumed for power generation (WC10, WC100, WC1000, and WC10000) and then repeated for water withdrawals (WW10, WW100, WW1000, and WW10000). Table 4.5 defines each scenario in terms of the water costs applied.

Each scenario attempted to meet the historical 2011 ERCOT load profile considered in the baseline model, meaning that total generation required by ERCOT to meet electricity demand remained equal to the 2011 baseline scenario for each of the 8,760 hour time-steps computed in each model. Thus, a decrease in generation by one set of EGUs had to be met by an equivalent increase in generation by another set of EGUs to meet the historical hourly load in each scenario.

Table 4.5: Nine water price scenarios (including the baseline) were simulated with the UC&D model to assess the impact of water cost on water use in ERCOT.

Scenario Identifier	Total Electricity Generation (TWh)	Water Cost Applied to Consumed Water (USD per acre-ft)	Water Cost Applied to Withdrawn Water (USD per acre-ft)
Baseline	335	0	0
WC10	335	10	0
WC100	335	100	0
WC1000	335	1000	0
WC10000	335	10000	0
WW10	335	0	10
WW100	335	0	100
WW1000	335	0	1000
WW10000	335	0	10000

4.4 Results

An overview of results for the nine scenarios (including the baseline) defined in Table 4.5 is provided in Table 4.6. Results suggest that the water use reductions following increases in the cost of water to power generators are non-linear and vary according whether the increased cost is applied to the subset of consumed water (i.e. the WC10, WC100, WC1000 and WC10000 scenarios) or the entire volume of withdrawn water (i.e. the WW10, WW100, WW1000, and WW10000 scenarios). Total wholesale generation costs increase from the baseline due to (1) increased water costs and (2) increased generation costs (independent of water costs) since the dispatch order shifts from the optimal cost baseline towards water-lean (but more expensive) generators. (Total Generation Cost in Table 4.5 includes total fuel, VO&M, start-up and shut-down, and water costs across all ERCOT generators.)

Figure 4.3 summarizes the results for water consumption (WC) and full water withdrawal (WW) cost scenarios. Water savings for WC scenarios were modest compared to WW scenarios. Although water savings in WW scenarios consistently increased with water cost, the reductions associated with the WW10000 scenario were only marginally better than the WW1000 scenario and incurred a significant increase in total generation cost, suggesting that there might be an optimal water cost for reducing water use in the power sector.

The sections to follow provide more detailed illustrations of generation and water use characteristics for each water cost scenario. The subsequent discussion section provides detailed comparisons of the various scenarios.

4.4.1 Baseline Water for Power Generation in ERCOT

Figure 4.4 summarizes 2011 electricity generation (first row), water consumption (second row), and water withdrawals (third row) in ERCOT on an annual (first column), weekly (second column), and daily (third column) basis. EGUs are categorized by fuel, cooling technology, and prime mover. Generally, within a particular fuel and prime mover category, once-through cooled and recirculating cooled plants are

Table 4.6: Raising the cost of water to EGUs across ERCOT resulted in varying levels of water reductions. Increasing the cost of water withdrawals incurred larger water reductions than increasing the cost of consumed water alone, but also incurred larger costs.

Scenario Identifier	Annual Generation (TWh)	Annual Water Costs (billion USD)	Annual Total Generation Cost* (billion USD)	Annual Water Consumption (trillion gallons)	Change in Annual Consumption	Annual Water Withdrawals (trillion gallons)	Change in Annual Withdrawals
Baseline	335	0	8.25	0.118	–	9.33	–
WC10	335	0.00366	8.27	0.118	0.0%	9.33	0.0%
WC100	335	0.0362	8.30	0.118	−0.1%	9.32	−0.1%
WC1000	335	0.358	8.62	0.117	−1.3%	9.28	−0.6%
WC10000	335	3.21	11.64	0.105	−11.5%	8.89	−4.7%
WW10	335	0.285	8.54	0.118	−0.5%	9.21	−1.3%
WW100	335	1.69	10.6	0.105	−11.3%	5.51	−40.9%
WW1000	335	7.34	18.1	0.0906	−23.4%	2.39	−74.4%
WW10000	335	71.9	82.8	0.0875	−25.9%	2.34	−74.9%

*Total Generation Cost (wholesale) includes includes total fuel, VO&M, start-up and shut-down, and water costs for EGUs across ERCOT.

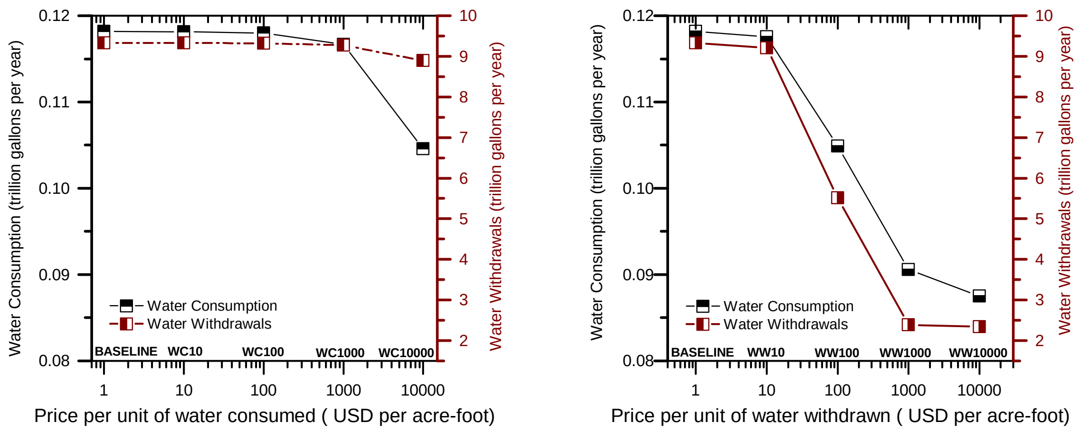

Figure 4.3: Scenarios that increased the cost of total water withdrawn for power generation resulted in larger water savings than those that only increased the cost of consumed water.

represented in a darker and lighter shade of a common color category, respectively.

In the baseline 2011 scenario, nuclear EGUs operated at a constant level of approximately 5 GW for the majority of the year. Coal EGUs with recirculating cooling also operated at a relatively steady capacity, averaging 4.5 GW over the year. Coal EGUs cooling with once-through cooling also served as steady baseload capacity but did exhibit some ramping up and down, especially in mild months when electricity demand was low (e.g. February, April, October, and November). Natural gas combined-cycle plants with recirculating cooling represented nearly 30% of total annual ERCOT generation in the baseline case, but exhibited daily ramping up and down according to fluctuations in demand. These combined-cycle units provided as much as 28 GW of operating capacity during the hours of highest demand in 2011, and as little as 8 GW during hours of low load. Natural gas plants with steam boilers typically only operated in summer afternoons when demand was highest.

Comparing baseline generation profiles with the water consumed and with-

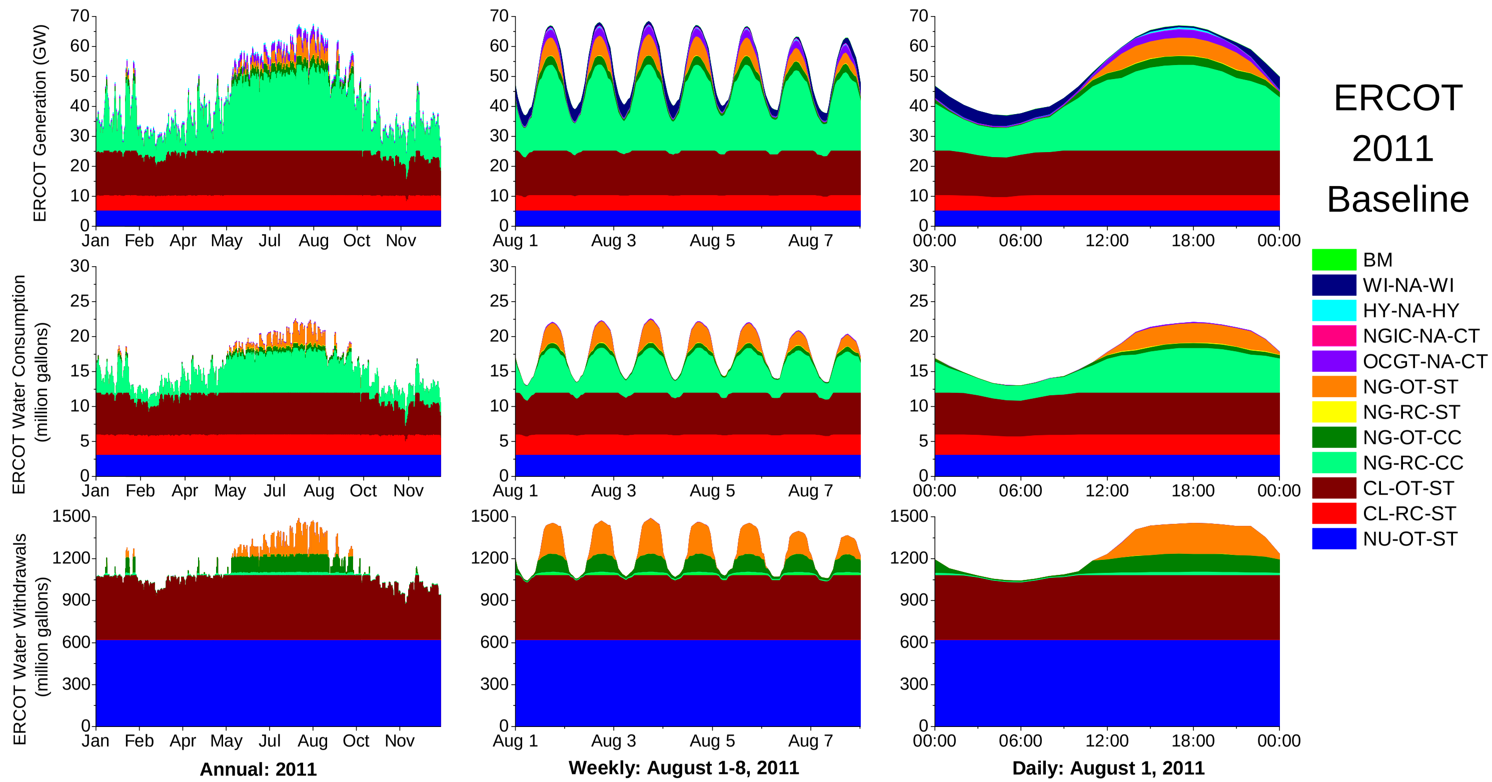

Figure 4.4: Baseline power generation in ERCOT in 2011 was simulated using historical fuel prices and the 2011 load profile from that year. Nuclear and coal EGUs provide steady baseload across the year, while natural gas combined-cycle plants ramp up and down to meet variable daily and seasonal loads.

drawn by the 12 categories of power plants summarized in Figure 4.4 yields interesting insights. In general, water consumption profiles of EGUs in ERCOT were similar to generation profiles when compared on corresponding time-scales. Water withdrawal profiles, on the other hand, were skewed heavily towards water withdrawal intensive once-through cooled plants. For example, once-through cooled coal and nuclear EGUs represented 95% of the water withdrawn in ERCOT, but only represented 47% of annual generation. Natural gas combined-cycle and coal plants with recirculating cooling represented only 1% of annual ERCOT withdrawals, but provided 41% of annual generation. In terms of water consumption, once-through cooled coal and nuclear EGUs represented 69% of water consumption, which is more consistent with their generation. Natural gas combined-cycle and coal plants with recirculating cooling represented 38% of annual water consumption, which is also similar to generation.

Power generation across ERCOT varies seasonally and diurnally, since electricity demand depends on fluctuations in ambient temperature due to cooling and heating loads, as well as fluctuations in electricity demand throughout the day. Typically load is low in mild months and high during the hot summer months. Within a given day, load is generally lower during the night when the majority of electricity consumers are sleeping and is highest in the afternoon and early evening when people are at home.

Figure 4.5 illustrates two-day electricity generation and water use profiles in January, August, and November. Each profile varies in terms of magnitude and shape (i.e. the peaks and valleys), as well as generator commitment. Electricity loads in January and November are much lower than in August due to mild temperatures and relatively low heating and cooling loads. The loads in August and November

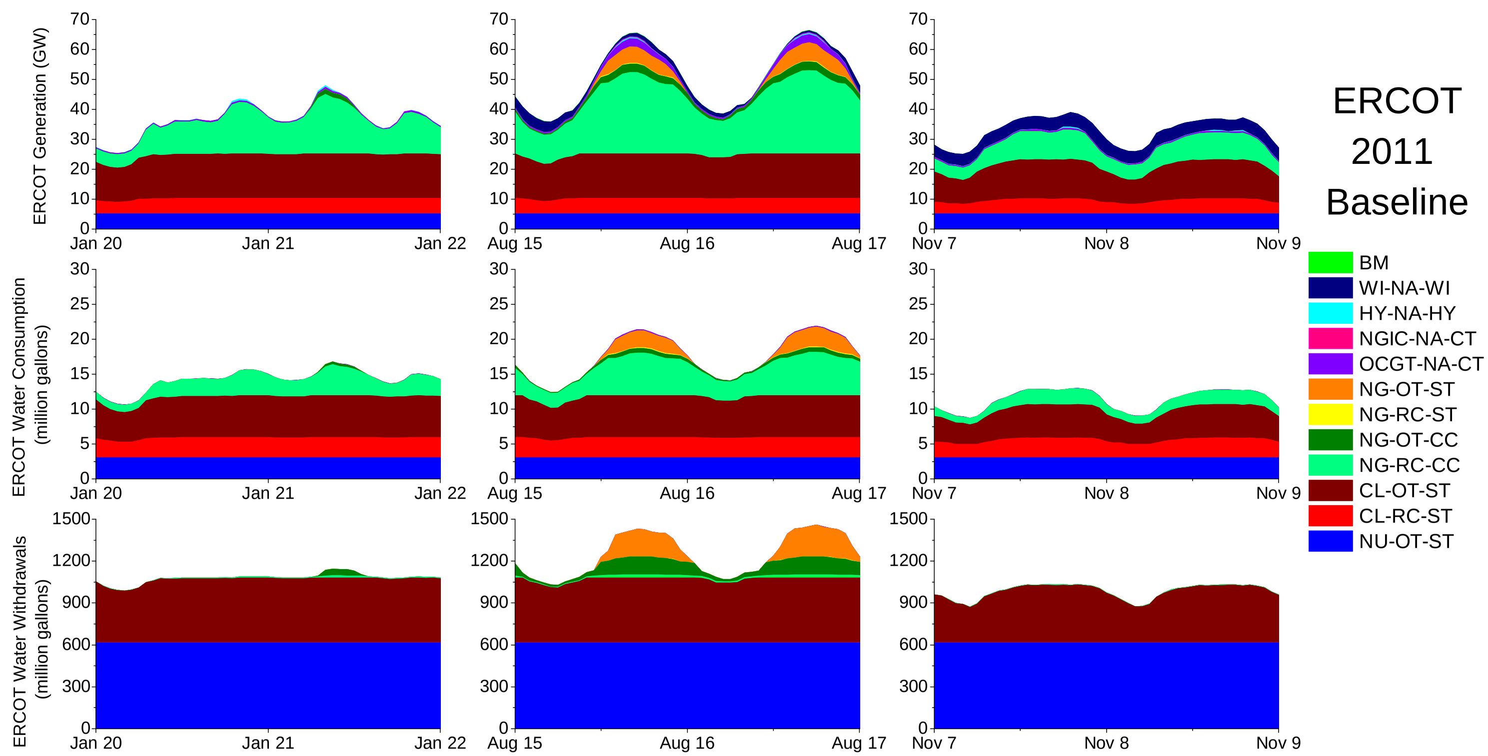

Figure 4.5: ERCOT's electricity generation profile and water requirements vary seasonally and diurnally. Mild months have less variation in demand throughout the day due to low cooling and heating loads. Wind generation is higher in the fall than summer months.

generally have one major peak towards the afternoon and early evening hours when people are most likely to be at home and running power intensive appliances. The load in January tends to be relatively flat, exhibiting more-frequent, but less-predictable peaks. Accordingly, less ramping up and down of baseload coal and nuclear generators occurs. Electricity demand in August is considerably higher than more mild months, and therefore, exhibits more diversity of power generators due to the ramping up and down of peaking plants to meet load requirements. Wind generation varies according to wind resource availability, which has seasonal and diurnal variability. In November there is a larger contribution of electricity from wind generators than in January and August, when wind resources tend to be less available.

4.4.2 Water Consumption Cost Scenarios

A set of four water cost scenarios were simulated to assess the impact of charging EGUs increased water costs for the subset of water consumed from a cooling reservoir or river. Figures 4.6, 4.7, 4.8, and 4.9 illustrate the generation, consumption, and withdrawals that result for incremental cost increases of \$10, \$100, \$1,000 and \$10,000 per acre-ft, respectively (WC10, WC100, WC1000, and WC10000), for the water consumed for power generation in ERCOT. Generally, the resulting decreases in water withdrawals and consumption for these scenarios were more modest than scenarios that applied the same water cost to the entire volume of water withdrawn from a reservoir. Thus, only small changes in the profiles detailed in Figures 4.6, 4.7, and 4.8 can be detected from the baseline scenario. Changes in generation and water use characteristics between these three scenarios and the baseline are detailed in the discussion section for more clarity.

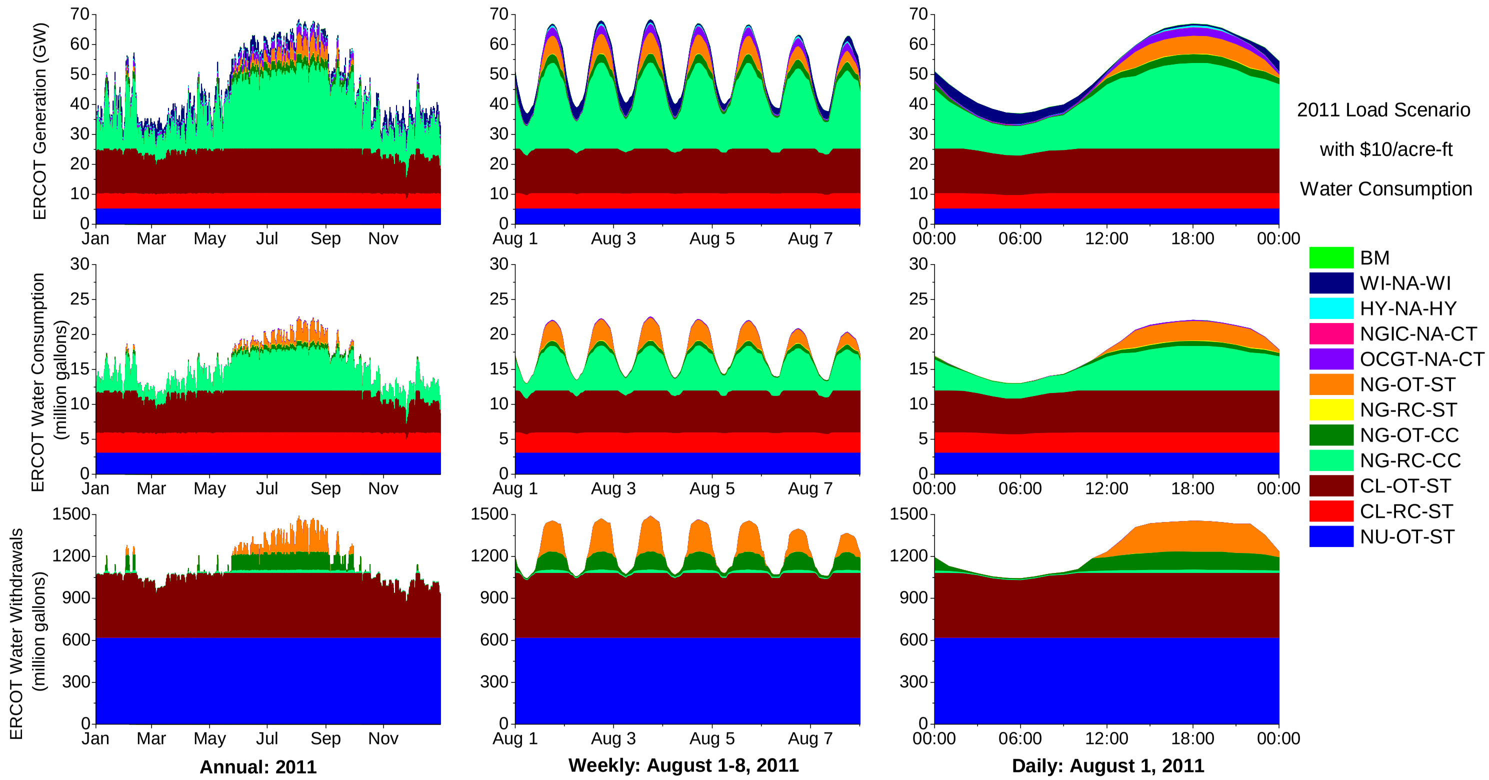

Figure 4.6: Applying a water cost of \$10 per acre-ft for water consumption resulted in a 0.015% and 0.030% reduction in water withdrawals and consumption, respectively. At this water cost, there are very few changes from the baseline scenario.

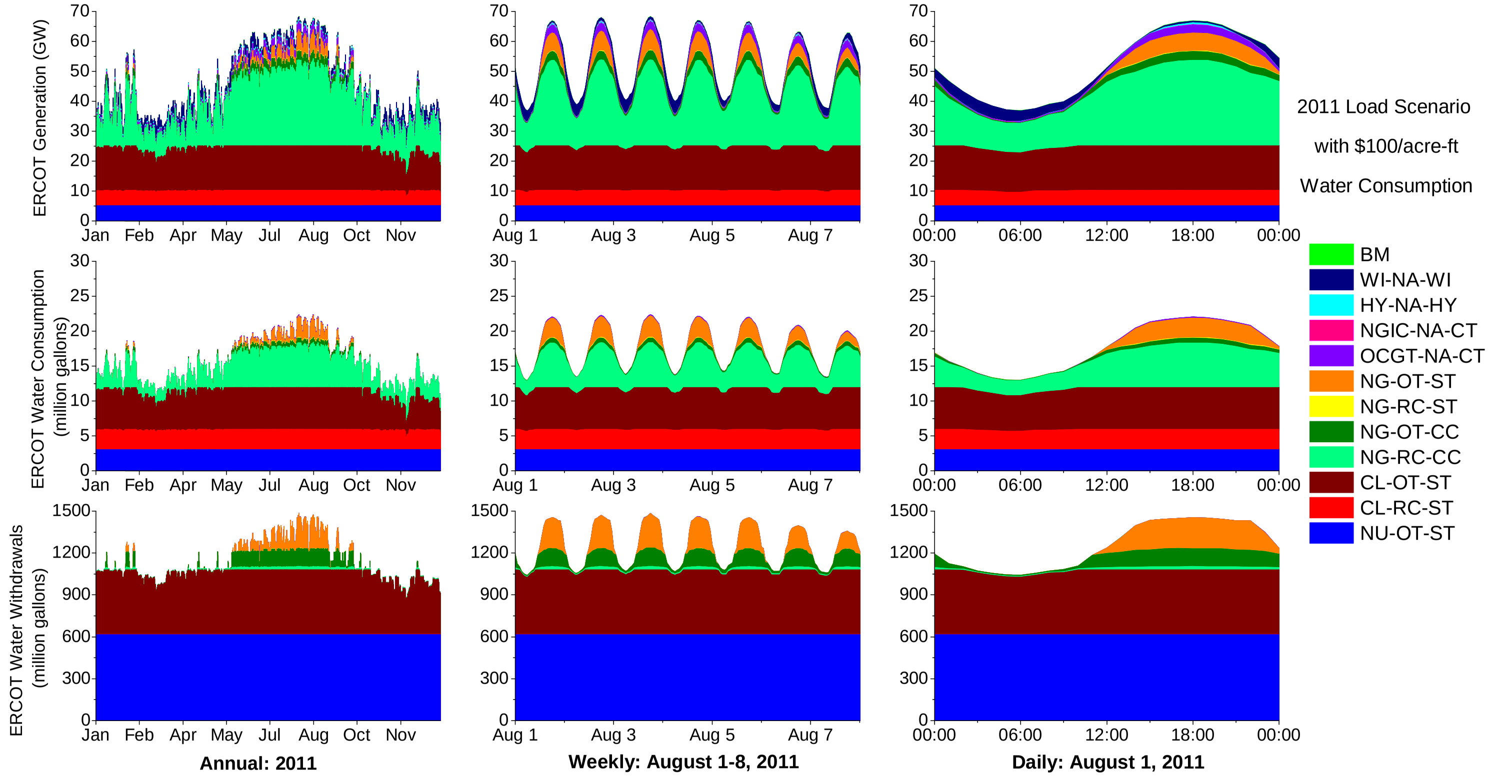

Figure 4.7: Applying a water cost of \$100 per acre-ft for water consumption resulted in a 0.074% and 0.14% reduction in water withdrawals and consumption, respectively. The generation fleet, water consumption, and withdrawals change very little from the baseline.

4.4.3 Water Withdrawal Cost Scenarios

Four scenarios evaluated the impact of increasing the cost of water withdrawals on generation characteristics, water consumption, and water withdrawals in ERCOT in 2011. These scenarios are detailed in Figures 4.10 through 4.13 and discussed further in the discussion section to follow.

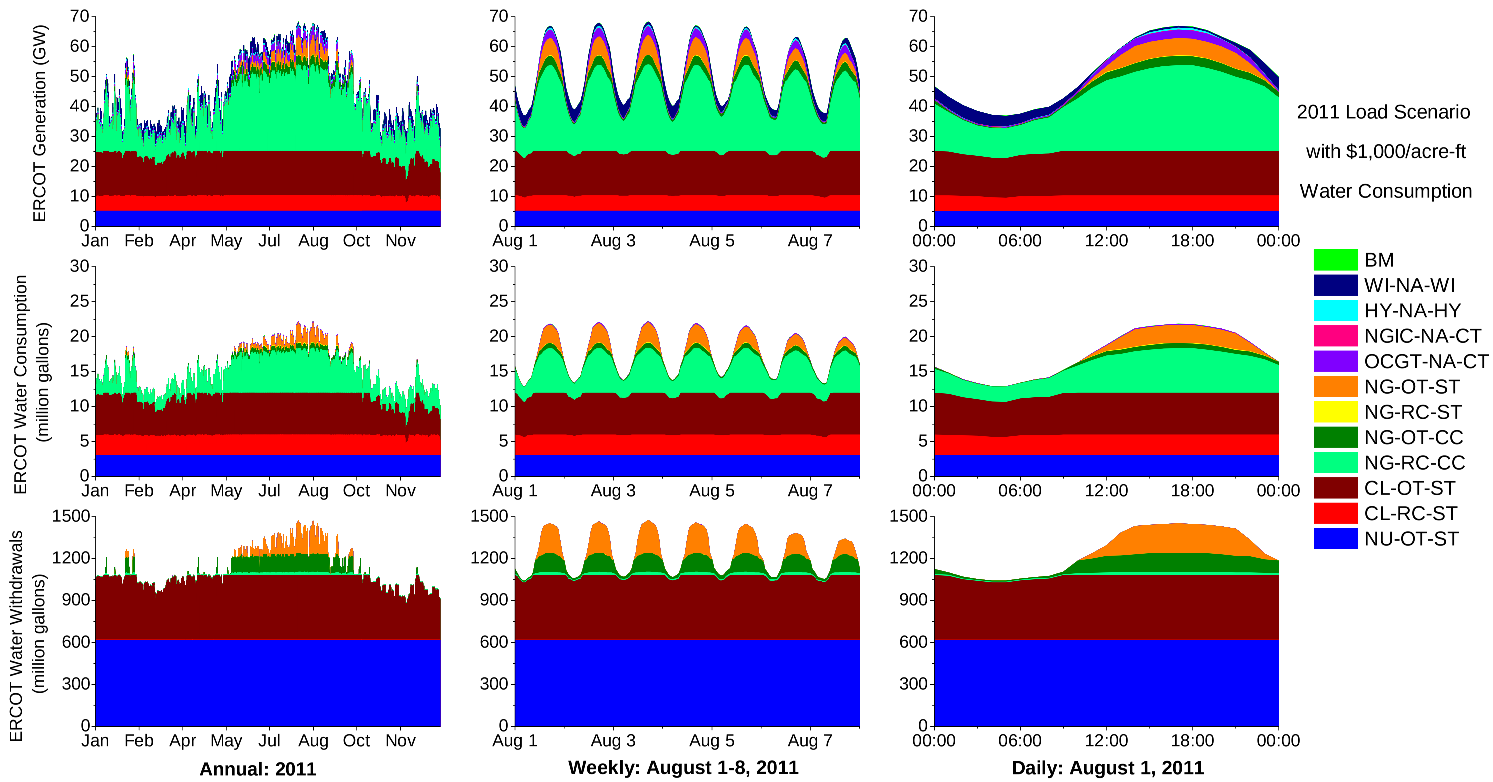

Figure 4.8: Applying a water cost of $1,000 per acre-ft for water consumption resulted in a 0.58% and 1.3% reduction in water withdrawals and consumption, respectively. Changes are still slight, but small increases in NG-RC-CC are accommodated by decreases across CL-RC-ST, CL-OT-ST, NG-RC-ST, and NG-OT-ST generators.

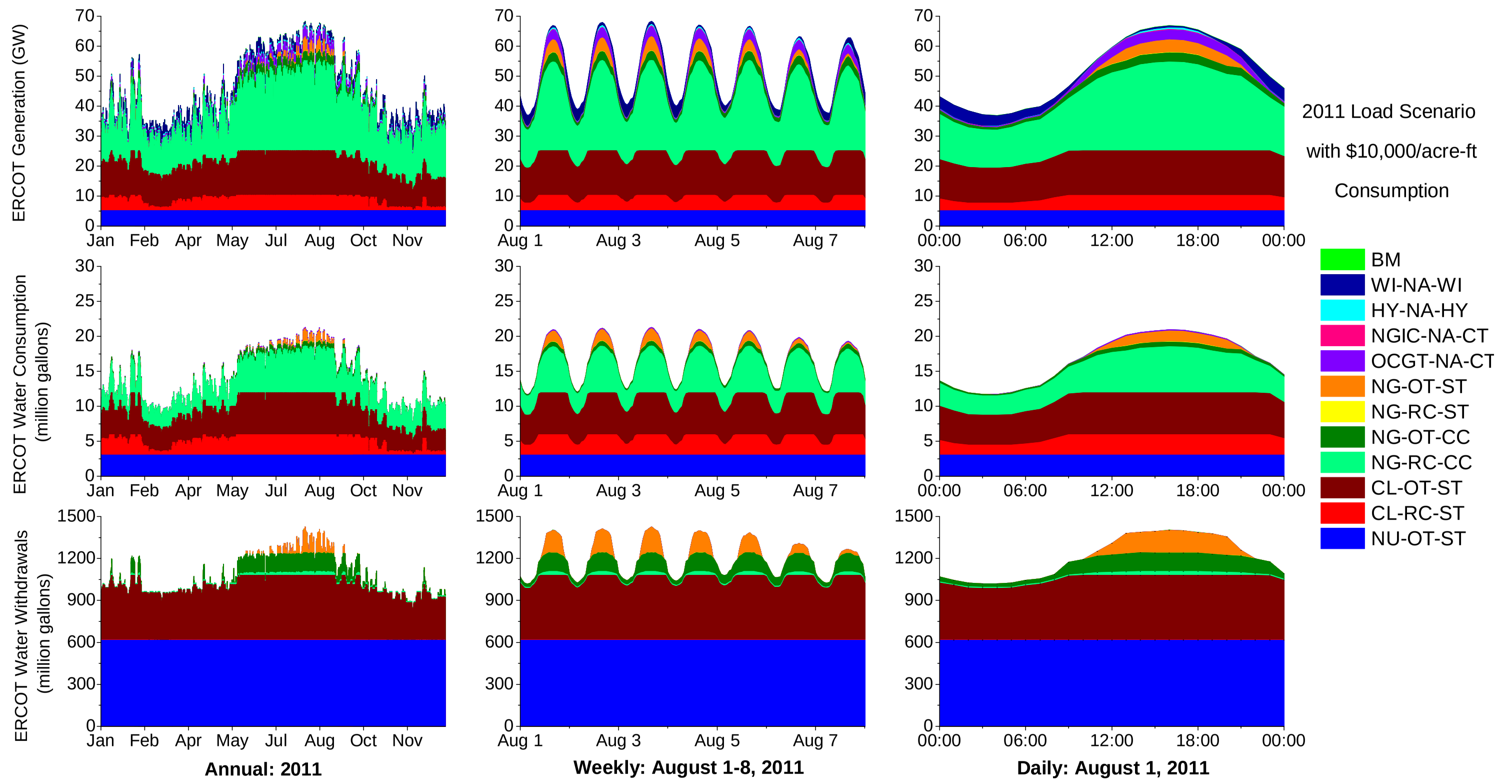

Figure 4.9: Applying a water cost of \$10,000 per acre-ft for water consumption resulted in a 4.7% and 12% reduction in water withdrawals and consumption, respectively. CL-RC-ST and CL-OT-ST generation decreases by 35% and 12%, respectively. NG-OT-ST, NG-RC-ST, and NG-OT-CC generation decreases by 67%, 64%, and 34%, respectively, from the baseline. These decreases are met by increases in generation by NG-RC-CC and OCGT-NA-CT EGUs.

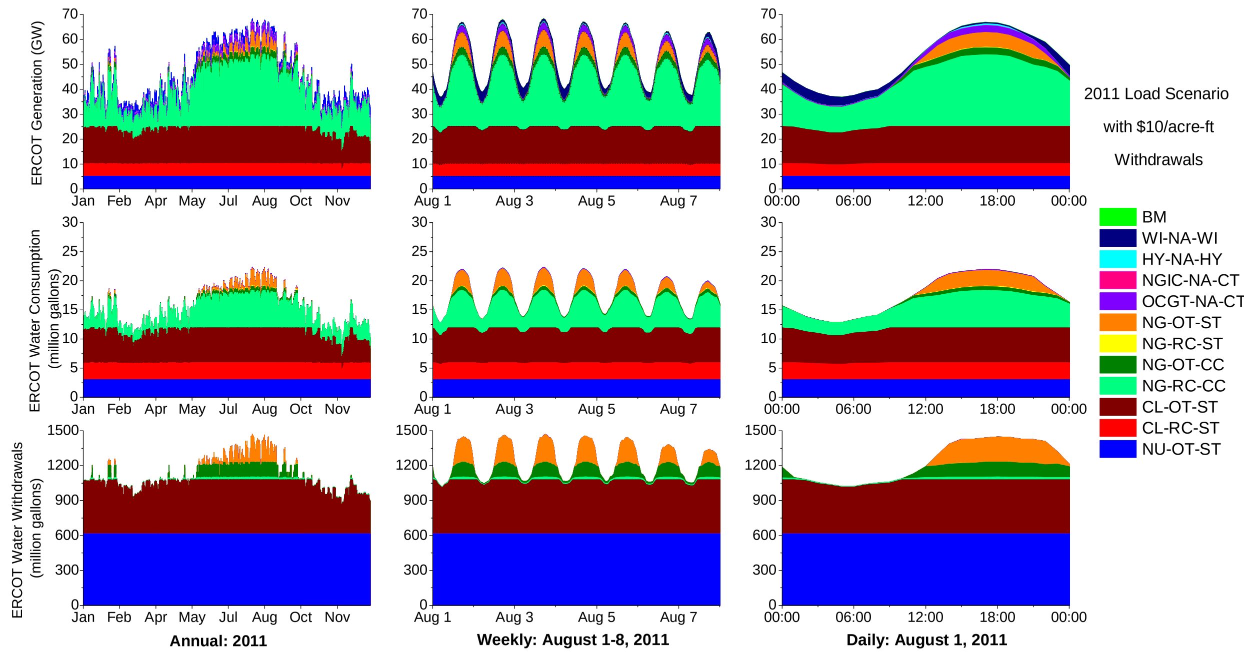

Figure 4.10: Imposing a water cost of \$10 per acre-ft of water withdrawn for power generation reduces withdrawals and consumption by 1.3% and 0.51%, respectively. Very slight decreases in NG-OT-ST are met by slight increases in NG-RC-CC, in comparison to the baseline.

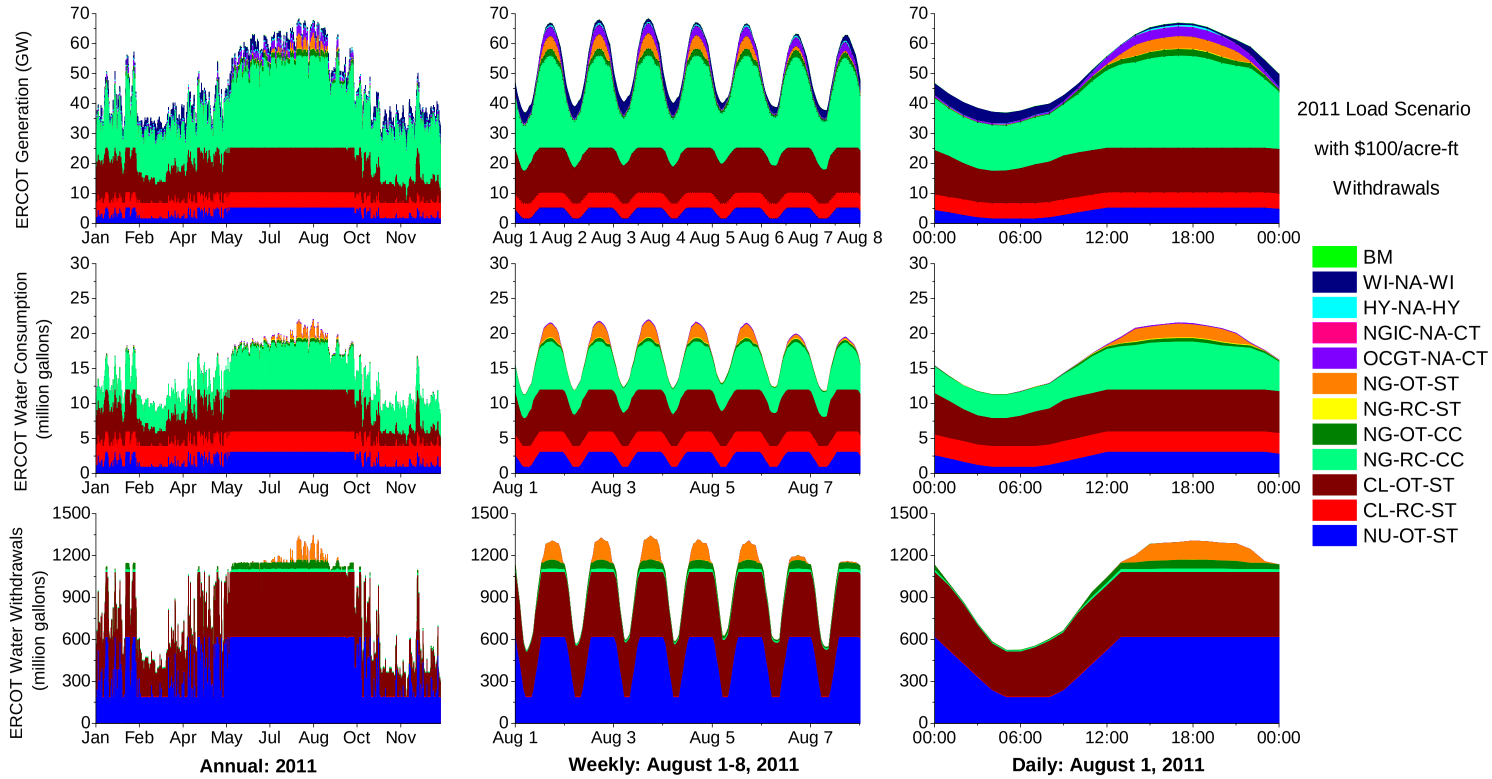

Figure 4.11: Applying a water cost of \$100 per acre-ft for water withdrawals resulted in a 41% and 11% reduction in water withdrawals and consumption, respectively. Nuclear EGUs ramp-up and down with load. Annual generation by nuclear EGUs is 50% of the baseline.

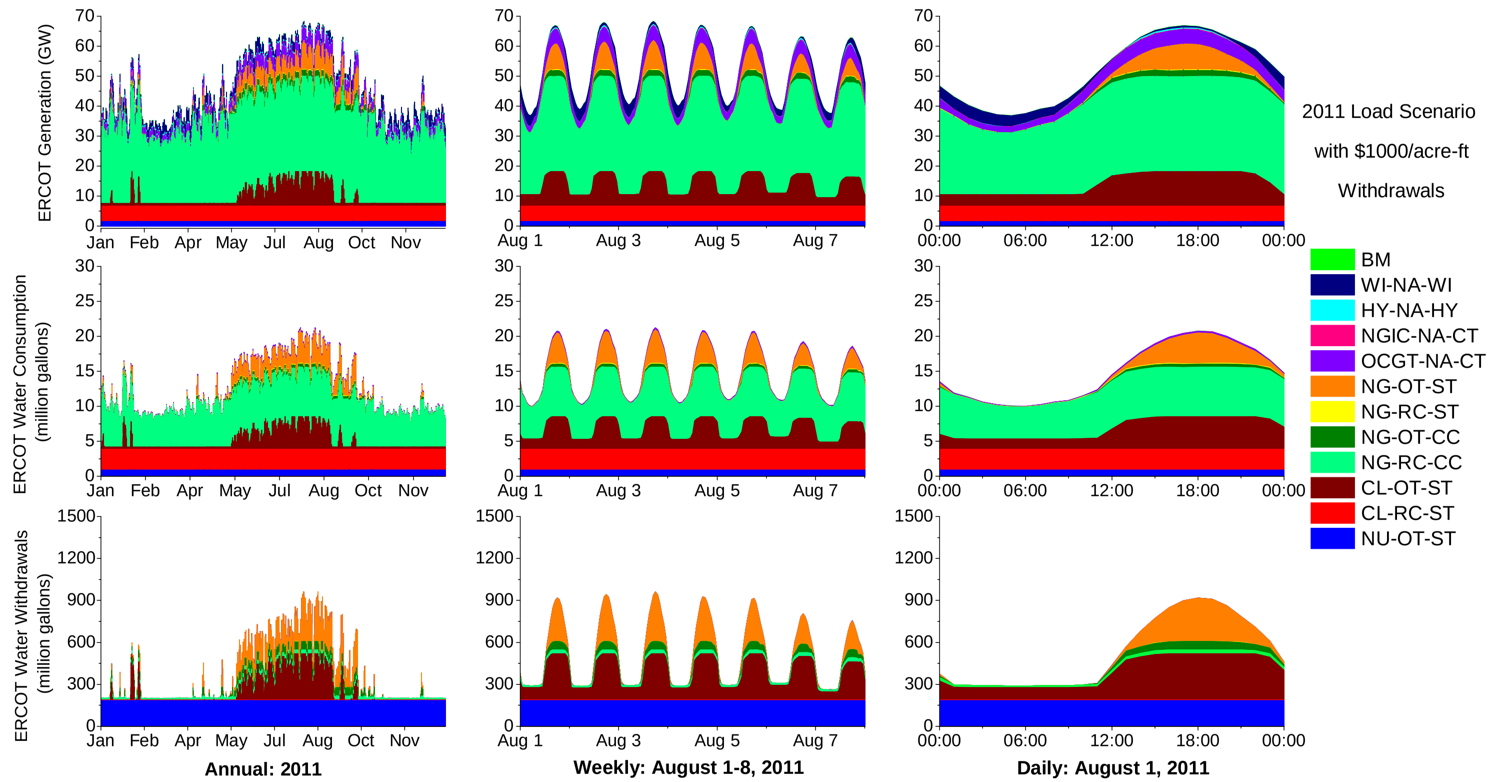

Figure 4.12: Applying a water cost of $1,000 per acre-ft for water withdrawals resulted in a 74% and 23% reduction in water withdrawals and consumption, respectively. Generation from once-through cooled EGUs decreases by a total of 75% from the baseline. CL-OT-ST generators begins ramping. Generation by NG-RC-CC and OCGT-NA-CT increases by 110% and 250%, respectively, from the baseline.

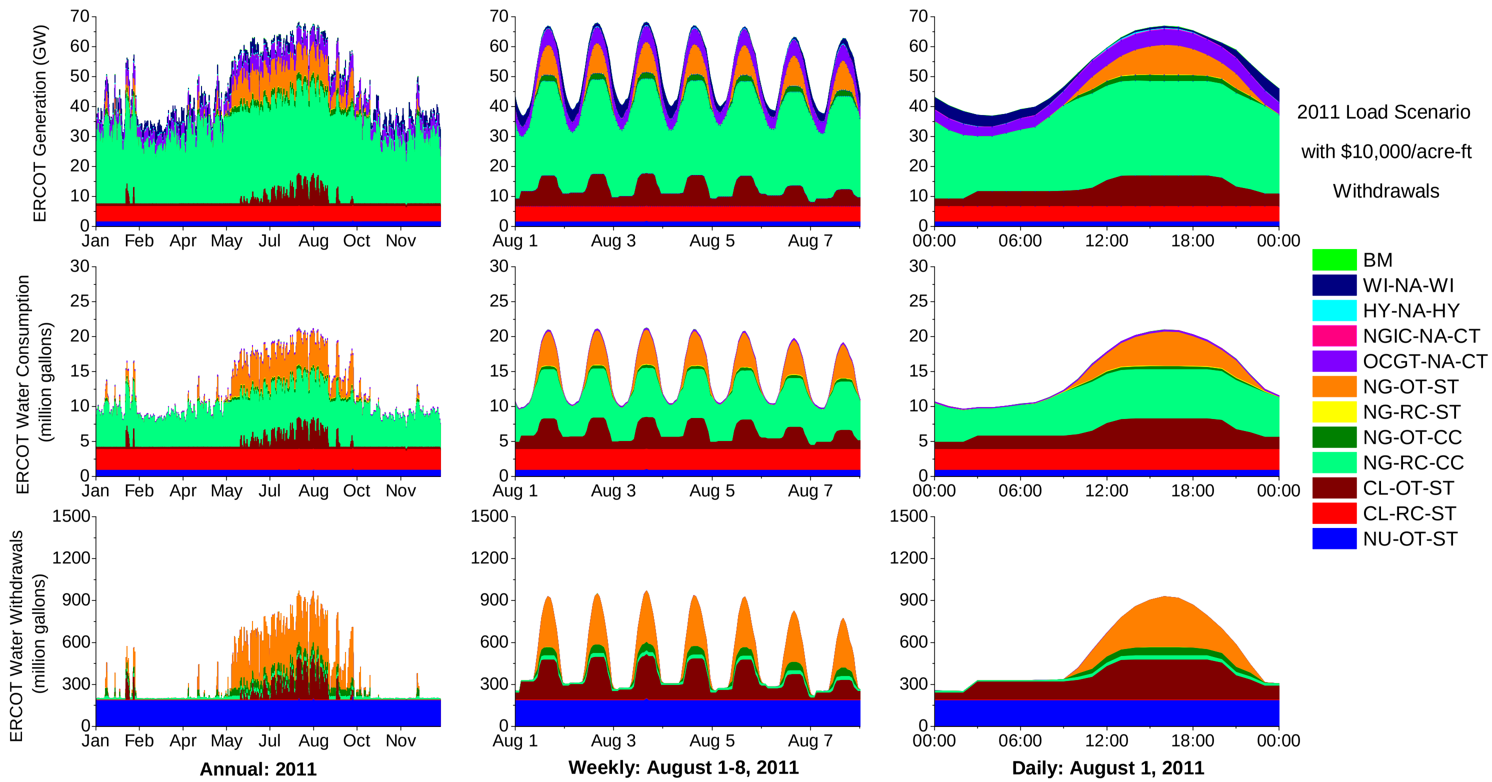

Figure 4.13: Applying a water cost of \$10,000 per acre-ft for water withdrawals resulted in a 75% and 26% reduction in water withdrawals and consumption, respectively. Shifts from the baseline are very similar to the WW1000 scenario.

4.5 Discussion

Imposing water costs on the water consumed or withdrawn for power generation in ERCOT prompted changes to 2011 generation characteristics. Capacity factor is a measure of the ratio of electricity that an EGU generates over a period of time compared to the maximum electricity that the EGU could generate if it operated at full power for the over the same period. Table 4.7 details the annual 2011 capacity factors for each EGU type in each simulation. These values provide insight into the annual shifts in generation from one EGU type to another.

Differences in capacity factor amongst the baseline, WC10, WC100, WC1000, and WW10 scenarios are small. However, changes in the capacity factors of EGUs in the WW100, WW1000, and WW10000 scenarios show significant changes in the generation characteristics of these proposed cost regimes. (Full details regarding the annual generation, total generation costs, average heat rate, capacity factor, and water use characteristics for each generator type across all scenarios are in Appendix C.)

4.5.1 Water Consumption Cost Scenarios

In general, raising the cost of water consumed for power generation caused only small changes in the generation fleet (Figure 4.14), generation costs (Figures 4.15 and 4.16), water withdrawals (Figure 4.17), and water consumption (Figure 4.18) from 2011 baseline trends in ERCOT. Changes from the baseline were erratic, indicating that differences oscillated between positive and negative from one hour interval to the next. These trends suggest that increasing the price of consumed water caused a large number of generators to bid into ERCOT with similar SRMCs. Thus, slight changes to the dispatch order occurred across most time intervals, causing small, but

Table 4.7: Increasing the cost of water in the power sector caused shifts in generation, illustrated here by shifts in capacity factor. The most dramatic changes from the baseline occurred in the WW1000 and WW10000 scenarios, where large increases in natural gas combined-cycle with recirculating cooling offset decreases in nuclear and coal generation with once-through cooling.

	2011 Capacity Factor (%)								
Scenario	Baseline	WC10	WC100	WC1000	WC10000	WW10	WW100	WW1000	WW10000
All Generators	33	33	33	33	32	33	30	35	37
NU-OT-ST	100	100	100	100	100	100	47	30	30
CL-RC-ST	90	90	90	88	57	91	98	99	96
CL-OT-ST	85	85	85	84	74	83	68	14	9.0
NG-RC-CC	31	31	31	31	41	31	46	69	66
NG-OT-CC	13	13	13	14	19	12	9.0	9.0	10
NG-RC-ST	10	10	10	10	10	10	10	10	10
NG-OT-ST	2.0	2.0	2.0	2.0	1.0	2.0	1.0	4.0	8.0
OCGT-NA-CT	10	10	10	10	10	10	10	10	10
NGIC-NA-CT	22	22	22	22	28	21	18	46	76
HY-NA-HY	29	29	29	29	29	29	29	28	28
WI-NA-WI	28	28	28	28	28	28	28	28	28
BM	17	17	17	18	23	18	21	58	41

erratic shifts from the baseline (potentially within the margin of error).

In general there were slightly net positive increases in natural gas combined-cycle plants with recirculating cooling across the WC scenarios. There was a net decrease in coal EGUs with recirculating cooling, since these generators generally have higher consumption rates than natural gas or coal plants with once-through cooling. There was also a net decrease in natural gas once-through cooled EGUs with steam boilers during the summer when demand was high. This generation was typically replaced by natural gas combined-cycle plants with recirculating cooling, as well as open-cycle gas turbines in the WC1000 and WC10000 scenarios.

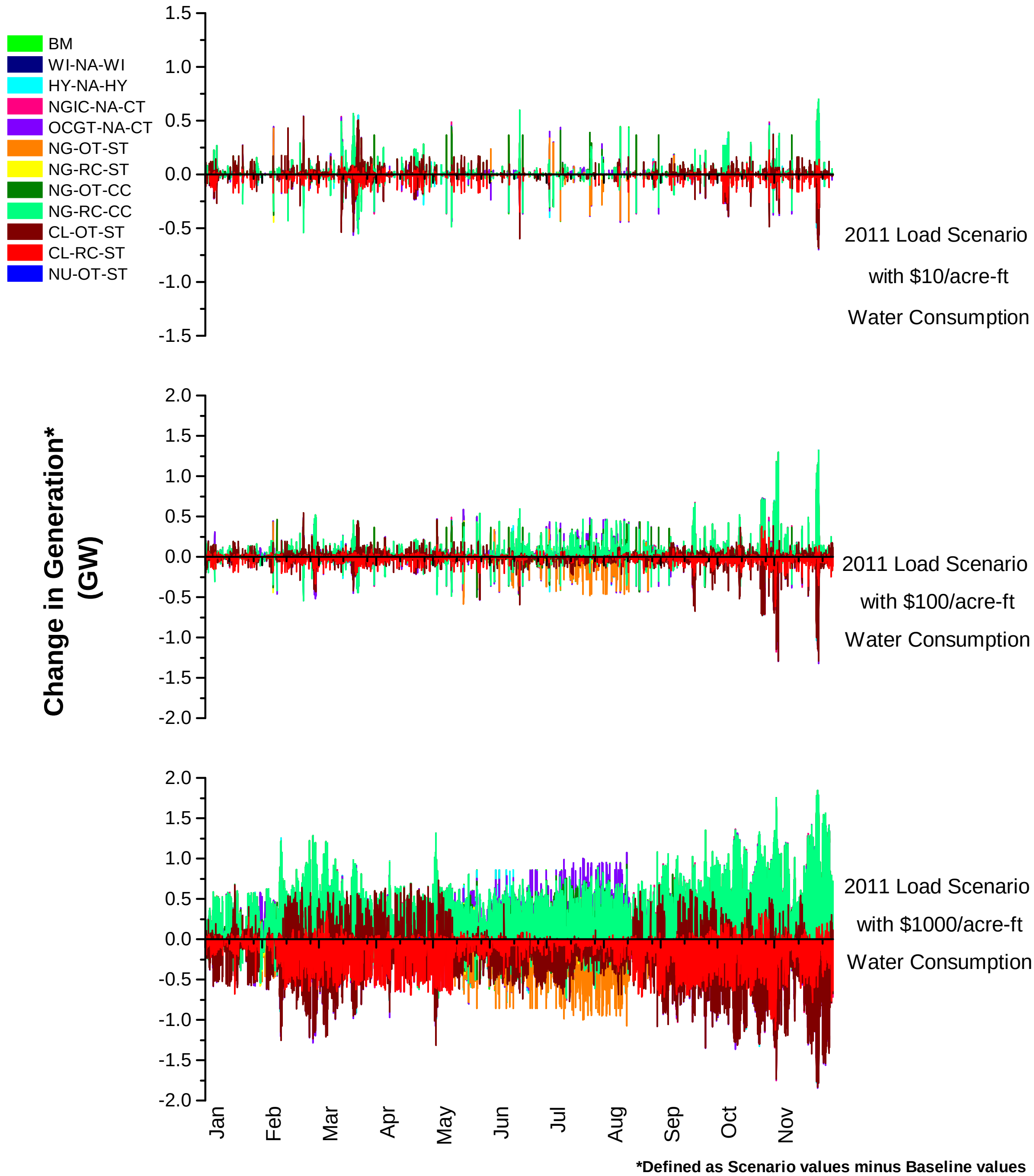

Figure 4.14: Increasing water costs on water consumed during power production resulted in smaller shifts in generation than increasing the cost of water withdrawals.

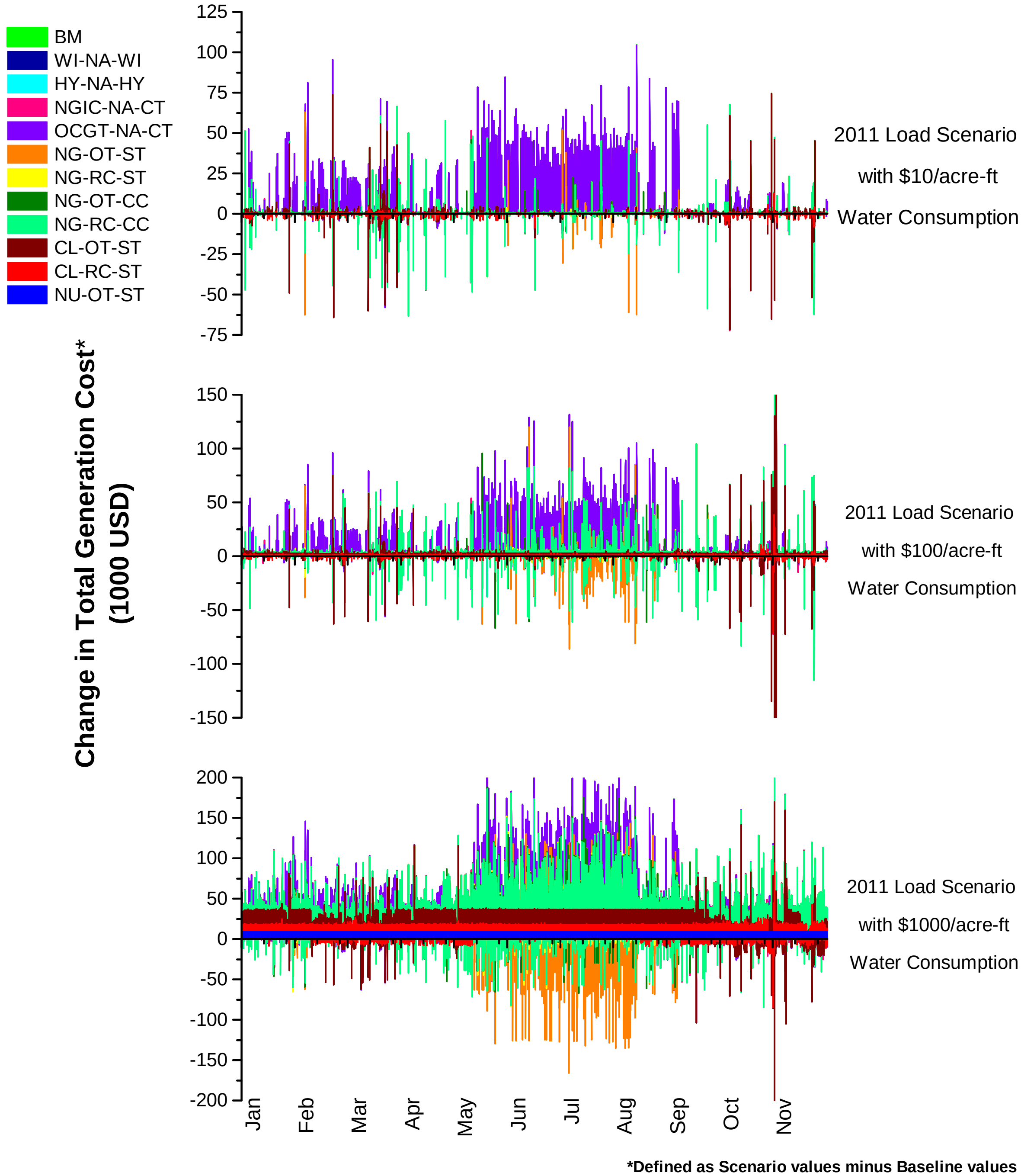

Figure 4.15: Shifts in total generation cost, which includes fuel, VO&M, start-up and shut-down, and water costs, due to increased water consumption costs were generally an order of magnitude less than scenarios that increase costs for total water withdrawals. Increases in natural gas combined-cycle and open-cycle EGUs represented the largest increases in total generation costs from the baseline because of increases in electricity production by these generators.

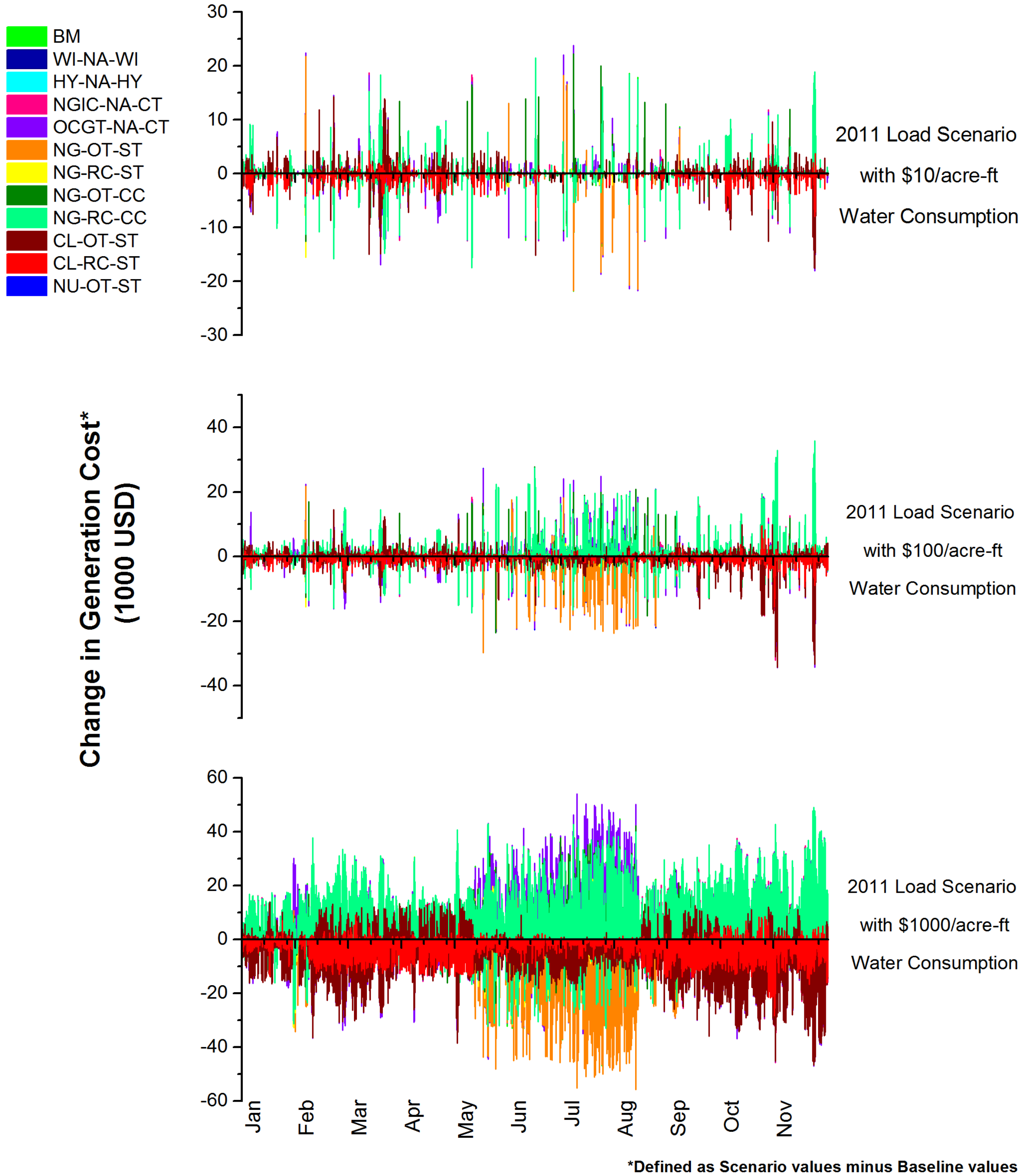

Figure 4.16: These shifts in generation costs, excluding water costs, demonstrate that additional costs are incurred by switching from the least-cost merit order (i.e. the baseline scenario) to more expensive generators that are more water lean.

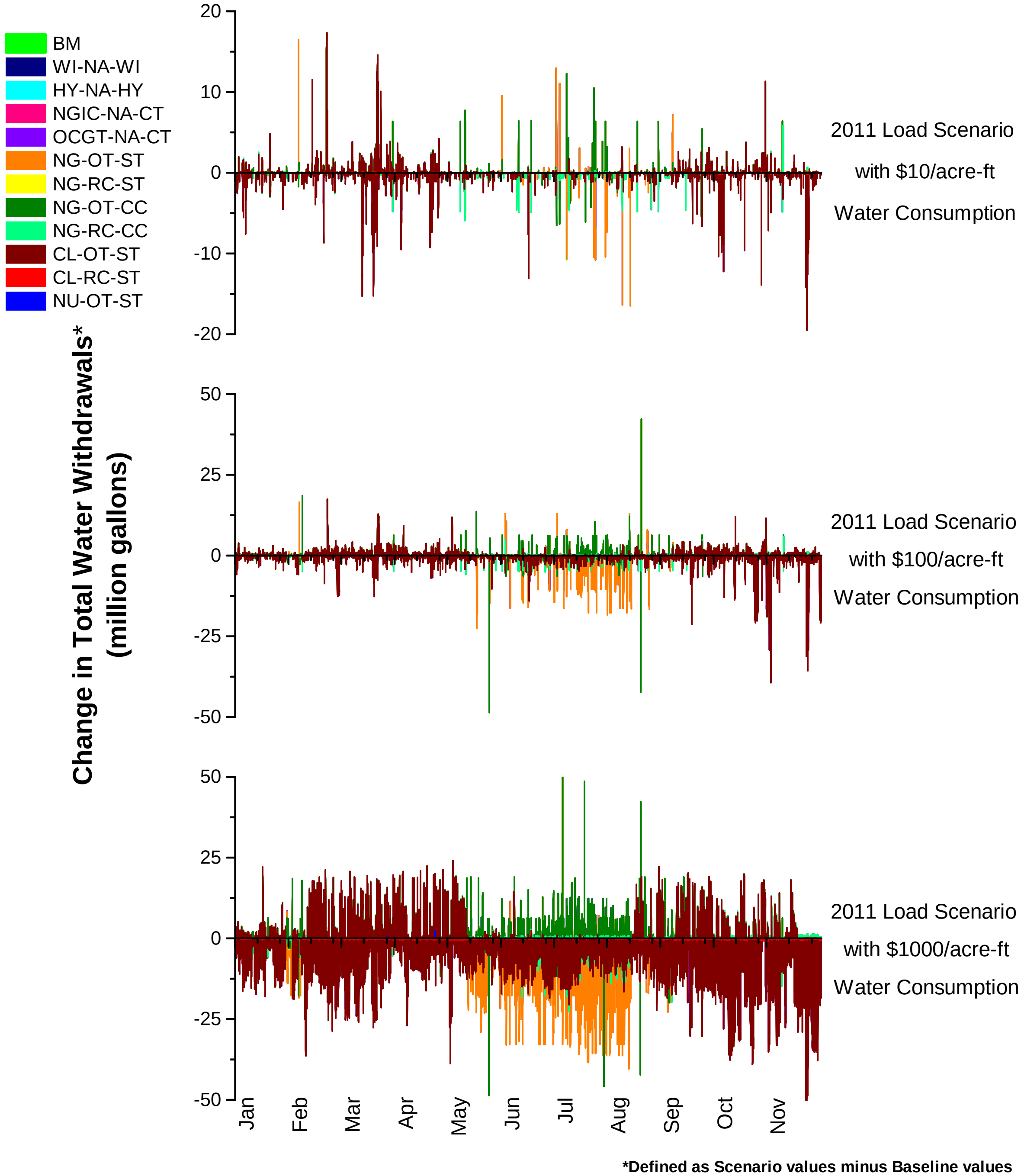

Figure 4.17: Reductions in the water withdrawn by ERCOT generators due to increased water consumption costs are more modest than in increased water withdrawal cost scenarios.

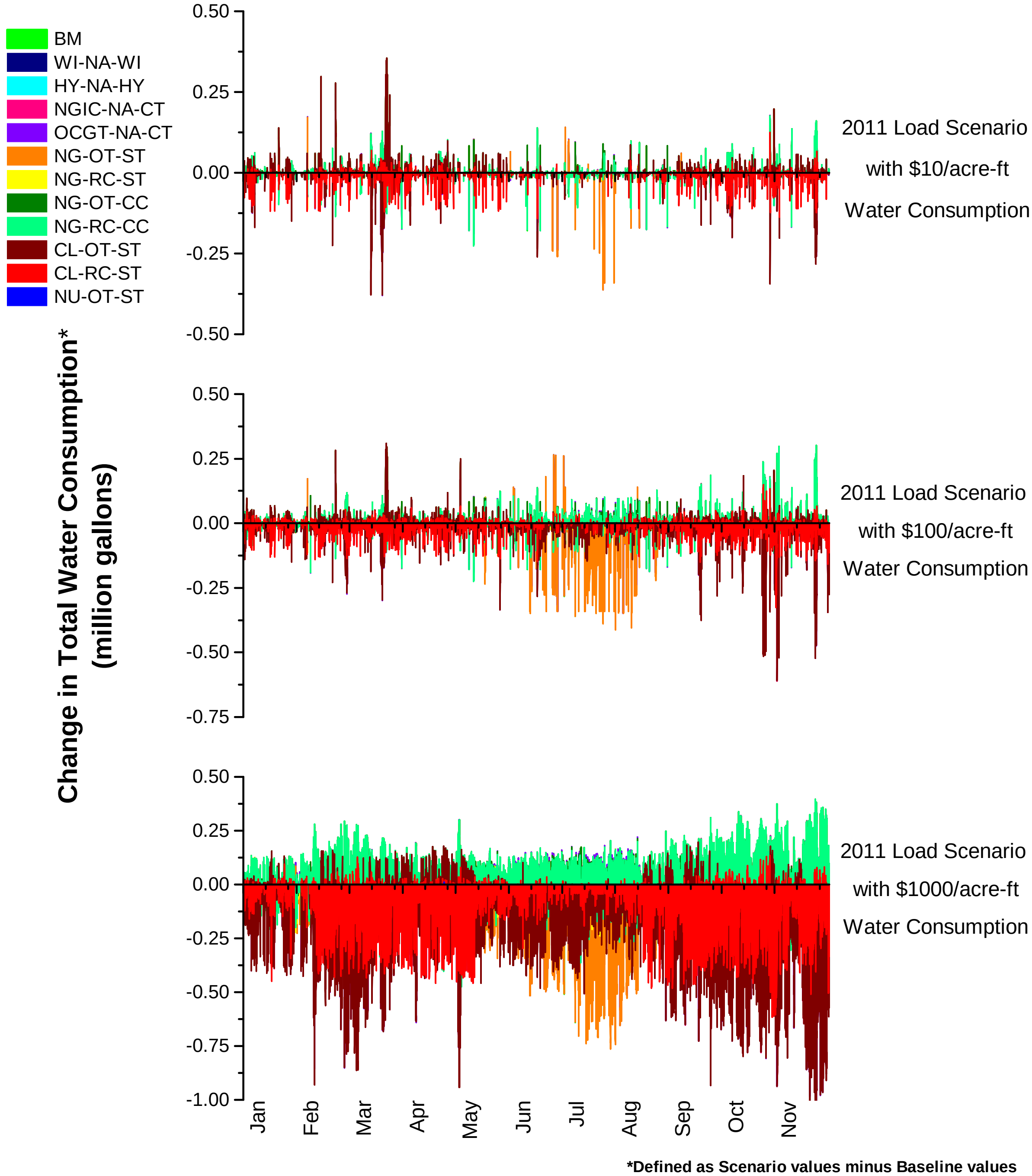

Figure 4.18: Reductions in the water consumed by generators in ERCOT due to increased water consumption costs of $10–$1000 per acre-ft are very slight in magnitude.

4.5.2 Water Withdrawal Cost Scenarios

Increasing the cost of water withdrawn for power generation prompted much larger shifts in the generation fleet (Figure 4.19), generation costs (Figures 4.20 and 4.21), water withdrawals (Figure 4.22), and water consumption (Figure 4.23) from 2011 baseline trends in ERCOT, as compared to WC cost scenarios.

Figure 4.19 illustrates changes from the baseline generation fleet for the \$10, \$100, and \$1,000 per acre-ft cost scenarios. Unlike the WC cost scenarios, which were erratic and difficult to characterize, the WW scenarios showed defining trends. In all three scenarios, the largest reduction in generation by generator type was by once-through cooled coal EGUs. Large decreases in nuclear generation also characterized the \$100 and \$1,000 scenarios. These reductions were offset by large increases in natural gas combined-cycle plants with recirculating cooling and slight increases in coal EGUs with recirculating cooling systems. In the WW1000 scenario, increases in generation by open-cycle gas turbines were also observed. (Although the WW10000 is not shown in Figure 4.19, trends are very similar to the WW1000 scenario.)

Increases in total generation costs (which include water costs) were significant, especially in the WW100, WW1000, and WW10000 scenarios (See Figure 4.20). These scenarios had increased costs of 25%, 113%, and 870%, respectively. Cost increases during the summer peak months were especially high since water-intensive once-through cooled EGUs were required to operate to meet demand. The change in costs incurred by natural gas once-through cooled steam-cycle plants was negative in the WW10 and WW100 scenarios, but positive in the WW1000 and WW10000 scenarios. This shift occurred because nuclear generation in the WW1000 and WW10000 was so costly that nuclear was not economical at any point during the year; accordingly, these once-through cooled natural gas systems had to operate during summer peak periods to meet demand when nuclear baseload was not available.

Comparing Figure 4.20 and Figure 4.21 reveals insight into the magnitude of water costs versus other generation costs. In the WW10 and WW100 scenarios, water costs account for 3% and 16% of total generation costs, respectively. In the WW1000 and WW10000 scenarios, these water costs increase to 41% and 88% of total generation costs, respectively. .

Reductions in water withdrawals grow substantially as water withdrawal price is increased up to $1,000 per acre-ft. Water withdrawal savings in the WW1000 scenario as compared to the WW10000 scenario are relatively small, but total generation costs in the latter scenario increase by a factor of four. The largest reductions in water withdrawals are realized through decreases in the dispatch of once-through cooled generators, especially nuclear- and coal-fired generators.

The changes in the water consumed in the WW scenarios, illustrated in Figure 4.22, resemble the changes in generation illustrated in Figure 4.19 in terms of profile. Large reductions in once-through coal and nuclear generation are offset by smaller increases in the water consumed by natural gas combined-cycle and coal EGUs equipped with recirculating cooling systems. Decreases in water consumption for the WW scenarios are larger than decreases in the WC scenarios across similar water cost points.

4.5.3 Cost-Effectiveness of Water Conservation in ERCOT

Table 4.8 summarizes the cost-effectiveness of water reductions through the power sector for each of the eight cost scenarios evaluated. Here cost-effectiveness is defined as the volume of water reduced per dollar of total generation cost in excess of the baseline scenario. Overall, the WW100 scenario offered significant and relatively

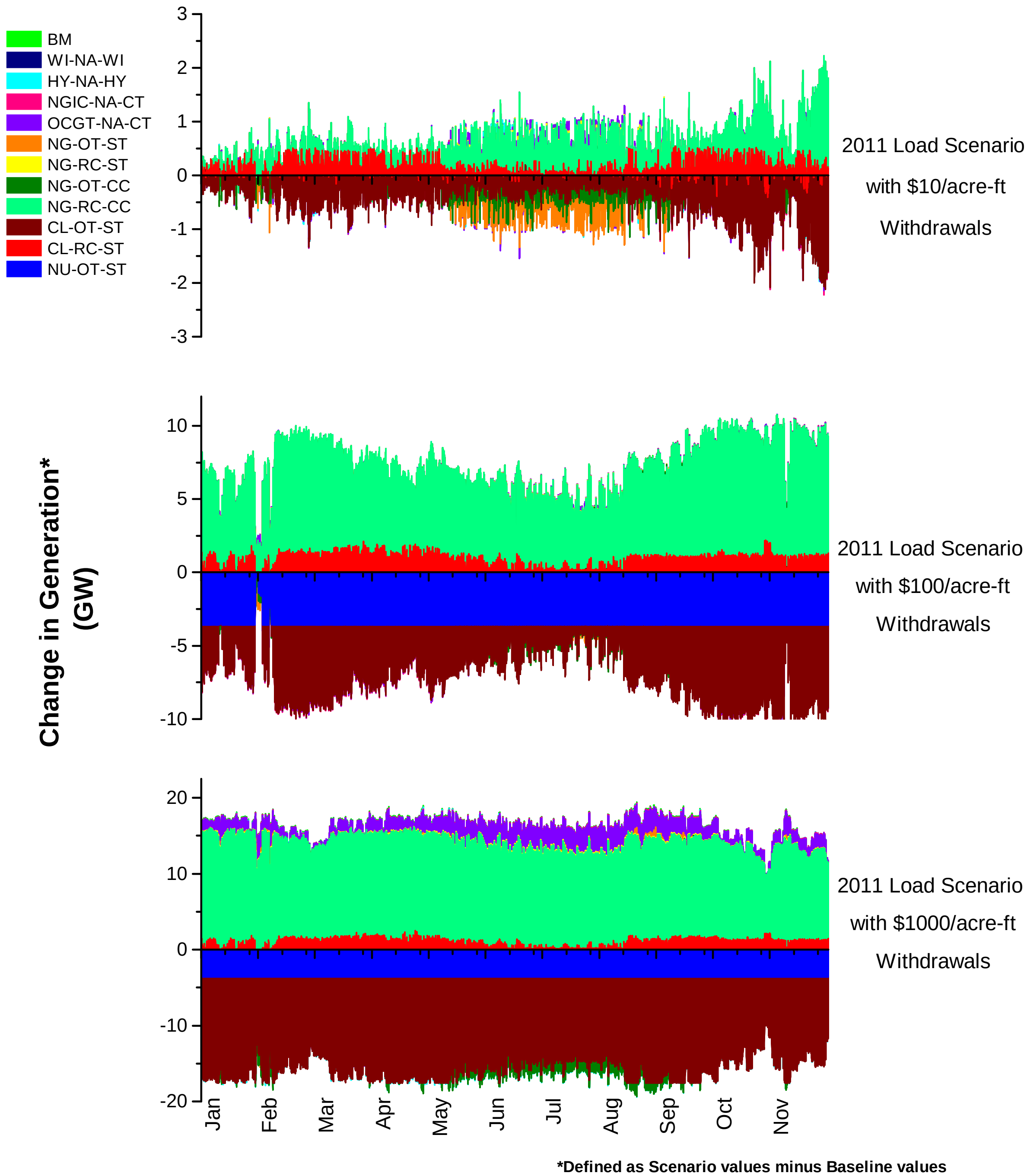

Figure 4.19: Imposing an increased water cost on water withdrawals results in shifts in generation to meet load. Generally, generation from natural gas combined-cycle plants and coal plants with recirculating cooling increases, while generation from once-through cooled coal, nuclear, and natural gas plants decreases.

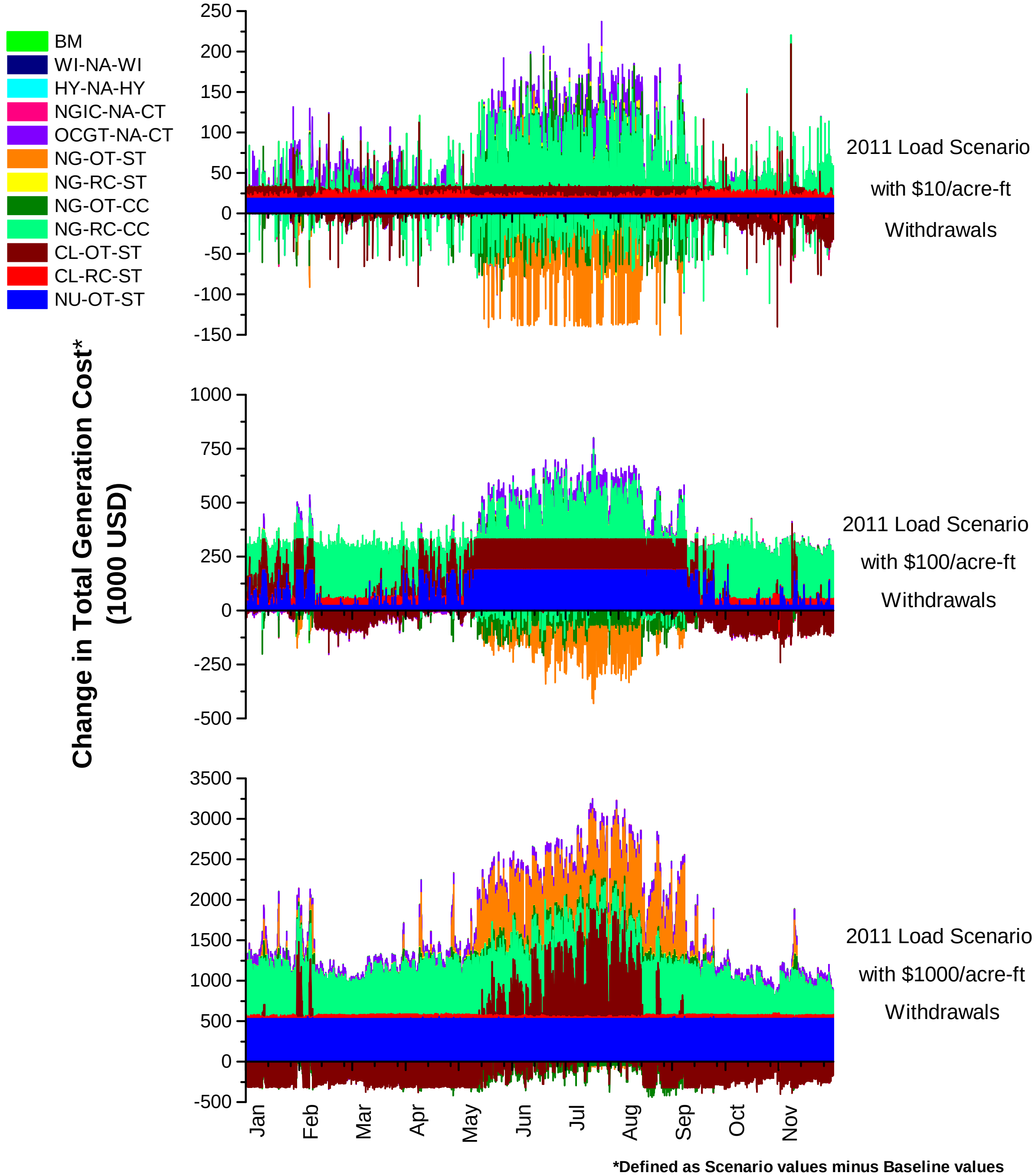

Figure 4.20: Total generation costs (including fuel, VO&M, start-up and shut-down, and water costs) across ERCOT rise in the presence of an increased cost on water withdrawals, especially during peak generation when water-intensive plants must be on to meed demand. Cost reductions occur when generation shifts offline in comparison to the baseline scenario.

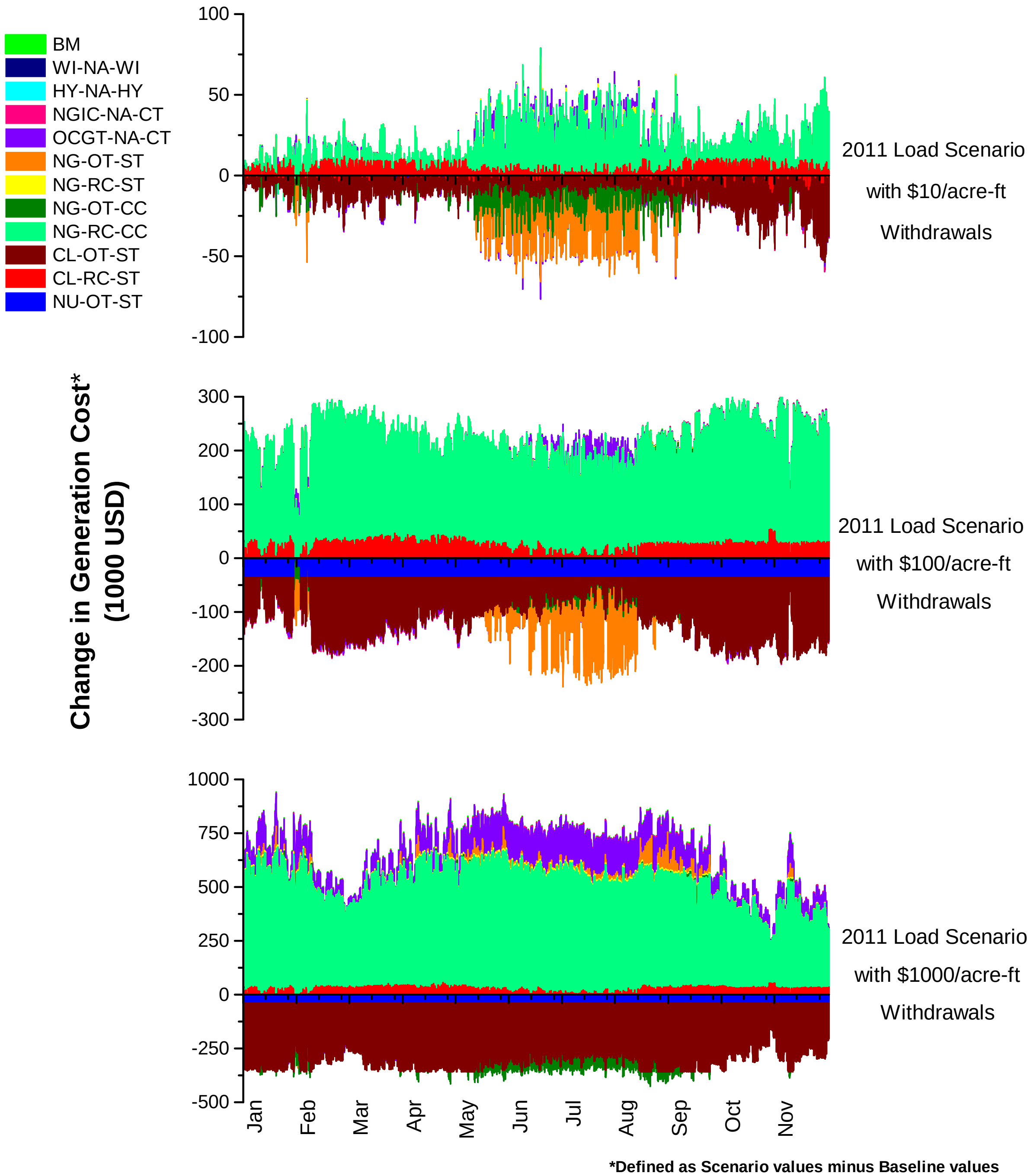

Figure 4.21: Additional costs are incurred by switching from the least-cost merit order to more expensive generators that are more water lean. There are large differences in shape profile when comparing changes in *total* generation costs (which includes water costs in Figure 4.20) and changes in generation costs excluding water costs.

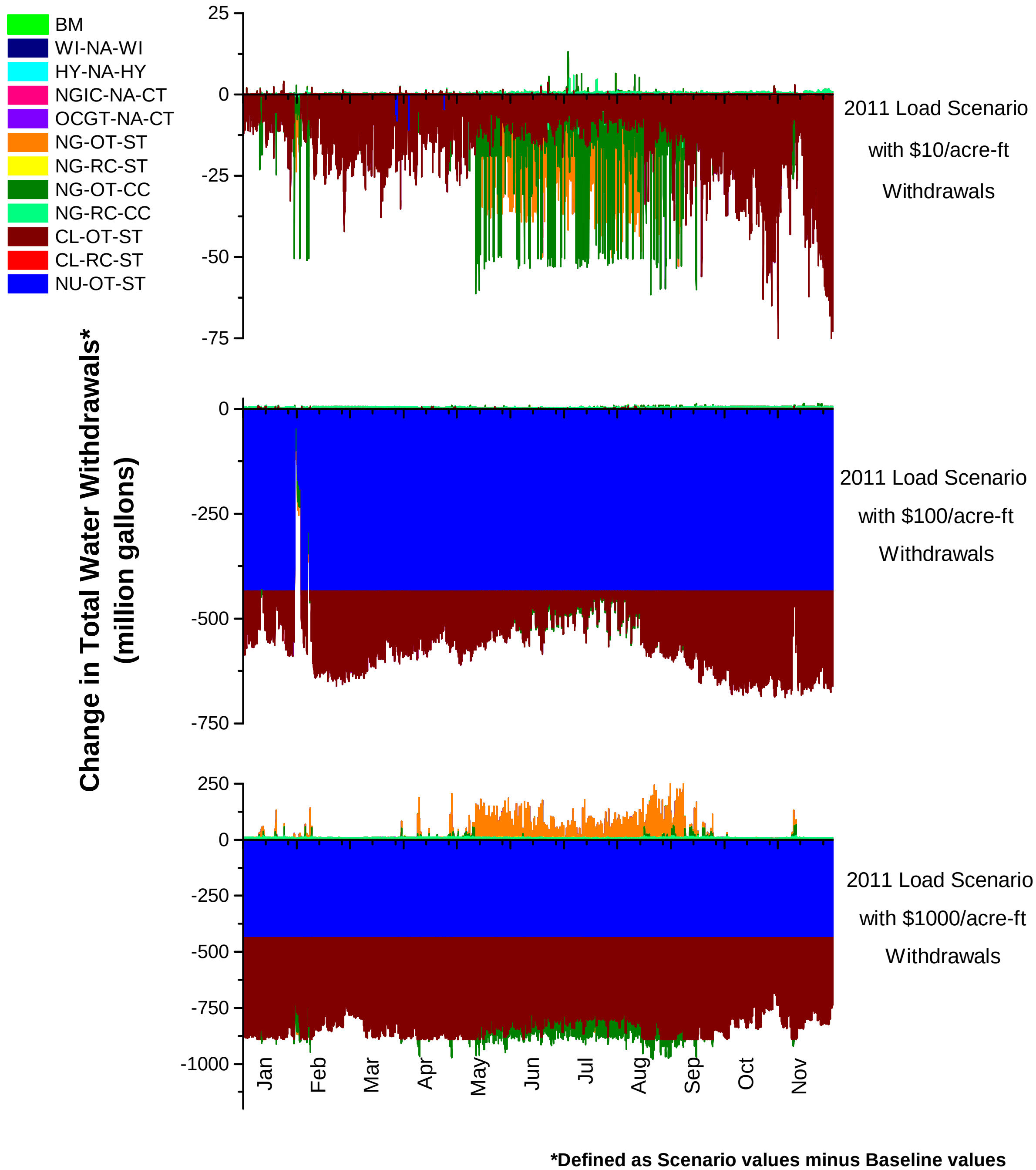

Figure 4.22: Large reductions in nuclear and once-through cooled coal plants occur when water withdrawal costs increase to $100 per acre-ft.

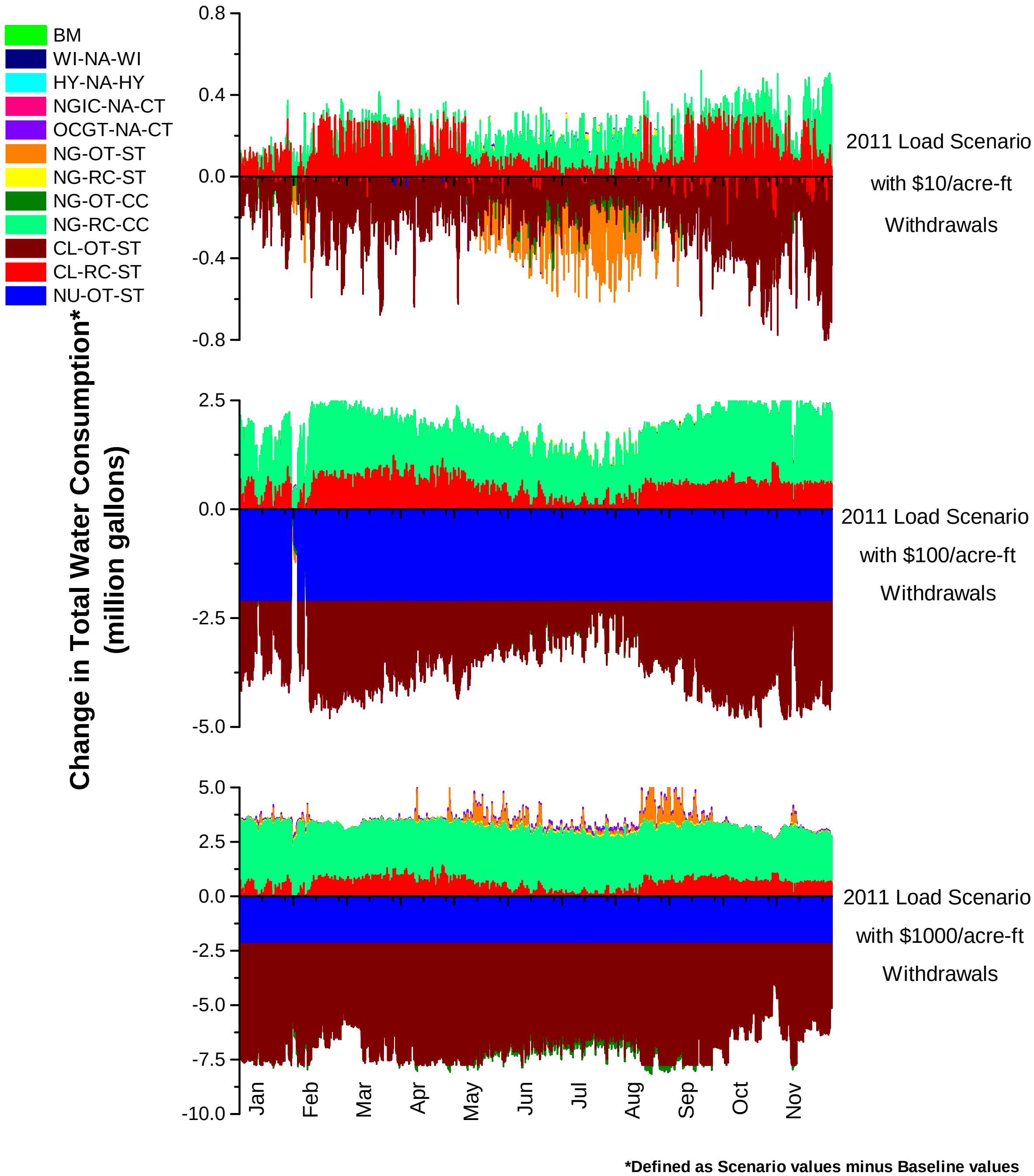

Figure 4.23: Decreases in the water consumed by nuclear and coal generators were moderated by increases in water consumption by natural gas combined-cycle EGUs.

cost-effective water consumption and withdrawal volume reductions across ERCOT.

Table 4.8: The cost effectiveness of reducing water consumption was highest in the WC10 scenario; however, the scale of reduction was near negligible. The WW100 scenario offered large water withdrawal and consumption savings relatively cost effectively in comparison to other scenarios.

Scenario Identifier	Cost Effectiveness of Reducing Consumed Water (gallons reduced per USD)	Cost Effectiveness of Reducing Withdrawals (gallons reduced per USD)
Baseline	NA	NA
WC10	9.54	376
WC100	4.54	190
WC1000	4.25	150
WC10000	4.24	137
WW10	2.09	433
WW100	7.86	2260
WW1000	3.78	945
WW10000	0.426	97.1

Table 4.9 summarizes the cost of reducing a unit of consumed or withdrawn water in each scenario. For comparison, Table 4.10 details average costs for water management strategies proposed in the TWDB's 2012 State Water Plan. In general, water conservation through the power sector is comparable to TWDB water management strategies when considering water withdrawals; however, since the State Water Plan does not differentiate between withdrawals and consumption, comparison is difficult. The cost of reducing water consumption tended to be more expensive through the power sector than other water management strategies.

4.5.4 Spatial Shifts in Water Use

In addition to temporal shifts in water use, imposing higher water costs also shifted water use spatially. Figure 4.24 illustrates how water withdrawals shift across

Table 4.9: The cost of water conservation through ERCOT is summarized for each scenario. Overall, the WW100 scenario offered the cheapest cost per gallon of withdrawn water reduced.

Scenario Identifier	Cost of Reducing Consumed Water (USD per gallon reduced)	Cost of Reducing Withdrawals (USD per gallon reduced)
Baseline	NA	NA
WC10	0.104	0.00266
WC100	0.220	0.00526
WC1000	0.235	0.00666
WC10000	0.236	0.00730
WW10	0.478	0.00231
WW100	0.127	0.000443
WW1000	0.266	0.00106
WW10000	2.35	0.0103

Table 4.10: Average costs of water management strategies in Texas were calculated from the Texas Water Development Board's State Water Plan.

Description	(USD per acre-ft)	(USD per gallon)
Average Lease Rate in Texas	100	0.000307
New SW/GW supplies in Texas; Municipal water costs	1,000	0.003069
New Desalination	10,000	0.030689
Bottled Water	1,000,000	3.068883

the state of Texas in response to higher water costs for power generators. In general, the very water intensive generators reduced water withdrawals significantly in the WW1000 scenario shown, but more water-lean generators actually increased their water requirements, which might affect water users or ecosystems that share a common reservoir. Spatial shifts in water use are a factor that will be explored further in future analyses, since they were not examined in depth in the current analysis.

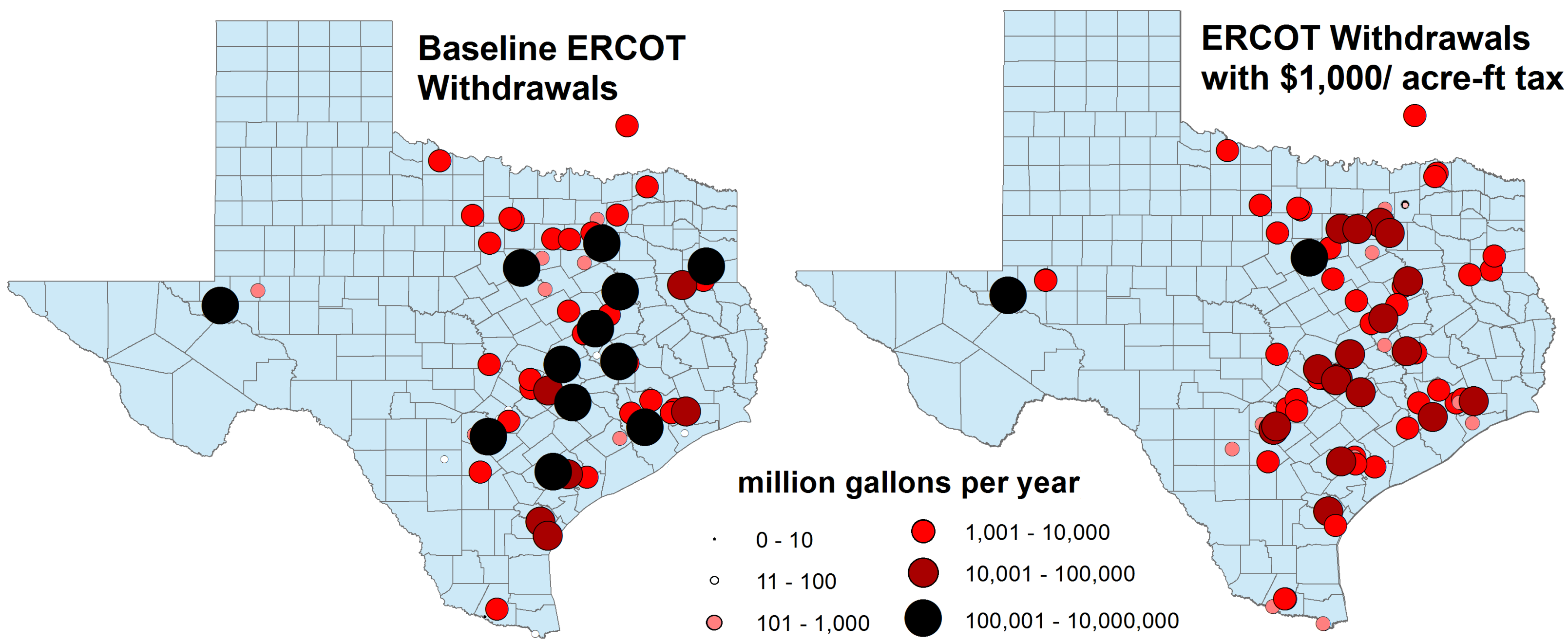

Figure 4.24: Increasing the cost of water for power generators shifts water use spatially and temporally.

4.6 Conclusion

This analysis evaluated the impact of increased water costs to power generators in ERCOT by means of a UC&D model. Although it proposed water cost scenarios, suggesting policy mechanisms to implement such cost strategies was beyond the scope of the analysis.

Results suggest that higher water costs might be an effective policy lever for reducing water withdrawals; however, raising water costs was not as effective for reducing the water consumed for power generation. Water consumption was more difficult to target for reduction because many power generators within ERCOT have very similar water consumption rates. Thus, increasing the cost of water consumption resulted in small erratic shifts in generation that had little correlation to the magnitude of cost increases. Water withdrawal rates by EGUs, on the other hand, differ by many orders of magnitude, so there were clear, predicable changes in the generation fleet in the presence of higher water withdrawal costs. When water conservation costs were compared to other proposed water management strategies in Texas, raising the cost of electricity generation through water prices was relatively cost-effective for reducing water withdrawals, but not for reducing water consumed.

Future analyses will explore the spatial shifts in water withdrawals and consumption in the presence of higher water costs. Transmission constraints, which were not imposed in this analysis, will also be explored to see if results are sensitive to congestion.

Chapter 5

Summary

This dissertation addressed four major objectives:

1. Quantifying the energy consumed for water in the US,
2.
3. Determining effective modes of energy conservation through regional changes to residential water heating technologies,
4. Calibrating a unit commitment and dispatch (UC&D) model to simulate 2011 power generation, generation costs, water consumption, and water withdrawals for electricity production in the Electric Reliability Council of Texas (ERCOT), and
5. Utilizing the UC&D model to assess the role of water prices in reducing water use across ERCOT.

The following sections summarize the major conclusions and lessons learned from these studies.

5.1 Quantifying US Energy Consumption for Water Services

Chapter 2 presented analysis that is the first to quantify water-related energy-consumption in the US residential, commercial, industrial, and power sectors. It is also the first to differentiate consistently between primary and secondary uses of energy for water, incorporate the relative efficiencies for power plants and direct use, integrate the most recent primary data and statistics collected by relevant agencies, and allocate embedded energy for a broad range of relevant appliances and functions. Results suggest that the energy embedded in the US water system represented 12.6% of national primary energy consumption in 2010. Residential and commercial water heating were identified as viable areas for strategic energy conservation efforts.

5.2 Evaluating Energy and Emissions Reductions Through Shifts in Residential Water Heating

Chapter 3 extended the analysis presented in Chapter 2 to evaluate potential energy conservation strategies through changes to regional water heating fleets. Results suggest that regional energy use and climate characteristics affect the energy performance and environmental trade-offs of end-use appliances. In regions with GHG-intensive generation mixes and low solar resources, the shift from electric storage water heaters to natural gas water heaters was more effective in reducing regional carbon emissions from water heating than shifting to SWHs. In other regions, switching from electric storage water heaters to SWHs with electric auxiliary systems was more effective in reducing emissions. However, regions most likely to switch to SWHs also tended to be regions that had less GHG intensive electricity generation, and therefore, derived less benefit than switching in coal-intensive regions.

5.3 Evaluating Water Reductions Through Changes in the Power Sector

In Chapter 4, a UC&D model of ERCOT was calibrated to represent water usage characteristics for ERCOT's 2011 generation fleet and load profile. Scenarios were selected to assess the effect of increased water prices for power generators on total water withdrawals and consumption at the grid-scale. Results suggest that significant reductions in water consumption and withdrawals could be achieved by increasing water costs; however, these costs increase total generation costs by several billion dollars in most scenarios.

5.4 Future Work

Future analyses will assess additional opportunities for carbon and energy reductions via water conservation efforts, efficiency improvements, and new technologies. Additionally, future work will aim to identify a general framework for characterizing the energy and carbon intensities of water systems based on regional variability in geography, climate, and policy frameworks. This extension of the analysis will become increasingly important as population growth, water scarcity, and increasing drinking water quality standards force regional planners to identify solutions for ensuring adequate drinking water to the US population without exacerbating energy and carbon expenditures.

In terms of the water withdrawn and consumed in the power sector, future analyses will explore the spatial shifts in water use that occur in the presence of higher water costs. Although this dissertation explored large scale changes in water use across ERCOT, a more detailed look into changes in water use at the cooling reservoir level would be useful. Many power plants in ERCOT have their own cooling reservoir, and thus have little impact on other water users, while others share water, so distinguishing these characteristics is pertinent, though overlooked here. In each of these cases, developing metrics to assess power reliability and water reliability would be useful. Similarly, better metrics for evaluating the trade-offs between consumed water versus withdrawn water would be useful, since the literature is not consistent in valuing the importance of reducing one against the other.

Appendices

Appendix A

Quantifying US Energy Consumption for Water Services

This section provides details regarding the assumptions made in in Chapter 2 regarding the quantification of water-related energy in the Residential, Commercial, Industrial, and Power sectors.

A.1 Water-related Energy in the Residential Sector

Space Heating

Several types of space heating systems use water as a medium to transfer heat and are included in the *Indirect Steam Use* category of the analysis. Approximately 9-11% of US residences heat homes with boilers that burn natural gas or oil in order to transfer heat from combustion gases to water or steam, which is then is distributed through pipes to heat spaces by means of radiators, radiant floor systems, or coils (Lekov et al., 2004; Navigant Consulting Inc, 2007). Hydronic systems are less-popular, but also use water as a medium to transfer heat through closed-pipe systems for space heating and cooling. According to the 2009 Residential Energy Consumption Survey (RECS), 12% of all natural gas space heating systems and 30% of all petroleum-based heating systems (propane, Liquid Petroleum Gas (LPG), fuel oil, and kerosene) were steam or hot water systems (EIA, 2011c). Although 2009 RECS data are proportioned by physical units, rather than by energy consumption, we assume the difference between the two are within the margin of error assigned to

Table A.1: The US Residential Sector consumed approximately 22.1 quadrillion BTUs of primary energy (with retail electricity losses); twenty-one percent of this energy is directly water-related.

	Energy Consumption By Primary and Secondary Fuel [Trillion BTU]							
Residential	**Coal**	**Natural Gas**	**Oil**	**Renewable Energy**	**Total On-site**	**Purchased Electricity**	**Total Energy**	**Error**
Space Heating	**20**	**3290**	**770**	**440**	**4520**	**1340**	**5860**	–
Percentage water-related	100%	12%	30%	5%	15%	0%	11%	–
for Steam (Indirect)	20	395	231	22	668	0	668	20%
Water Heating	**0**	**1340**	**180**	**5**	**1525**	**1380**	**2905**	–
Percentage water-related	100%	100%	100%	100%	100%	100%	100%	–
for Direct Water Services	0	1340	180	5	1525	1380	2905	0%
Air Conditioning	**0**	**0**	**0**	**0**	**0**	**3490**	**3490**	–
Percentage water-related	0%	0%	0%	0%	0%	3%	3%	–
for Direct Water Services	0	0	0	0	0	105	105	20%
Wet Cleaning	**0**	**50**	**0**	**0**	**50**	**970**	**1020**	–
Percentage water-related	95%	95%	95%	95%	95%	95%	95%	–
for Direct Water Services	0	48	0	0	48	922	970	15%
Range, Stove, and Oven	**0**	**220**	**30**	**0**	**250**	**340**	**590**	–
Percentage water-related	35%	35%	35%	35%	35%	35%	35%	–
for Direct Water Services	0	77	11	0	88	119	207	30%
Hot tubs/Spas, Swimming	**0**	**190**	**30**	**0**	**220**	**150**	**370**	–
Pools, Electric Water Bed								–
Percentage water-related	100%	100%	100%	100%	100%	100%	100%	–
for Direct Water Services	0	190	30	0	220	150	370	15%
Refrigerator	**0**	**0**	**0**	**0**	**0**	**1140**	**1140**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	–
Separate Freezer	**0**	**0**	**0**	**0**	**0**	**250**	**250**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	–
Television	**0**	**0**	**0**	**0**	**0**	**1070**	**1070**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	–
Personal Computer	**0**	**0**	**0**	**0**	**0**	**560**	**560**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	–
Lighting	**0**	**0**	**0**	**0**	**0**	**2220**	**2220**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	0%
Other	**0**	**130**	**0**	**0**	**0**	**2670**	**2670**	–
Percentage water-related	5%	5%	5%	5%	5%	5%	5%	–
for Direct Water Services	0	7	0	0	7	126	133	30%
Total Energy Consumption	**20**	**5090**	**1010**	**445**	**6575**	**15580**	**22145**	–
Total: Direct Water Services	**0**	**1472**	**191**	**5**	**1688**	**2802**	**4470**	–
Total: Indirect Steam Use	20	395	231	22	668	0	668	–

the category.

Wood-fired space heaters consume the majority of the renewable energy for Space Heating in Table A.1. The US Environmental Protection Agency (EPA) estimates that there are twelve million wood stoves nationwide, but only a small fraction are used to pipe hot water to residences for heat and hot water (EPA, 2013b). Geothermal heat pumps are another type of space heating that transfer heat indirectly through water circulated beneath the ground but are not widely used. These systems use 40-70% less energy than conventional systems and typically require only electricity to move the water (Dougherty).

Table A.1 details the assumptions we used to estimate the amount of energy that was consumed for residential space heating with boilers. We assumed that 11% of the energy consumed for residential space heating was done by means of boilers fueled with coal, natural gas, and petroleum. We considered this energy use in the *Indirect Steam Use* category. Since natural gas and petroleum also provide non-boiler space heating, assumptions were chosen to reflect residential boiler fuel consumption reported by the EIA.

A.1.1 Water Heating

All energy use in this category is considered in the *Direct Water Services* category since water is delivered as an end-product. No uncertainty was assigned to this estimate, since we do not attempt to anticipate error in EIA reporting.

A.1.2 Air Conditioning

The majority of residential air-conditioners use vapor-compression refrigeration cycles that absorb heat from a cool environment and reject it to a warm environment by means of a refrigerant. A small percentage of residential cooling systems, referred to as evaporative coolers or "swamp" coolers, however, cool space by pulling dry air from the outside through moist pads. The air is cooled by evaporation as it travels through the pads and is pumped throughout the house. These systems are suitable for hot climates with very low humidity, as their efficacy decreases as the ambient humidity rises. Although these systems use only a quarter of the energy that standard air-conditioners use, their use in the state of California (where the climate is favorable for these systems) is still estimated to be less than 5% (Klein et al., 2005). Desiccant cooling systems and other dehumidifiers that remove moisture from air can be coupled with evaporative coolers to improve performance.

Like space heating, water can also be used to achieve air cooling by means of geothermal (a type of renewable energy) cooling systems or hydronic cooling systems that pump chilled water through pipes to cool spaces. These technologies represent only a small fraction of air cooling in the US today.

A.1.3 Wet Cleaning

We assume 95% of the energy used for wet cleaning devices is for direct water-related services (Table A.1). Descriptions of typical processes are described below.

A.1.4 Clothes Washers

The majority of energy consumed for clothes washers is dedicated to circulating water with an agitator and then spinning the tub to remove water. Pumps are responsible for recirculating and draining water. (The washer is typically attached to a hot and cold water line, so water heating is done before it enters the washer.)

A.1.5 Clothes Dryers

Clothes dryers consume energy is by removing water from wet clothes. Air is typically drawn in through a nichrome-wire heating element and pushed into the clothing tumbler to heat up wet clothes. As water heats, it is pushed through an exhaust vent in the form of steam. We assume that the majority of energy is consumed directly to remove water from the clothes.

A.1.6 Dishwashers

Dishwashers add water to fill the basin at the base of the washer, which is then heated to 130-140 degrees Fahrenheit. Jets spray water in high pressure streams to wash and rinse the dishes. Dirty water is pumped out and a heating element inside the dishwasher heats the air to evaporate off the remaining water. Like clothes washers and dryers, we assume that the majority of energy is water-related.

A.1.7 Ranges, Stoves, and Ovens

Data regarding the end-use preparation of food and drinks are not available. Energy use varies substantially by household depending on eating patterns, family size, demographic, etc. Examples of common, water-related energy consumption in this category include boiling, steaming, blanching, dehydrating, pressure cooking, tea steeping, and coffee making. Since water is used directly to prepare food and drinks, we include this energy consumption in the *Direct Water Services* category. Large uncertainty in this category accounts for large variations across residences.

A.1.8 Hot tubs/Spas, Swimming Pools, Electric Water Beds

All energy use in this category is considered in the *Direct Water Services* category since water is delivered at end-use.

A.1.9 Other

This category includes electric devices, heating elements, motors, outdoor grills, and natural gas outdoor lighting. Water-related energy consumption in this category is difficult to categorize, but we assume 5% of energy-use is attributed to the direct end-use preparation of water in this sector.

A.2 Water-related Energy in the Commercial Sector

A.2.1 Space Heating

In 2005, the Energy and Environmental Analysis, Inc. (EEA) estimated that two-thirds of commercial boiler demand was for space heating (Energy and Environmtental Analysis, 2005). Assuming that total energy use and trends in space heating did not change significantly between 2005 and 2010, boilers would represent 45% of the 2010 energy use in the sector (1,082 trillion BTU). Data from the EIA's most recent Commercial Buildings Energy Consumption Survey (CBECS) indicate that 29% and 19% of the energy consumed for space heating in non-mall buildings was provided by boilers and district heat in 2003, respectively, which is relatively consistent with EEA's findings (EIA, 2006).

We assume that coal and the majority of oil in this category were consumed in boilers. The remaining volume of fuel was assumed to be used in natural gas boilers. We placed a relatively large margin of error on this estimate, since the distribution of boiler fuels was not well documented in these reports.

A.2.2 Water Heating

All energy use in this category is considered in the direct water services category since water is delivered at end-use.

Table A.2: The US Commercial Sector consumed approximately 18.2 quadrillion BTUs of primary energy in 2010 (with retail electricity losses); fifteen percent of this energy is directly water-related.

	Energy Consumption By Primary and Secondary Fuel [Trillion BTU]							
Commercial	**Coal**	**Natural Gas**	**Oil**	**Renewable Energy**	**Total On-site**	**Purchased Electricity**	**Total Energy**	**Error**
Space Heating	**53**	**1613**	**189**	**0**	**1855**	**550**	**2405**	–
Percentage water-related	100%	52%	95%	0%	47%	0%	45%	–
for Steam (Indirect)	53	849	180	0	1082	0	1082	20%
Water Heating	**0**	**455**	**20**	**0**	**475**	**290**	**765**	–
Percentage water-related	100%	100%	100%	100%	100%	100%	100%	–
for Direct Water Services	0	455	20	0	475	290	765	0%
Public Water and Wastewater Utilities	**0**	**0**	**0**	**0**	**0**	**501**	**501**	–
Percentage water-related	100%	100%	100%	100%	100%	100%	100%	–
for Direct Water Services	0	0	0	0	0	501	501	10%
Air Conditioning	**0**	**44**	**0**	**30**	**74**	**1820**	**1894**	–
Percentage water-related	30%	30%	30%	30%	30%	30%	30%	–
for Direct Water Services	0	12	0	9	21	546	567	20%
Ventilation	**0**	**0**	**0**	**0**	**0**	**1600**	**1600**	–
Percentage water-related	5%	5%	5%	5%	5%	5%	5%	–
for Direct Water Services	0	0	0	0	0	80	80	20%
Refrigeration/Freezers	**0**	**0**	**0**	**0**	**0**	**1181**	**1181**	–
Percentage water-related	12%	12%	12%	12%	12%	12%	12%	–
for Direct Water Services	0	0	0	0	0	141	141	30%
Food Service Equipment	**0**	**0**	**0**	**0**	**0**	**49**	**49**	–
Percentage water-related	5%	5%	5%	5%	5%	5%	5%	–
for Direct Water Services	0	0	0	0	0	3	3	30%
Cooking	**0**	**179**	**0**	**0**	**179**	**70**	**249**	–
Percentage water-related	35%	35%	35%	35%	35%	35%	35%	–
for Direct Water Services	0	0	0	0	0	25	25	30%
Electronics and Computers	**0**	**0**	**0**	**0**	**0**	**1480**	**1480**	–
Percentage water-related	3%	3%	3%	3%	3%	3%	3%	–
for Direct Water Services	0	0	0	0	0	44	44	30%
Lighting	**0**	**0**	**0**	**0**	**0**	**3200**	**3200**	–
Percentage water-related	0%	0%	0%	0%	0%	0%	0%	–
for Direct Water Services	0	0	0	0	0	0	0	–
Other	**0**	**885**	**350**	**0**	**1235**	**3634**	**4869**	
Percentage water-related	0%	0%	0%	0%	0%	0%	5%	–
for Direct Water Services	0	0	0	0	0	182	182	30%
Percentage water-related	0%	31%	75%	0%	43%	0%	11%	–
for Steam Generation (Direct)	0	270	263	0	533	0	533	30%
Total Energy Consumption	**53**	**3176**	**559**	**30**	**3818**	**14375**	**18193**	–
Total: Direct Water Services	**0**	**467**	**20**	**9**	**496**	**1812**	**2308**	–
Total: Direct Steam Use	**0**	**270**	**263**	**0**	**533**	**0**	**533**	–
Total: Indirect Steam Use	53	849	180	0	1082	0	1082	–

A.2.3 Water and Wastewater Treatment

National data regarding the energy use at public water and wastewater utilities only include electricity usage (Goldstein and Smith, 2002), so other fuel sources used at these facilities are not included in this analysis. (However, the California Energy Commission indicates that primary fuel inputs at these facilities are very small in comparison to electricity use, so these omissions are not likely to significantly affect the results (Klein et al., 2005).) The energy consumed at these facilities is categorized in the commercial sector to be consistent with EIA's definitions, even though a large amount of water from these facilities is distributed to the residential and industrial sectors. Private water and wastewater treatment facilities are not included in this category.

Electricity consumption data regarding US public water utilities in 2010 is based on Electric Research Power Institute's (EPRI) water utility electricity projections (Goldstein and Smith, 2002). EPRI's 2010 energy consumption projection for water utilities was 33.2 billion kWh, which corresponds to 294 trillion BTU of primary energy at the power plant, assuming the national 2010 average heat rate described in the main text. Public wastewater utility energy consumption in 2010 was 207 trillion BTU based on EPRI's 2010 projection. Water utility energy consumption listed in Table A.2 was subtracted from EIA's "Other" category defined in the *2010 Commercial Energy End-Use Splits* dataset (See (DOE, 2011)) so that water utility energy usage would not be double counted, as EIA typically includes public water utilities in this category. Although we did not assign uncertainty to any EIA datasets, we did include uncertainty in this category, since EPRI's projections were made in 2000 and are likely to deviate from actual energy consumption.

A.2.4 Air Conditioning

Unlike residential cooling, there are a range of technologies that provide cooling for commercial facilities. There are generally three types of commercial air-conditioning (AC) system categories including central, packaged, and individual AC. Central AC systems distribute chilled water to cool spaces; they often include a boiler to heat water for heating as well. District chilled water systems also chill water to be pumped into buildings for water. The latter two categories typically do not use water as a transfer medium for cooling, and therefore, are not considered in this analysis, although there are exceptions such as water loop heat pumps (Westphalen and Koszalinski, 1999). An analysis by Westphalen and Koszalinski estimates that 35% of the energy consumed for cooling in the US commercial sector was for central chiller systems in 1995 (Westphalen and Koszalinski, 1999). The 2003 EIA CBECS indicated that central chillers and district chilled water technologies consumed 19% and 7% of the fuel used for cooling for non-mall buildings in the US, respectively. Evaporative coolers consume an additional 2% of this energy consumption by dehumidifying air as it passes through moist pads (EIA, 2006). Since the CBECS is based on self-reported data, there are discrepancies between it and the EIA's Annual Energy Review, we base our estimates on the CBECS and Westphalen and Koszalinski's report and include an appropriate uncertainty assignment to account for these discrepancies.

A.2.5 Ventilation

Water-related energy use in this category is attributed to ventilation systems that capture and eject steam (i.e. commercial kitchens).

A.2.6 Refrigeration

Large commercial refrigerators utilize energy for such purposes as water-cooled condensing coils, evaporators, defrost coolers, etc; they also cool and freeze water directly. Since there are not comprehensive data sets that detail refrigeration technologies and inventories, we assume that water-related expenditures are 5% of the total energy for commercial supermarket, walk-ins, vending machines, and beverage merchandisers in the US is allocated to chilling water for cooling or drinking and other water-related purposes (i.e. evaporating, freezing, defrosting, etc.). We allocate 100% of water-related energy to beverage ice machines since their function is limited to freezing water. The assumption listed in Table A.2 for this category reflects these estimates based on the distribution of refrigeration and ice machines energy consumption in the category.

A.2.7 Food Service Equipment

There are diverse technologies included in this category. We assume that a fraction of energy in this category is consumed by food equipment for purposes such as on-site water treatment, pumping, and pressurization.

A.2.8 Cooking

Like residential cooking, commercial cooking is done by millions of distributed entities, whose use is difficult to generalize. Water-related energy in this category is assumed to be for processes such as boiling, steaming, blanching, coffee brewing, pressurizing, etc. We estimate that this energy is 35% of total category use and assign a relatively large degree of uncertainty to characterize the variations in water for cooking.

A.2.9 Electronics and Computers

Several types of liquid cooled systems are available to cool high-powered electronic devices, data centers, and other IT environments as alternatives to air-cooled systems. Water-cooled systems, chilled-water systems, and humidifiers are common systems that use (or remove) water directly or indirectly to cool electrical devices safely. Much of this energy use is contained in the air-conditioning category, but smaller systems are categorized here.

A.2.10 Other

Water-related energy in this category is difficult to characterize since it includes many diverse activities. However, we assume that hot water production by boilers is included in this category, since it is not classified in the EIA's hot water heating category. We distribute boiler fuel in this category according to a 2005 EEA report regarding commercial boiler energy use (Energy and Environmtental Analysis, 2005). We also assume that 5% of the electricity consumed in this category is for direct water-related purposes, since electricity is the most common fuel source for water pumping, treatment, and pressurization.

A.3 Water-related Energy in the Industrial Sector

Quantifying water-related energy-use in the industrial sector is difficult since most industries consider their energy consumption proprietary. Furthermore, high-level energy reporting in the industrial sector is not done on a regular basis. The Energy Information Administration's Manufacturing Energy Consumption Survey (MECS), the authoritative data set on the manufacturing industry, was last published in 2006, so the 2010 energy consumption statistics in Table A.3 are reference case

Table A.3: The US Industrial Sector consumed approximately 30.3 quadrillion BTUs of primary energy (with retail electricity losses); seventeen percent of this energy is directly water-related.

	Energy Consumption By Primary and Secondary Fuel [Trillion BTU]							
Industrial	**Coal**	**Natural Gas**	**Oil**	**Renewable Energy**	**Total On-site**	**Purchased Electricity**	**Total Energy**	**Error**
Chemical Industry	**102**	**2167**	**3547**	**0**	**5816**	**1508**	**7324**	–
Percentage water-related	0%	0%	0%	0%	0%	10%	2%	–
for Direct Water Services	0	0	0	0	0	151	151	20%
Percentage water-related	50%	20%	15%	0%	17%	0%	27%	–
for Steam (Direct)	51	431	498	0	980	0	980	20%
Percentage water-related	50%	20%	15%	0%	17%	0%	27%	–
for Steam (Indirect)	51	431	498	0	980	0	980	20%
Refining Industry	**60**	**1451**	**2054**	**0**	**3565**	**611**	**4176**	–
Percentage water-related	0%	0%	0%	0%	0%	15%	2%	–
for Direct Water Services	0	0	0	0	0	92	92	20%
Percentage water-related	50%	21%	35%	0%	30%	0%	26%	–
for Steam (Direct)	30	309	726	0	1065	0	1065	20%
Percentage water-related	50%	21%	35%	0%	30%	0%	26%	–
for Steam (Indirect)	30	309	726	0	1065	0	1065	20%
Paper and Pulp	**8**	**1567**	**141**	**6**	**1722**	**507**	**2229**	–
Percentage water-related	0%	5%	0%	0%	5%	10%	10%	–
for Direct Water Services	0	78	0	0	78	51	129	20%
Percentage water-related	75%	58%	67%	0%	59%	0%	45%	–
for Steam (Direct)	6	913	94	0	1013	0	1013	20%
Percentage water-related	25%	25%	28%	0%	25%	0%	19%	–
for Steam (Indirect)	2	391	40	0	433	0	433	20%
Construction	**0**	**339**	**1378**	**339**	**2056**	**339**	**2395**	–
Percentage water-related	5%	5%	5%	5%	5%	5%	5%	–
for Direct Water Services	0	17	69	17	103	17	120	20%
Percentage water-related	2%	2%	2%	0%	0%	0%	0%	–
for Steam (Indirect)	0	1	3	1	5	1	6	20%
Mining	**8**	**1567**	**141**	**6**	**1722**	**507**	**2229**	–
Percentage water-related	10%	10%	10%	10%	10%	10%	10%	–
for Direct Water Services	1	157	14	1	173	51	224	30%
Food	**152**	**733**	**18**	**46**	**949**	**839**	**1788**	–
Percentage water-related	0%	10%	0%	0%	8%	10%	9%	–
for Direct Water Services	0	73	0	0	73	84	157	30%
Percentage water-related	86%	34%	78%	80%	45%	0%	24%	–
for Steam (Direct)	130	247	14	37	428	0	428	30%
Percentage water-related	9%	4%	11%	9%	5%	0%	3%	–
for Steam (Indirect)	14	27	2	4	47	0	47	30%
Iron, Steel, and Aluminum	**707**	**293**	**58**	**20**	**1078**	**753**	**1831**	**–**
Percentage water-related	0%	5%	0%	0%	1%	5%	3%	–
for Direct Water Services	0	15	0	0	15	38	53	20%
Percentage water-related	3%	3%	3%	0%	3%	0%	2%	–
for Steam (Direct)	21	9	2	0	32	0	32	15%
Percentage water-related	57%	58%	57%	10%	56%	0%	33%	–
for Steam (Indirect)	403	169	33	2	607	0	607	20%
Agricultural	**0**	**164**	**600**	**25**	**789**	**450**	**1239**	–
Percentage water-related	0%	5%	5%	5%	5%	75%	27%	–
for Direct Water Services	0	8	30	1	39	338	377	30%
Other	**296**	**1792**	**203**	**189**	**2480**	**4599**	**7079**	–
Percentage water-related	0%	5%	0%	0%	0%	0%	5%	–
for Direct Water Services	0	90	0	0	90	230	320	30%
Percentage water-related	4%	2%	2%	3%	2%	0%	1%	–
for Steam (Direct)	13	27	5	5	50	0	50	30%
Percentage water-related	85%	29%	48%	48%	38%	0%	13%	–
for Steam (Indirect)	253	511	97	90	951	0	951	30%
Total Energy Consumption	**1333**	**10073**	**8140**	**631**	**20177**	**10113**	**30290**	–
Total: Direct Water Services	1	430	83	18	532	714	1246	
Total: Direct Steam Use	251	1838	1339	42	3568	0	3568	
Total: Indirect Steam Use	753	1838	1396	97	4083	0	4083	

projections published in the 2011 EIA Annual Energy Outlook.

A.3.1 Chemical Industry

Although the chemical manufacturing industry is among the highest energy consuming sectors in the US, detailed data regarding energy-consuming processes in the sector are proprietary, and therefore, not publicly available. An EEA report published in 2005 estimated that the chemicals industry consumes 1,800 trillion BTU for boilers, annually, to produce steam and electricity on-site. The report indicates that nearly all of the coal consumed in the industry is used as boiler fuel and approximately 43% of the 1,800 trillion BTU consumed in boilers was natural gas(792 trillion BTU) (Energy and Environmtental Analysis, 2005).

We compared the data published in the EEA report, with the energy reported in the MECS, to see if the trends were consistent across the two data sources. The EEA reported energy use for boilers in the chemicals industry is slightly less than what would be predicted by extending the general fuel distribution of 2006 MECS data to 2010 net consumption, which would predict natural gas boiler usage to be 932 trillion BTU (EIA, 2011a; Energy and Environmtental Analysis, 2005).

We took the average of these values to predict 2010 natural gas boiler consumption (862 trillion BTU). Assuming that this growth in natural gas usage between 2005 and 2010 was consistent with overall boiler energy consumption, we predict that energy for boilers grew approximately 8.8% to 1,959 trillion BTU. Using this growth rate, we estimate that petroleum fueled boiler use was nearly 40% of total petroleum consumption in the industry in 2010.

A percentage of steam generated in boilers in the chemical industry is used directly for process use, while the remaining proportion is used indirectly for electricity generation or indirect process heat. Sixty percent of the steam used is produced on-site with conventional boilers and through cogeneration; the rest is purchased from off-site facilities, which is not included in the chemical industry's tally.

The chemical industry uses steam for many processes, but the largest are listed here. We include the category of water-related energy use that we considered these processes in for the purpose of the analysis. *Direct Steam Use* was defined as steam which comes intro direct contact with process constitutes, while *Indirect Steam Use* is steam that does not come in direct contact with process.

The following bulleted list modified from (Energy and Environmtental Analysis, 2005) and (Resource Dynamics Corporation, 2002) includes the water-related, energy consuming activities that we considered in the Chemical Industry. (Many of these activities are also considered in the Refining Sector.) We note the category of water-related energy use for each activity in parentheses.

- Stripping: steam removes undesired contaminates from process fluid.(*Direct Steam Use*)
- Fractionalization: steam is injected at the base of fractionating towers to separate volatile products from desired products as it moves up the tower. (*Direct Steam Use*)
- Quenching: steam is injected directly into a reaction to regulate temperature. (*Direct Steam Use*)
- Dilution: steam is injected in order to dilute a process gas to minimize deposition of chemical products. (*Direct Steam Use*)
- Vacuum draw: Steam is injected through a nozzle or diffuser to create a vacuum. (*Direct Steam Use*)

- Pressure regulation: Steam is injected into a process to control pressure. (*Direct Steam Use*)

- Injection: Steam is injected to transport products. (*Direct Steam Use*)

- Process water: Steam is injected as a source of water for use as a solvent or feedstock in a process. (*Direct Steam Use*)

- Power generation: Steam is used to drive electric turbines. (*Indirect Steam Use*)

- Mechanical drive: Steam is used to drive a motor. (*Indirect Steam Use*)

- Process heat: Steam is used directly or indirectly to heat chemical process.

Source:(Energy and Environmtental Analysis, 2005; Resource Dynamics Corporation, 2002)

The most energy intensive step in the petrochemical industry is a process called steam cracking, which is used to make products such as ethylene, propylene, butadiene, etc. Ethylene production alone accounts for 34% of the energy use (Worrell, Ernst and Phylipsen, Dian and Einstein, Dan and Martin, 2000) and 25% of total steam used in the chemical industry due to the steam intensive nature of the cracking process (Resource Dynamics Corporation, 2002). During cracking, steam is used to break hydrocarbon feedstocks that are then rapidly cooled via quenching. Water is added until the mixture reaches 40-50 degrees Celsius, and then products are separated from the mixture by fractionalization. High pressure steam is used to drive compressors and pumps, which we consider indirect use for the purposes of this analysis. Medium and low-pressure steam are used for dilution and direct process heating, respectively. According to data listed in Worrell *et al.* approximately 30-50% of the energy consumed for ethane cracking can be attributed to direct use of steam for cracking and separation (Worrell, Ernst and Phylipsen, Dian and Einstein, Dan and Martin, 2000).

Steam methane reforming is another widely used process in the industry that uses steam to convert methane into hydrogen and carbon monoxide. This process is used to produce ammonia and nitrogenous fertilizers, which consumes approximately half that of ethylene production

In 2006, 68% of the total energy consumed for steam was used for process heating, 8% was used for machine drive, and 4% was used for non-process uses. The remaining steam (20%) was lost (Energetics Incorporated, 2010). The majority of steam for process heating is assumed to be in the (*Direct Steam Use*) category (since the steam heats via direct injection), whereas machine drive and non-process use steam is assumed in the (*Indirect Steam Use*) category.

To estimate the percentage of energy consumed in steam production for direct use in process heating, we assume that 47% of 2010 chemical energy use is dedicated to steam production based on data from (Energetics Incorporated, 2010). We multiply 47% by 68% to account for the energy used for process heating. Of this fraction of energy, we conservatively assume that 50% of steam for process heating is done by direct injection of steam and the other 50% is done by the indirect use of steam. This calculation indicates that 16% of the total energy consumed by the chemical industry is used to generate steam for direct process heating, alone.

Water and wastewater treatment, cooling processes, and mechanical water pumps are also important processes in chemical manufacturing, to ensure adequate quality for water discharge from the facility to a reservoir or public wastewater treatment plant. Electricity is the predominant fuel used to treat, pump, and pressurize water; however, the quantity of electricity used for these purposes is not well documented. The 2010 Energetics report indicates that approximately 5% of energy consumed in the chemical energy is used for water pumping (Energetics Incorporated, 2010). Thus, we assume that 10% of electricity is dedicated to pumping, treatment, and pressurization. We include this energy in the *Direct Water Services* category of the analysis.

A.3.2 Refining Industry

The refining industry converts crude oil into secondary products such as transportation fuels, lubricants, and chemical feedstocks. Steam is an important input for most processes at crude refineries. For example, steam methane reforming is used to produce over 95% of the hydrogen used for refinery operations. Many other steam-intensive processes are very similar to those in described in the chemical industry section. Only 3% of the energy consumed in the sector for steam was used to generate electricity in 1994, although an additional 6% was used to cogenerate electric and thermal power. The DOE estimates that the refining industry consumed 1,675 trillion BTU or 51% of the refining industry's energy in 1995 for steam production, which is generated in boilers, combustion turbines, and heat recovery steam generators (Resource Dynamics Corporation, 2002). EEA estimated that the refining industry consumed 374 trillion BTU for steam boilers in 1998, so the latter two categories of technologies are used to generate more steam than conventional boilers. Unlike the other industries, refinery gas and carbon monoxide by-products are the primary fuels for boilers (58 %), followed by natural gas (29 %) and residual oil (11 %) (Energy and Environmtental Analysis, 2005).

Our estimates regarding boiler use in the refining industry reflect trends published in (Resource Dynamics Corporation, 2002) and (Energy and Environmtental Analysis, 2005). We include refinery gas and other by-products in the "oil" category, as they are residuals from oil refining processes. Boiler energy consumption is divided into the *Direct Steam Use* and *Indirect Steam Use* categories based on the conventions detailed in the Chemicals industry section.

The refining industry generates large volumes of wastewater that often require primary, secondary, and tertiary treatment to meet quality regulations mandated by the EPA's Clean Water Act (Pellegrino et al., 2007). Between 65 and 90 gallons of water are withdrawn for every barrel of crude oil processed and 20 to 40 gallons of wastewater is produced, on average. The majority of refinery wastewater is derived from processes in which it has been in direct contact with crude, and therefore, requires more advanced treatment processes than non-process wastewater (i.e. cooling water). Wastewater is typically treated on-site with primary and secondary treatment processed and then discharged to a surface water reservoir if it meets CWA standards or pumped to a public water treatment plant for further treatment. Sour crude waste streams must be treated with stripping processes prior to primary water treatment. These processes use steam or gas to separate sour oil from water (Pellegrino et al., 2007).

We assume water pumping, pressurization, and treatment consumes 15% of total energy used in the refining industry as a conservative estimate. We include this energy in the *Direct Water Services* category of the analysis.

A.3.3 Paper and Pulp Industry

Paper manufacturing typically requires 5 steps after the wood feedstock is prepared including: pulp production, pulp processing and chemical recovery, pulp bleaching, stock preparation, and paper manufacturing. Mechanical pulp production typically requires steam in conjunction with high pressures and temperatures to break the lignin bonds of the paper feedstock, while chemical pulping utilizes chemicals to remove lignin bonds. The second step involves a series of processes to wash the pulp. The major impurity, referred to as "black liquor" is separated and collected to be run through a series processes to recover chemicals, so that only "white liquor" remains. First, the black liquor is sent through evaporation processes to reduce the quantity of water in the solution. The organics that are present in the remaining slurry are burned off as fuel in recovery boilers that provide electricity for other process use. The remaining inorganic smelt is discharged from the boiler and then recausticized so that the residual chemicals can be recycled (Koch et al., 2002). The third step, bleaching, uses chemicals to remove color from the pulp and steam to maintain adequate temperatures (Resource Dynamics Corporation, 2002). During the fourth step, the pulp is processed into a liquid stock and is blended, beaten, and refined into a state in which it can be dried to 10% water content and transferred from the pulp mill to a paper mill (Koch et al., 2002; Klaas et al., 2009). Drying is often done with natural-gas fired dryers and typically requires 4.2 MMBtu of steam per ton of pulp (U.S. Environmental Protection Agency, 2010; Klaas et al., 2009). At the paper mill, water is added to the dried pulp until the water content is more than 99%. The pulp slurry then travels through moving belts which compress the fibers and remove the excess water. Then the dry sheet is sent through a series of steam-heated rollers that bond the pulp fibers together as it is compressed (Koch et al., 2002). After wastewater is treated to the mandated standard for recycling or release, wastewater treatment plant residuals can be dewatered and burned in an on-site boiler (U.S. Environmental Protection Agency, 2010).

A 2005 EEA report concludes that the pulp and paper industry consumes 2.2 quads of energy for industrial boiler use, annually, nearly 90% of the energy consumed in the category (Energy and Environmtental Analysis, 2005). The DOE conducted a similar study in 2002 based on the 1994 MECS, and estimated that 84% of total pulp and paper industry energy consumption was attributed to steam production (Resource Dynamics Corporation, 2002). Another 2007 EPA study indicates that 95% of the criteria air pollutants (CAPs) in the industry are caused by burning fuel in boilers, which concurs with these findings (Outcomes, 2007). 2010 EIA data indicate that the industry has grown slightly to use 2.5 trillion BTU per year, but trends are assumed to be similar to the 2002 study detailed in Table A.3.3 (EIA, 2012).

Unlike the food industry that uses an extensive number of small boilers, the paper industry generally utilizes large boilers, with relatively high capacity factors (average 66%). Biomass (black liquor and wood/bark) represents over half of the total energy use in the pulp and paper industry (Energy and Environmtental Analysis, 2005; U.S. Environmental Protection Agency, 2010). Natural gas is also used for boiler use, but more-so to provide process heat and for drying applications. Coal and petroleum boilers are used, but to a lesser extent. Large boiler CHP systems are used to provide steam and electricity to pulp mills (Energy and Environmtental Analysis, 2005).

Although the pulp and paper industry is extremely steam intensive, estimating industry-wide water-related energy requires differentiating between steam that is used directly for process use and that which is used indirectly to provide heat or spin turbines to generate electricity. Control Components Inc. (CCI) asserts that the primary purpose of boilers in this industry is to provide high-quality steam of a specific temperature and pressure directly for process use, and "generating electricity is merely a benefit as the electrical needs can be imported if necessary" (CCI, 2003). Steam is also an important working fuel for flash dryers to remove water from the wet pulp. It also heats drying cylinders that press water out of rolls of paper at the paper mill. Although steam in this case is used to provide heat, we consider it in the

Direct Steam Use category as all of the energy consumed during this activity is done so for the purpose of removing water from the fibrous product.

Table A.3.3 details the energy consumed in the Paper and Pulp industry. Although these data are for the year 2002, we used these general trends to make our assumptions about water-related energy use. Based on the distribution of data, we estimate that 84% of the primary energy consumed (excluding retail electricity production) in the paper and pulp industry is used for steam production. Energy consumed in the "Steam" column was considered in the *Direct Steam Use* or *Indirect Steam Use* categories based on whether or not steam came into contact with process feedstocks or not. As discussed above, the energy consumed for drying, pressing, and evaporation were also considered in the *Direct Steam Use* category, since it was used to remove water from the pulp during these processes. Overall, we estimate that 70% of this steam is used directly for process use, and the remaining is used for indirect process heating and electricity production. We estimate that an additional 5% and 10% of direct natural gas and electricity consumption, respectively, is used for direct water services such as wastewater treatment (i.e. "Environmental, Wastewater, and Utilities" category of Table A.3.3), pumping, heating, and pressurization.

A.3.4 Mining Industry

The majority of base or precious-metal mining sites include an underground or open pit and a mineral processing plant or mill. Surface mines represent 65%, 92%, and 96% of US coal, metals, and industrial metal mines, respectively. Underground mining operations represent the difference and are typically more energy-intensive (BCS Incorporated, 2007).

Processing mills typically use wet processes that have large water requirements to extract valuable minerals (Gunson, A. J. et al., 2010). Ore is suspended in water that is agitated and aerated to separate mineral particles (Norgate and Haque, 2010). Modern mills recycle a large quantity of the water that they extract, but water withdrawals are still large since a lot of water is lost in mining processes. While process water and water for dust suppression can be lower in quality, water for cooling systems, pump gland seal water, reagent mixing and dilution water, spray water, and wash water must be of relatively high quality. On-site water treatments include filtration, flocculation, chemical precipitation, ion exchange, and reverse osmosis. Acceptable requirements for water quality, quantity, temperature, and pressure are generally defined by equipment vendors (Gunson, A. J. et al., 2010). Pumping requirements for water extraction and mine dewatering are also large energy consumers (Norgate and Haque, 2010).

Table A.3.4 details the average energy requirements for coal, metal, and mineral mining operations, but this consumption varies a great deal depending on specific operations. Although wastewater treatment is not explicitly stated, 4.59 million metric tons of wastewater treatment plant effluent are generated annually from the production of copper ore processing alone, indicating that water treatment is likely a substantial energy consumer in the ancillary services category (BCS Incorporated, 2002).

We estimate that 10% of total mining energy use is for *Direct Water Services*. Since the fuel distribution of this energy use is not widely available, our estimate is distributed evenly across all fuels. No energy use was included in the Direct or Indirect Steam Use categories since energy data in Table A.3.4 and the literature do not indicate that steam and onsite electricity generation are widely used for mining processes.

A.3.5 Food Industry

The water-related energy consumption in the food industry is difficult to quantify as the industry spans more than 26,000 of facilities in the US that serve many diverse purposes. It is also one of the top five energy consuming industries in the United States. The EPA estimates that process heating and cooling consumes 75% of the food industry's total energy consumption, while motor-driven systems consume another 12% of energy (Outcomes, 2007). Non-process energy consuming activities such as heating, ventilation, refrigeration, lighting, facility support, onsite transportation, and conventional electricity generation represented less than 8% of the sector (Okos, 1998).

Over one-half of the industry's energy consumption was to produce steam through the use of boilers, the majority of which are fueled by natural gas. These units tend to be smaller, with lower capacity factors, than other large energy consuming industries, due to the distributed and seasonal nature of the industry (Energy and Environmtental Analysis, 2005). The steam might be used directly (*Direct Steam Use*) for processes such as boiling, steaming, scalding, blanching, cleaning, and sterilization among many others or it can be used indirectly for electricity generation (i.e. *Indirect Steam Use*). However, most of the electricity consumed in the sector is purchased, rather than generated by on-site boilers; only six percent of the food industry's energy use was generated on-site by cogeneration (Okos, 1998). Sugar, malt beverages, corn milling, and meat packing are particularly steam intensive. External combustion by boilers to produce steam in this sector is estimated to cause 94% of the industry's total emissions (Outcomes, 2007).

In addition to steam processes, other energy-intensive, water-related activities include, evaporating, pumping, and pressurizing water. Food preservation techniques such as thermal processing and dehydration require energy-intensive processes to remove water from products to ensure adequate safety provisions. Many processes, such as canning, require pumps to circulate water for cooling. High-pressured sprays and high-temperature steam are typically used for cleaning and sterilizing facilities.

Water used for processes is typically purchased from a treatment facility or pumped from a well and treated at the processing plant. Wastewater is generally sent directly to a treatment facility or pretreated at the plant before being sent to a treatment facility. For many food processing facilities, volumes of wastewater are substantial. Raw milk production, for example, produces an average of 3 kilograms of wastewater per kilogram of finished milk (Verheijen et al., 1996). A wide range of on-site water purification techniques might be employed from passive filtration processes to highly energy-intensive reverse osmosis.

We assume that 50% of primary on-site energy consumption is used to generate steam. The majority of coal and oil are assumed to be consumed as boiler fuel and the remaining fraction of steam generating fuel is dedicated to natural gas production. We assume that 90% of the energy consumed for steam generation in the *Direct Steam Use* category of the analysis for boiling, steaming, scalding, blanching, cleaning, and sterilization, etc. The remaining fraction of steam is assumed to be used indirectly for process heating and electricity generation, and this categorized in the *Indirect Steam Use* category. Additionally, we assume that 10% of natural gas and 10% of electricity is used for direct water services such as heating, pressurization, pumping, and onsite treatment.

A.3.6 Primary Metals Industry (Iron, Steel, and Aluminum)

According to EEA estimates, primary metal industries consume 7% of the energy used in steam-driven boilers in the US industrial sector (Energy and Environmtental Analysis, 2005). In 1998 the primary metals industry consumed 468 trillion BTU of energy for boiler fuel, which accounted for 18% of the industry's primary energy consumption. Coke oven gas and blast furnace gas by-product fuels represent approximately 63 percent of boiler fuel in the primary metals industry, followed by natural gas (29%), and coke/coke breeze (6%) (Energy and Environmtental Analysis, 2005). We assumed that this trend stays relatively constant for steel, iron, and aluminum production through 2010, as data regarding the energy consumption for primary metals are not widely available.

Seventy percent of steam driven boilers in the primary metal industries are located at integrated steel mills and are used for on-site power generation. Although steel has traditionally been made at steel mills, which utilize large quantities of steam, domestic steel production has made a shift towards with electric mini-mills that do not use large quantities of steam. Thus, the industry might be becoming less steam intensive with time; however, data availability restricted our ability to account for these changes.

A.3.7 Agriculture

Water pumping is a major energy consumer in the agricultural sector. Energy is required to construct the water supply source, provide the conveyance works, field irrigation system installation and for operation and maintenance (Khan et al., 2009). According to the EPA, less than 15% of the land dedicated to crop production is irrigated in the US; however, irrigated cropland is among the most highly productive (EPA, 2013b).

The energy used for pumping water in irrigation systems are sparse, so we based our analysis on work done by a 2009 analysis done by Khana *et al.* and a California study by Dinar published in 1994. Khana *et al.* measured the water-energy ratio (defined as the ratio of energy consumed for irrigation to the total energy input) for wheat, barley, and rice production. The water-energy ratio was higher for tubewell systems (pump irrigated), than in canal or rainfed systems. Pump irrigated systems had a water-energy ratio of 19.0, 35.4, and 47.5 for wheat, barley, and rice production, respectively. Canal irrigated systems had a water-energy ratio of 12.7, 12.9, and 37.9 for wheat, barley, and rice production, respectively. Water-energy ratio values for rainfed production were zero (Khan et al., 2009). (These values offered insight into the relative percentage of water-related energy use for several irrigation practices, that we could then weight according to farming practices in the United States.) A prior energy analysis, published by Dinar in 1994, on California's agriculture sector. It concludes that in 1972, 68% of the electricity and 2% of diesel in the agriculture industry were for irrigation, and by 1991, 87% of agricultural electricity demand was for irrigation in California suggesting that electricity is playing a larger role in irrigation systems. During this time, approximately 80% of the pumps sold to agricultural producers were run by electricity; the remainder were diesel (Dinar, 1994).

We assume 75% and 2% of electricity and diesel used in the agriculture industry is for water-related activities, respectively. We base this estimate on the premise that the majority of fuel used on the farm is in the form of liquid transportation fuel for farm machinery, whereas electricity is not widely used for purposes other than irrigation, lighting, and other small stationary loads. We include a large margin of uncertainty on this estimate since little data are available regarding energy consumption in the agriculture industry.

A.3.8 Other

The remaining industries not explicitly analyzed in the preceding section are included in Table A.3. These industries represented less than 15% of total industrial energy consumption in 2010 and are not considered to be extremely steam intensive, as in the case of the refining and chemical industries.

We make several general approximations to estimate the water-related energy use of these industries. The majority of coal, 30% of natural gas, 50% of petroleum, and 50% of renewable (as wood waste) is assumed to be consumed in industrial boilers, which is likely a conservative estimate of boiler energy use. Only 5% of steam generation is considered in the *Direct Steam Use* category, since there are not data to indicate otherwise; all other energy for boilers is considered in the *Indirect Steam Use* category. An additional 5% of natural gas use and purchased electricity is attributed to *Direct Water Services* category for activities such as industrial wastewater treatment, pumping, and pressurization, which is also likely a conservative estimate. Our error assignment is higher in this category to reflect the uncertainty in our assumptions.

A.4 Water-related Energy in the Power Generation Sector

A.4.1 Steam-driven Electric Power Generation

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

Traditionally, one of two wet cooling technologies is used for condensing steam at thermoelectric plants: open-loop cooling or closed-loop cooling. Open-loop cooling (also referred to as once-through cooling) withdraws large volumes of water from a source (typically a lake, river, or ocean) that are passed through the tubes of a condenser to cool steam discharged from the turbine. The water, now warm from heat transferred from the steam, is released back into its original reservoir. The water implications of these systems are primarily from water withdrawals, since most of the water is returned to the original source and minimal water is released through evaporation. However, water is returned to its original reservoir at temperature higher than natural reservoir temperatures, which can have detrimental effects on natural ecosystems existing in the area. These systems are becoming less common and are being phased out in some states like California, due to these detrimental thermal effects as well as risks posed to aquatic organisms that become trapped against water intake screens (Corbett, 2009).

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

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

Approximately 42.7% of thermoelectric generation the US uses once-through cooling, 41.9% and 14.5% use wet recirculating with cooling towers and cooling ponds, respectively, and 0.9% use dry cooling (Shuster, 2008). (These estimates only include thermoelectric power plants that exceed 100 MW generating capacity.)

A.4.2 Electric Power Plant Use

Power plants use a small fraction of their net electricity consumption for their own, internal plant use. In 2010, 790 trillion BTU were consumed for internal power plant operations. We estimate 20% of this electricity use is dedicated to pumping, pressurizing, and treating water on-site for the activities described above based on (Lee, 2012). However, this is likely a very conservative estimate to characterize all US power plant operations.

A.4.3 Pumped Hydro

Pumped storage systems move water from lower elevations to higher elevations when electricity demand and price are low, so that it can be released through turbines during periods of high demand to generate electricity. The US consumed 29.5 billion kWh for pumped storage in 2010 in order to generate 25.5 billion kWh, resulting in a net electricity consumption of 4.09 billion kWh (36 trillion BTUs of primary energy) (EIA, 2011b). (Although pumped storage systems are often net-electricity consumers, they are valuable load balancers in times of high electricity demand.)

A.4.4 Steam Powered Electricity Generation

This category includes all energy consumed for steam-powered generating technologies in the US, which accounts for 75.5% of US generation (EIA, 2011b). Applicable technologies include steam turbines, the steam portion of combined-cycle systems, and combined-cycle single-shaft combustion turbines and steam turbines that share a single-generator.

Table A.4: 2002 Energy Consumption in the Paper and Pulp Industry (Klaas et al., 2009).

Description of Process	Electrical Energy Trillion BTU	Steam Energy Trillion BTU	Direct Fuel Energy Trillion BTU
Wood Preparation	17.8	14.4	0
Cooking	18.9	130.1	0
Grinding, Refining	36.8	-3	0
Screening/ Cleaning	13.1	0	0
Evaporation	8.7	186	0
Chemical Preparation	9.4	30.3	100.2
Bleaching	15.6	64.8	0
Recycled/ Pulp Substitutes	38.2	26.7	0
Pulp Manufacturing Subtotal	158.6	449.2	100.2
Wet End	103.2	107.8	0
Pressing	36.5	0	0
Drying	45	422.3	13.4
Dry End	18.4	0	0
Coating Preparation	1.2	2.5	0
Coating Drying	0	0	17.9
Super Calendering	2.7	5.3	0
Pulp Manufacturing Subtotal	206.9	542.3	31.3
Total Process		1,484	
Environmental, Wastewater & Utilities		122	
Total Manufacturing		1,606	
Powerhouse Losses		755	
Total Paper and Pulp Industry		2,361	

Table A.5: Average Energy Consumption Distribution in Coal, Metal, and Mineral Mining Operations in 2002 (BCS Incorporated, 2002).

	Equipment	Current Energy Consumption Distribution across Coal, Metal, and Mineral Mining
Extraction	Drilling	5.40%
	Blasting	1.90%
	Digging	6.30%
	Ventilation	9.80%
	Dewatering	2.20%
Materials Handling	Diesel Equipment	16.90%
	Electric Equipment	–
	Conveyor (Motor)	0.20%
	Load-haul dump machines	3.50%
	Pumps	0.20%
Beneficiation and Processing	Crushing and Grinding	43.80%
	Centrifuge	0.60%
	Floatation	0.60%
	Other Separations	2.60%
Ancillary Operations		6.00%
Total		100%

Table A.6: The US Power Generating Sector consumed approximately 40.4 quadrillion BTUs of primary energy in 2010, 75% of which was consumed by steam-driven power systems; less than one percent of this energy is directly water-related.

	Energy Consumption By Primary and Secondary Fuel [Trillion BTU]							
Power	**Coal**	**Natural Gas**	**Oil**	**Renewable Energy**	**Total On-site**	**Purchased Electricity**	**Total Energy**	**Error**
Plant Use	**0**	**0**	**0**	**0**	**0**	**790**	**790**	–
Percentage water-related	0%	0%	0%	0%	0%	20%	20%	–
for Direct Water Services	96	10	2	50	158	0	158	30%
Pumped Hydro (net consumption)	**0**	**0**	**0**	**0**	**0**	**36**	**36**	–
Percentage water-related	0%	0%	0%	0%	0%	100%	100%	–
for Direct Water Services	0	0	0	0	0	36	36	30%
Steam-driven Power	**19662**	**2058**	**365**	**10249**	**1525**	**1380**	**32334**	–
Percentage water-related	100%	100%	100%	100%	100%	100%	100%	–
for Direct Water Services	19662	2058	365	10249	1525	1380	32334	0%
Total: Direct Water Services	**96**	**10**	**2**	**50**	**158**	**36**	**194**	–
Total: Indirect Steam Services	**19662**	**2058**	**365**	**10249**	**1525**	**1380**	**32334**	–

Appendix B

Evaluating Energy and Emissions Reductions Through Shifts in Residential Water Heating

B.1 Summary of Regression Model Performance

Tables B.1, B.2, and B.3 summarize the output of three high-performing fitted models of the data based on a geometric distribution (i.e. a negative binomial distribution with the shape parameter $\theta = 1$). Tables B.4, B.5, and B.6 summarize the output of three high-performing fitted models of the data based on a negative binomial distribution.

Table B.1: Fitted Zero-inflated Geometric Model 1

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-8.226	0.395	-20.812	$<2\times10^{-16}$	***
Mean July DNI	0.738	0.026	28.456	$<2\times10^{-16}$	***
Avg. Electricity Price	0.373	0.016	24.067	$<2\times10^{-16}$	***
Population Density	1.641	0.054	30.500	$<2\times10^{-16}$	***
Cost of Living Index	0.042	0.004	9.638	$<2\times10^{-16}$	***
Policy Incentives	0.167	0.013	12.864	$<2\times10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	8.345	0.689	12.118	$< 2\times10^{-16}$	***
Population Density	-1.341	0.085	-15.751	$< 2\times10^{-16}$	***
Avg. Electricity Price	-0.576	0.035	-16.300	$< 2\times10^{-16}$	***
Mean July DNI	-0.462	0.045	-10.198	$< 2\times10^{-16}$	***
Policy Incentives	-0.030	0.019	-1.569	0.12	
Cost of Living Index	0.001	0.006	0.159	0.87	

Table B.2: Fitted Zero-inflated Geometric Model 2

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-8.167	-0.396	20.627	$< 2\times10^{-16}$	***
Mean July DNI	0.736	0.026	28.543	$< 2\times10^{-16}$	***
Population Density	1.622	0.055	29.467	$< 2\times10^{-16}$	***
Avg. Electricity Price	0.364	0.016	22.604	$< 2\times10^{-16}$	***
Cost of Living Index	0.040	0.004	9.032	$< 2\times10^{-16}$	***
Democrat.Vote	0.568	0.261	2.175	0.03	*
Policy Incentives	0.163	0.013	12.369	$< 2\times10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	8.339	0.687	12.133	$<2\times10^{-16}$	***
Population Density	-1.335	0.085	-15.685	$<2\times10^{-16}$	***
Avg. Electricity Price	-0.580	0.035	-16.500	$<2\times10^{-16}$	***
Mean July DNI	-0.461	0.045	-10.197	$<2\times10^{-16}$	***
Cost of Living Index	0.001	0.006	0.138	0.89	

Table B.3: Fitted Zero-inflated Geometric Model 3

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-9.809	0.342	-28.710	$< 2{\times}10^{-16}$	***
Avg. Electricity Price	0.350	0.015	22.715	$< 2{\times}10^{-16}$	***
Population Density	1.559	0.051	30.875	$< 2{\times}10^{-16}$	***
Cost of Living Index	0.036	0.004	8.244	$< 2{\times}10^{-16}$	***
Democratic Vote	0.672	0.262	2.569	0.0102	*
Policy Incentives	0.169	0.013	12.777	$< 2{\times}10^{-16}$	***
Mean July DNI	0.728	0.021	34.621	$< 2{\times}10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	6.932	0.773	8.972	$< 2{\times}10^{-16}$	***
Population Density	-1.248	0.087	-14.403	$< 2{\times}10^{-16}$	***
Avg. Electricity Price	-0.563	0.036	-17.699	$< 2{\times}10^{-16}$	***
Mean July DNI	-0.430	0.045	-9.536	$< 2{\times}10^{-16}$	***
Policy Incentives	-0.028	0.019	-1.475	0.14	***
Democratic Vote	-0.371	0.349	-1.063	0.29	
Cost of Living Index	0.004	0.006	0.705	0.48	
Mean July DNI -0.430	0.045	-9.536	$< 2{\times}10^{-16}$	***	

Table B.4: Fitted Zero-inflated Negative Binomial Model 1

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-8.690781	0.594	-14.625	$<2\times10^{-16}$	***
Mean July DNI	0.756698	0.039	19.360	$<2\times10^{-16}$	***
Avg. Electricity Price	0.396443	0.024	16.807	$<2\times10^{-16}$	***
Population Density	1.688875	0.079	21.306	$<2\times10^{-16}$	***
Cost of Living Index	0.041569	0.007	6.326	2.51×10^{-10}	***
Policy Incentives	0.175369	0.020	8.937	$<2\times10^{-16}$	***
Log(theta)	-0.908882	0.057	-15.975	$<2\times10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	7.756055	0.781	9.936	$< 2\times10^{-16}$	***
Population Density	-1.38022	0.107406	-12.851	$< 2\times10^{-16}$	***
Avg. Electricity Price	-0.579165	0.040	-14.386	$< 2\times10^{-16}$	***
Mean July DNI	-0.45321	0.051196	-8.852	$< 2\times10^{-16}$	***
Policy Incentives	-0.001429	0.022	-0.064	0.949	
Cost of Living Index	0.00249	0.006681	0.373	0.709	

Table B.5: Fitted Zero-inflated Negative Binomial Model 2

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	7.76	0.781	9.936	$< 2\times10^{-16}$	***
Mean July DNI	-0.45	0.051	-8.852	$< 2\times10^{-16}$	***
Population Density	-1.38	0.107	-12.851	$< 2\times10^{-16}$	***
Avg. Electricity Price	-0.58	0.040	-14.386	$< 2\times10^{-16}$	***
Cost of Living Index	0.00	0.007	0.373	0.709	
Policy Incentives	0.00	0.022	-0.064	0.949	

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	7.769226	0.780	9.962	$<2\times10^{-16}$	***
Population Density	-1.37444	0.107	-12.830	$<2\times10^{-16}$	***
Avg. Electricity Price	-0.579623	0.040	-14.546	$<2\times10^{-16}$	***
Mean July DNI	-0.453742	0.051157	-8.87	$<2\times10^{-16}$	***
Cost of Living Index	0.002442	0.007	0.365	0.715	

Table B.6: Fitted Zero-inflated Negative Binomial Model 3

Count model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	-8.46	0.530	-15.979	$< 2\times10^{-16}$	***
Avg. Electricity Price	0.37	0.023	15.968	$< 2\times10^{-16}$	***
Population Density	1.61	0.075	21.475	9.95×10^{-8}	***
Cost of Living Index	0.04	0.007	5.328	9.95×10^{-8}	***
Democratic Vote	0.70	0.395	1.771	0.077	.
Policy Incentives	0.18	0.020	8.929	$< 2\times10^{-16}$	***
Mean July DNI	7.44E-01	0.033	22.705	$< 2\times10^{-16}$	***
Log(theta)	-9.01E-01	0.051	-17.670	$< 2\times10^{-16}$	***

Zero-inflation model coefficients	Coefficient Estimate	Std. Error	Z-value	P-value	Significance
(Intercept)	6.932	0.773	8.972	$< 2\times10^{-16}$	***
Population Density	-1.248	0.087	-14.403	$< 2\times10^{-16}$	***
Avg. Electricity Price	-0.563	0.036	-17.699	$< 2\times10^{-16}$	***
Mean July DNI	-0.430	0.045	-9.536	$< 2\times10^{-16}$	***
Policy Incentives	-0.028	0.019	-1.475	0.14	***
Democratic Vote	-0.371	0.349	-1.063	0.29	
Cost of Living Index	0.004	0.006	0.705	0.48	
Mean July DNI	-0.430	0.045	-9.536	$< 2\times10^{-16}$	***

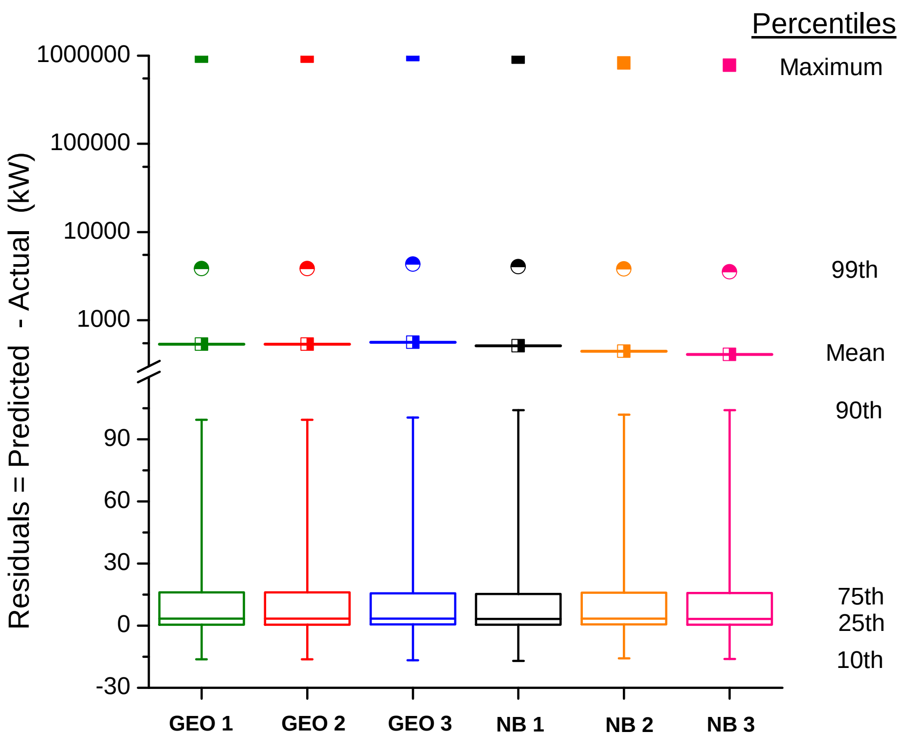

Figure B.1: Over 80% of all residuals in the fitted model fell within 40 kW of the true value of installed PV for a given county, suggesting a very good fit. Approximately 3% of residuals showed deviations from the predicted model of over 1,000 kW, suggesting that the model is not adequate in predicting counties that have very large amounts of solar PV. (Outliers are not shown.)

Appendix C

Evaluating Water Reductions in Texas Through Changes in the Power Sector

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C.1 EGU Classifications and Water Use Characteristics

This section provides details regarding water use characteristics of electricity generating units in ERCOT.

Table C.1: ERCOT Nuclear Plants with once-through cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Comanche Peak 1	NU	PD	ST	1230	579	120,000
Comanche Peak 2	NU	PD	ST	1179	579	120,000
South Texas 1	NU	PD	ST	1363	599	120,000
South Texas 2	NU	PD	ST	1360	599	120,000

Table C.2: ERCOT Coal Plants with once-through and pond cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Monticello 1	CL	OT	ST	590	220	32,941
Monticello 2	CL	OT	ST	590	220	32,941
Monticello 3	CL	OT	ST	791	220	32,941
Oak Grove SES Unit 1	CL	OT	ST	781	349	31,092
Oak Grove SES Unit 2	CL	OT	ST	792	349	31,092
Big Brown 1	CL	PD	ST	592	289	31,472
Big Brown 2	CL	PD	ST	612	289	31,472
Coleto Creek	CL	PD	ST	631	359	31,644
Fayette Power Project 1	CL	PD	ST	617	349	30,729
Fayette Power Project 2	CL	PD	ST	612	349	30,729
Fayette Power Project 3	CL	PD	ST	448	349	30,729
Gibbons Creek 1	CL	PD	ST	468	503	30,293
J K Spruce 1	CL	PD	ST	562	709	28,586
J K Spruce 2	CL	PD	ST	768	709	28,586
J T Deely 1	CL	PD	ST	443	709	30,146
J T Deely 2	CL	PD	ST	443	709	30,146
Martin Lake 1	CL	PD	ST	811	359	41,074
Martin Lake 2	CL	PD	ST	803	359	41,074
Martin Lake 3	CL	PD	ST	781	359	41,074
Sandow 5	CL	PD	ST	557	349	32,330
W A Parish 5	CL	PD	ST	642	509	32,243
W A Parish 6	CL	PD	ST	647	509	31,874

Table C.3: ERCOT Coal Plants with recirculating cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Limestone 1	CL	RC	ST	827	599	632
Limestone 2	CL	RC	ST	854	599	632
Oklaunion 1	CL	RC	ST	647	359	664
PUN25	CL	RC	ST	565	686	700
San Miguel 1	CL	RC	ST	393	867	775
Twin Oaks 1	CL	RC	ST	157	589	737
Twin Oaks 2	CL	RC	ST	157	589	737
W A Parish 7	CL	RC	ST	562	509	804
W A Parish 8	CL	RC	ST	597	509	710

Table C.4: ERCOT Hydroelectric Plants

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Amistad Hydro 1	HY	NA	HY	38	0	0
Amistad Hydro 2	HY	NA	HY	38	0	0
Austin 1	HY	NA	HY	8	0	0
Austin 2	HY	NA	HY	9	0	0
Buchanan 1	HY	NA	HY	18	0	0
Buchanan 2	HY	NA	HY	18	0	0
Buchanan 3	HY	NA	HY	18	0	0
Canyon 1	HY	NA	HY	3	0	0
Canyon 2	HY	NA	HY	3	0	0
Denison Dam 1	HY	NA	HY	40	0	0
Denison Dam 2	HY	NA	HY	40	0	0
Dunlop Schumansville 1	HY	NA	HY	4	0	0
Eagle Pass 1	HY	NA	HY	7	0	0
Falcon Hydro 1	HY	NA	HY	12	0	0
Falcon Hydro 2	HY	NA	HY	12	0	0
Falcon Hydro 3	HY	NA	HY	12	0	0
GBRA 4 and 5	HY	NA	HY	5	0	0
Granite Shoals 1	HY	NA	HY	30	0	0
Granite Shoals 2	HY	NA	HY	30	0	0
Inks 1	HY	NA	HY	14	0	0
Lewisville 1	HY	NA	HY	3	0	0
Marble Falls 1	HY	NA	HY	21	0	0
Marble Falls 2	HY	NA	HY	21	0	0
Marshall Ford 1	HY	NA	HY	36	0	0
Marshall Ford 2	HY	NA	HY	35	0	0
Marshall Ford 3	HY	NA	HY	36	0	0
McQueeney Abbott	HY	NA	HY	8	0	0
Morris Sheppard 1	HY	NA	HY	24	0	0
Whitney 1	HY	NA	HY	15	0	0
Whitney 2	HY	NA	HY	15	0	0

Table C.5: ERCOT Natural Gas Boiler Units with once through cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Cedar Bayou 1	NG	OT	ST	738	399	38,331
Cedar Bayou 2	NG	OT	ST	742	399	38,331
Decker Creek 1	NG	OT	ST	317	489	35,858
Decker Creek 2	NG	OT	ST	424	489	35,858
Graham 1	NG	OT	ST	223	349	38,869
Graham 2	NG	OT	ST	386	349	38,869
Powerlane Plant 1	NG	OT	ST	20	349	57,785
Powerlane Plant 2	NG	OT	ST	26	349	57,785
Powerlane Plant 3	NG	OT	ST	41	349	57,785
R W Miller 1	NG	OT	ST	74	359	39,846
R W Miller 2	NG	OT	ST	119	359	39,846
R W Miller 3	NG	OT	ST	206	359	39,846
Ray Olinger 1	NG	OT	ST	77	349	45,083
Ray Olinger 2	NG	OT	ST	106	349	45,083
Ray Olinger 3	NG	OT	ST	145	349	45,083
Sam Bertron 3	NG	OT	ST	228	399	46,196
Sam Bertron 4	NG	OT	ST	228	399	46,196
Sam Rayburn 3	NG	OT	ST	26	50	35,000
Thomas C Ferguson 1	NG	OT	ST	421	349	37,587
B M Davis 3	NG	OT	ST	717	270	98,188

Table C.6: ERCOT Natural Gas Boiler Units with cooling ponds

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Dansby 1	NG	PD	ST	109	353	40,516
Handley 3	NG	PD	ST	391	479	38,919
Handley 4	NG	PD	ST	431	479	38,919
Handley 5	NG	PD	ST	432	479	38,919
Lake Hubbard 1	NG	PD	ST	388	449	38,952
Lake Hubbard 2	NG	PD	ST	519	449	38,952
Mountain Creek 6	NG	PD	ST	121	479	39,000
Mountain Creek 7	NG	PD	ST	117	479	39,000
Mountain Creek 8	NG	PD	ST	562	479	39,000
O W Sommers 1	NG	PD	ST	406	709	41,584
O W Sommers 2	NG	PD	ST	396	709	41,584
Sim Gideon 1	NG	PD	ST	139	339	37,785
Sim Gideon 2	NG	PD	ST	139	339	37,785
Sim Gideon 3	NG	PD	ST	337	339	37,785
Stryker Creek 1	NG	PD	ST	169	289	39,554
Stryker Creek 2	NG	PD	ST	497	289	39,554
Trinidad 6	NG	PD	ST	224	669	40,762
V H Braunig 1	NG	PD	ST	218	1198	36,705
V H Braunig 2	NG	PD	ST	228	1198	36,705
V H Braunig 3	NG	PD	ST	408	1198	36,705
W A Parish 1	NG	PD	ST	172	509	18,216
W A Parish 2	NG	PD	ST	172	509	18,216
W A Parish 3	NG	PD	ST	275	509	18,216
W A Parish 4	NG	PD	ST	546	509	18,216

Table C.7: ERCOT Natural Gas Boiler Units with recirculating cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Leon Creek 3	NG	RC	ST	59	619	1,203
Leon Creek 4	NG	RC	ST	94	619	1,203
Pearsall 1	NG	RC	ST	25	197	1,607
Pearsall 2	NG	RC	ST	25	197	1,607
Pearsall 3	NG	RC	ST	24	197	1,607
AES Deepwater	OL/NG	RC	ST	139	299	864

Table C.8: Natural Gas Combined Cycle-Units with dry cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Hays Energy Facility 1	NG	DR	CC	231	100	100
Hays Energy Facility 2	NG	DR	CC	231	100	100
Hays Energy Facility 3	NG	DR	CC	241	100	100
Hays Energy Facility 4	NG	DR	CC	241	100	100
Midlothian 1	NG	DR	CC	231	50	50
Midlothian 2	NG	DR	CC	231	50	50
Midlothian 3	NG	DR	CC	231	50	50
Midlothian 4	NG	DR	CC	231	50	50
Midlothian 5	NG	DR	CC	241	50	50
Midlothian 6	NG	DR	CC	241	50	50

Table C.9: Natural Gas Combined-Cycle Units with once-through or pond cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
B M Davis 1	NG	OT	CC	332	270	20,000
Nueces Bay 8	NG	OT	CC	706	50	40,000
Rayburn 10 (sam rayburn)	NG	OT	CC	186	50	35,000
Arthur Von Rosenberg 1	NG	PD	CC	527	230	17,466
Lost Pines 1	NG	PD	CC	540	230	30,000

Table C.10: Natural Gas Combined-Cycle Units with recirculating cooling

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Silas Ray 5	NG	RC	CC	10	699	8,512
Bastrop Energy Center 1	NG	RC	CC	577	230	865
Bosque County CC 1	NG	RC	CC	498	230	814
Bosque County CC 2	NG	RC	CC	320	230	814
Brazos Valley 1	NG	RC	CC	592	230	801
Calenergy Falcon seaboard 1	NG	RC	CC	215	230	900
Cedar Bayou 4	NG	RC	CC	606	230	1,000
Colorado Bend Energy Center 1	NG	RC	CC	253	230	1,047
Colorado Bend Energy Center 2	NG	RC	CC	253	230	1,047
CVC Channelview 1	NG	RC	CC	631	230	909
Deer Park Energy Center 1	NG	RC	CC	993	230	934
Ennis Power Station 1	NG	RC	CC	349	230	300
Forney Energy Center 1	NG	RC	CC	921	230	835
Forney Energy Center 2	NG	RC	CC	921	230	835
Freestone Energy Center 1	NG	RC	CC	507	230	503
Freestone Energy Center 2	NG	RC	CC	507	230	503
Frontera 1	NG	RC	CC	471	230	235
Guadalupe Generating Station 1	NG	RC	CC	503	230	874
Guadalupe Generating Station 2	NG	RC	CC	495	230	874
Hidalgo 1	NG	RC	CC	499	230	1,572
Jack County Generation Facility 1	NG	RC	CC	624	230	683
Jack County Generation Facility 2	NG	RC	CC	551	230	683
Johnson County Generation Facility 1	NG	RC	CC	276	230	962
Kiamichi Energy Facility 1	NG	RC	CC	648	198	890
Kiamichi Energy Facility 2	NG	RC	CC	648	198	890
Lamar Power Project 1	NG	RC	CC	528	230	893
Lamar Power Project 2	NG	RC	CC	528	230	893
Magic Valley 1	NG	RC	CC	731	230	621
Odessa Ector Generating Station 1	NG	RC	CC	518	230	862
Odessa Ector Generating station 2	NG	RC	CC	522	230	862
Paris Energy Center 1	NG	RC	CC	274	135	1,456
PasGen	NG	RC	CC	533	230	435
Quail Run Energy 1	NG	RC	CC	236	230	1,291
Quail Run Energy 2	NG	RC	CC	236	230	1,291

Table C.11: Natural Gas Combined-Cycle Units with recirculating cooling (continued)

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Rio Nogales 1	NG	RC	CC	827	230	683
San Jacinto SES 1	NG	RC	CC	79	50	800
San Jacinto SES 2	NG	RC	CC	79	50	800
Sand Hill Energy Center 5a	NG	RC	CC	317	230	816
T H Wharton 3	NG	RC	CC	324	559	909
T H Wharton 4	NG	RC	CC	324	559	909
TC Texas City 1	NG	RC	CC	441	230	175
TF Tenaska Frontier 1	NG	RC	CC	907	230	762
TG Tenaska Gateway 1	NG	RC	CC	885	230	772
Victoria Power Station CC7	NG	RC	CC	296	699	900
Wise Tractebel Power Proj 1	NG	RC	CC	790	230	548
Wolf Hollow Power Proj 1	NG	RC	CC	771	339	1,099
Silas Ray 10	NG	RC	CC	47	50	256
PUN11	NG	RC	CC	556	230	256
PUN12	NG	RC	CC	324	230	256
PUN12dup	NG	RC	CC	324	230	256
PUN13	NG	RC	CC	282	230	256
PUN14	NG	RC	CC	1431	230	256
PUN17	NG	RC	CC	618	230	256
PUN18	NG	RC	CC	449	230	256
PUN19	NG	RC	CC	357	230	256
PUN23	NG	RC	CC	473	230	256
PUN24	NG	RC	CC	468	230	256
PUN3	NG	RC	CC	957	230	256
PUN5	NG	RC	CC	678	230	256
PUN7	NG	RC	CC	215	230	256
PUN9	NG	RC	CC	450	230	256

Table C.12: ERCOT Natural Gas Internal Combustion Units

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Covel Gardens LG	NG	NA	CT	10	50	50
Landfill Austin ALL	NG	NA	CT	6	50	50
Pearsall Power C10	NG	NA	CT	8	50	50
Pearsall Power C11	NG	NA	CT	8	50	50
Pearsall Power C12	NG	NA	CT	8	50	50
Pearsall Power C13	NG	NA	CT	8	50	50
Pearsall Power C14	NG	NA	CT	8	50	50
Pearsall Power C15	NG	NA	CT	8	50	50
Pearsall Power C16	NG	NA	CT	8	50	50
Pearsall Power C17	NG	NA	CT	8	50	50
Pearsall Power C18	NG	NA	CT	8	50	50
Pearsall Power C19	NG	NA	CT	8	50	50
Pearsall Power C20	NG	NA	CT	8	50	50
Pearsall Power C21	NG	NA	CT	8	50	50
Pearsall Power C22	NG	NA	CT	8	50	50
Pearsall Power C23	NG	NA	CT	8	50	50
Pearsall Power C24	NG	NA	CT	8	50	50
Pearsall Power IC1	NG	NA	CT	8	50	50
Pearsall Power IC2	NG	NA	CT	8	50	50
Pearsall Power IC3	NG	NA	CT	8	50	50
Pearsall Power IC4	NG	NA	CT	8	50	50
Pearsall Power IC5	NG	NA	CT	8	50	50
Pearsall Power IC6	NG	NA	CT	8	50	50
Pearsall Power IC7	NG	NA	CT	8	50	50
Pearsall Power IC8	NG	NA	CT	8	50	50
Pearsall Power IC9	NG	NA	CT	8	50	50
Powerlane GRNV IC1	NG	NA	CT	8	50	50
Powerlane GRNV IC2	NG	NA	CT	8	50	50
Powerlane GRNV IC3	NG	NA	CT	8	50	50

Table C.13: ERCOT Natural Gas Open-Cycle Gas Turbine Units

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Atkins 7	NG	NA	CT	20	50	50
Dansby 2	NG	NA	CT	47	50	50
Dansby 3	NG	NA	CT	47	50	50
Decker Creek G1	NG	NA	CT	53	50	50
Decker Creek G2	NG	NA	CT	53	50	50
Decker Creek G3	NG	NA	CT	53	50	50
Decker Creek G4	NG	NA	CT	53	50	50
DeCordova A	NG	NA	CT	82	50	50
DeCordova B	NG	NA	CT	82	50	50
DeCordova C	NG	NA	CT	82	50	50
DeCordova D	NG	NA	CT	82	50	50
ExTex La Porte 1	NG	NA	CT	40	50	50
ExTex La Porte 2	NG	NA	CT	40	50	50
ExTex La Porte 3	NG	NA	CT	40	50	50
ExTex La Porte 4	NG	NA	CT	40	50	50
Greens Bayou 73	NG	NA	CT	53	50	50
Greens Bayou 74	NG	NA	CT	53	50	50
Greens Bayou 81	NG	NA	CT	53	50	50
Greens Bayou 82	NG	NA	CT	63	50	50
Greens Bayou 83	NG	NA	CT	63	50	50
Greens Bayou 84	NG	NA	CT	63	50	50
Laredo Peaking 4	NG	NA	CT	94	50	50
Laredo Peaking 5	NG	NA	CT	94	50	50
Leon Creek Peaking 1	NG	NA	CT	47	50	50
Leon Creek Peaking 2	NG	NA	CT	47	50	50
Leon Creek Peaking 3	NG	NA	CT	47	50	50
Leon Creek Peaking 4	NG	NA	CT	47	50	50

Table C.14: ERCOT Natural Gas Open Cycle Gas Turbine Units (continued)

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Morgan Creek A	NG	NA	CT	79	50	50
Morgan Creek B	NG	NA	CT	79	50	50
Morgan Creek C	NG	NA	CT	79	50	50
Morgan Creek D	NG	NA	CT	79	50	50
Morgan Creek E	NG	NA	CT	79	50	50
Morgan Creek F	NG	NA	CT	79	50	50
Permian Basin A	NG	NA	CT	68	50	50
Permian Basin B	NG	NA	CT	70	50	50
Permian Basin C	NG	NA	CT	73	50	50
Permian Basin D	NG	NA	CT	73	50	50
Permian Basin E	NG	NA	CT	74	50	50
PUN1	NG	NA	CT	32	50	50
PUN10	NG	NA	CT	28	50	50
PUN15	NG	NA	CT	69	50	50
PUN16	NG	NA	CT	437	50	50
PUN2	NG	NA	CT	186	50	50
PUN20	NG	NA	CT	120	50	50
PUN21	NG	NA	CT	44	50	50
PUN27	NG	NA	CT	15	50	50
PUN28	NG	NA	CT	28	50	50
PUN4	NG	NA	CT	79	50	50
PUN6	NG	NA	CT	294	50	50
PUN8	NG	NA	CT	18	50	50
R W Miller 4	NG	NA	CT	113	50	50
R W Miller 5	NG	NA	CT	113	50	50
Ray Olinger 4	NG	NA	CT	82	50	50
Sam Bertron T2	NG	NA	CT	13	50	50
Sam Rayburn GT 1	NG	NA	CT	13	50	50
Sam Rayburn GT 2	NG	NA	CT	13	50	50
Sand Hill GT 1	NG	NA	CT	45	50	50
Sand Hill GT 2	NG	NA	CT	44	50	50
Sand Hill GT 3	NG	NA	CT	46	50	50

Table C.15: ERCOT Natural Gas Open Cycle Gas Turbine Units (continued)

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Sand Hill GT 4	NG	NA	CT	48	50	50
Sand Hill GT 5	NG	NA	CT	45	50	50
Sand Hill GT 6	NG	NA	CT	45	50	50
Silas Ray 69	NG	NA	CT	57	50	50
T H Wharton G 1	NG	NA	CT	57	50	50
T H Wharton GT 51	NG	NA	CT	13	50	50
T H Wharton GT 52	NG	NA	CT	57	50	50
T H Wharton GT 53	NG	NA	CT	57	50	50
T H Wharton GT 54	NG	NA	CT	57	50	50
T H Wharton GT 55	NG	NA	CT	57	50	50
T H Wharton GT 56	NG	NA	CT	57	50	50
TGS Texas Gulf Sulphur	NG	NA	CT	81	50	50
V H Braunig 5	NG	NA	CT	47	50	50
V H Braunig 6	NG	NA	CT	47	50	50
V H Braunig 7	NG	NA	CT	47	50	50
V H Braunig 8	NG	NA	CT	47	50	50
W A Parish T1	NG	NA	CT	13	50	50
Wichita Falls 1	NG	NA	CT	78	50	50
Winchester Power Park 1	NG	NA	CT	44	50	50
Winchester Power Park 2	NG	NA	CT	44	50	50
Winchester Power Park 3	NG	NA	CT	44	50	50
Winchester Power Park 4	NG	NA	CT	44	50	50

Table C.16: ERCOT Biomass Plants

Unit Name	Fuel Type	Cooling System	Prime Mover Technology	Capacity (MW)	Consumption (gal/MWh)	Withdrawal (gal/MWh)
Atascocita 1	BM	NA	CT	10	50	50
Bluebonnet 1	BM	NA	CT	4	50	50
Coastal Plains	BM	NA	CT	7	50	50
DFW Gas Recovery	BM	NA	CT	6	50	50
Lufkin Biomass	BM	NA	CT	47	50	1,188
Nacogdoches Project	BM	NA	CT	100	479	50
Tessman Road 1	BM	NA	CT	10	50	615

C.2 Detailed Summaries of Water Cost Simulations

Table C.17: Overall Summary of Annual Generation Characteristics by Simulation

	Baseline	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	335	335	335	335	335
Total Gen Cost (billion USD)	8.25	8.27	8.30	8.62	8.33
Water Consumption (trillion gallons)	0.118	0.118	0.118	0.117	0.105
Water Withdrawals (trillion gallons)	9.33	9.33	9.32	9.28	8.89
Capacity Factor (%)	33	33	33	33	32
Average Heat Rate (MMBTU/MWh)	7.7	7.7	7.7	7.7	7.7
Average Water Consumption Intensity (gall/MWh)	353	353	352	348	312
Average Water Withdrawal Intensity (gall/MWh)	27,841	27,837	27,821	27,681	26,530
	Baseline	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	335	335	335	335	335
Total Gen Cost (billion USD)	8.25	8.54	10.6	18.1	82.8
Water Consumption (trillion gallons)	0.118	0.118	0.105	0.091	0.088
Water Withdrawals (trillion gallons)	9.33	9.21	5.51	2.39	2.34
Capacity Factor (%)	33	33	30	35	37
Average Heat Rate (MMBTU/MWh)	7.7	7.7	7.7	7.7	7.7
Average Water Consumption Intensity (gall/MWh)	353	351	313	270	261
Average Water Withdrawal Intensity (gall/MWh)	27,841	27,473	16,443	7,136	6,993

Table C.18: Summary of Simulations: NU-OT-ST EGUs

NU-OT-ST	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (MWh)	45.0	45.0	45.0	45.0	44.9
Total Gen Cost (billion USD)	0.416	0.417	0.424	0.496	0.416
Water Consumption (trillion gallons)	0.026	0.026	0.026	0.026	0.026
Water Withdrawals (trillion gallons)	5.39	5.39	5.39	5.39	5.39
Capacity Factor (%)	100	100	100	100	100
Average Heat Rate (MMBTU/MWh)	10.5	10.5	10.5	10.5	10.5
Average Water Consumption Intensity (gall/MWh)	585	585	585	585	585
Average Water Withdrawal Intensity (gall/MWh)	120,000	120,000	120,000	120,000	120,000
NU-OT-ST	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (MWh)	45.0	45.0	21.1	13.5	13.5
Total Gen Cost (billion USD)	0.416	0.581	0.967	5.08	49.58
Water Consumption (trillion gallons)	0.026	0.026	0.012	0.008	0.008
Water Withdrawals (trillion gallons)	5.39	5.39	2.53	1.62	1.62
Capacity Factor (%)	100	100	47	30	30
Average Heat Rate (MMBTU/MWh)	10.5	10.5	10.5	10.5	10.5
Average Water Consumption Intensity (gall/MWh)	585	585	584	585	585
Average Water Withdrawal Intensity (gall/MWh)	120,000	119,999	120,000	120,000	120,000

Table C.19: Summary of Simulations: CL-RC-ST EGUs

CL-RC-ST	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	40.7	40.7	40.6	39.9	26.4
Total Gen Cost (billion USD)	0.933	0.933	0.939	0.986	0.617
Water Consumption (trillion gallons)	0.023	0.023	0.023	0.023	0.014
Water Withdrawals (trillion gallons)	0.029	0.029	0.029	0.028	0.018
Capacity Factor (%)	90	90	90	88	57
Average Heat Rate (MMBTU/MWh)	9.9	9.9	9.9	9.9	9.9
Average Water Consumption Intensity (gall/MWh)	576	576	575	574	548
Average Water Withdrawal Intensity (gall/MWh)	706	706	706	706	701
CL-RC-ST	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	40.7	41.3	44.4	44.8	43.8
Total Gen Cost (billion USD)	0.933	0.946	1.03	1.13	1.95
Water Consumption (trillion gallons)	0.023	0.024	0.025	0.026	0.025
Water Withdrawals (trillion gallons)	0.029	0.029	0.031	0.032	0.031
Capacity Factor (%)	90	91	98	99	96
Average Heat Rate (MMBTU/MWh)	9.9	9.9	10.0	10.0	10.0
Average Water Consumption Intensity (gall/MWh)	576	576	571	570	571

Table C.20: Summary of Simulations: CL-OT-ST EGUs

CL-OT-ST	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	113	113	113	112	99.8
Total Gen Cost (billion USD)	2.62	2.62	2.63	2.72	2.26
Water Consumption (trillion gallons)	0.044	0.044	0.044	0.043	0.035
Water Withdrawals (trillion gallons)	3.54	3.54	3.53	3.50	3.13
Capacity Factor (%)	85	85	85	84	74
Average Heat Rate (MMBTU/MWh)	10.3	10.3	10.3	10.3	10.3
Average Water Consumption Intensity (gall/MWh)	388	387	387	382	353
Average Water Withdrawal Intensity (gall/MWh)	31,178	31,172	31,165	31,197	31,347
CL-OT-ST	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	113	111	91.5	19.9	13.7
Total Gen Cost (billion USD)	2.62	2.67	2.95	1.69	6.32
Water Consumption (trillion gallons)	0.044	0.043	0.034	0.008	0.006
Water Withdrawals (trillion gallons)	3.54	3.46	2.77	0.376	0.195
Capacity Factor (%)	85	83	68	14	9
Average Heat Rate (MMBTU/MWh)	10.3	10.3	10.3	10.5	10.5
Average Water Consumption Intensity (gall/MWh)	388	386	375	393	414
Average Water Withdrawal Intensity (gall/MWh)	31,178	31,145	30,243	18,867	14,163

Table C.21: Summary of Simulations: NG-RC-CC EGUs

NG-RC-CC	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	96.3	96.3	96.5	98.6	123
Total Gen Cost (billion USD)	3.55	3.55	3.56	3.69	4.32
Water Consumption (trillion gallons)	0.022	0.022	0.022	0.022	0.027
Water Withdrawals (trillion gallons)	0.059	0.059	0.059	0.059	0.067
Capacity Factor (%)	31	31	31	31	41
Average Heat Rate (MMBTU/MWh)	8.0	8.0	8.0	8.0	7.9
Average Water Consumption Intensity (gall/MWh)	226	226	226	225	216
Average Water Withdrawal Intensity (gall/MWh)	616	614	611	597	541
NG-RC-CC	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	96.3	99.2	142	202	193
Total Gen Cost (billion USD)	3.55	3.65	5.02	7.84	10.6
Water Consumption (trillion gallons)	0.022	0.022	0.031	0.045	0.042
Water Withdrawals (trillion gallons)	0.059	0.061	0.086	0.127	0.112
Capacity Factor (%)	31	31	46	69	66
Average Heat Rate (MMBTU/MWh)	8.0	8.0	7.9	7.9	7.9
Average Water Consumption Intensity (gall/MWh)	226	226	222	220	217
Average Water Withdrawal Intensity (gall/MWh)	616	613	607	626	582

Table C.22: Summary of Simulations: NG-OT-CC EGUs

NG-OT-CC	*Baseline*	*WC*10	*WC*100	*WC*1000	*WC*10000
Generation (TWh)	4.436	4.444	4.449	4.501	5.936
Total Gen Cost (billion USD)	0.193	0.193	0.193	0.199	0.234
Water Consumption (trillion gallons)	0.001	0.001	0.001	0.001	0.001
Water Withdrawals (trillion gallons)	0.194	0.194	0.194	0.196	0.246
Capacity Factor (%)	13	13	13	14	19
Average Heat Rate (MMBTU/MWh)	8.3	8.3	8.3	8.3	8.3
Average Water Consumption Intensity (gall/MWh)	230	230	229	229	225
Average Water Withdrawal Intensity (gall/MWh)	43,623	43,582	43,563	43,452	41,446
NG-OT-CC	*Baseline*	*WW*10	*WW*100	*WW*1000	*WW*10000
Generation (TWh)	4.436	4.039	2.741	2.394	2.621
Total Gen Cost (billion USD)	0.193	0.183	0.140	0.324	2.359
Water Consumption (trillion gallons)	0.001	0.001	0.001	0.001	0.001
Water Withdrawals (trillion gallons)	0.194	0.175	0.075	0.065	0.072
Capacity Factor (%)	13	12	9	9	10
Average Heat Rate (MMBTU/MWh)	8.3	8.3	8.4	8.3	8.2
Average Water Consumption Intensity (gall/MWh)	230	230	230	222	218
Average Water Withdrawal Intensity (gall/MWh)	43,623	43,222	27,289	26,989	27,621

Table C.23: Summary of Simulations: NG-RC-ST EGUs

NG-RC-ST	*Baseline*	*WC*10	*WC*100	*WC*1000	*WC*10000
Generation (TWh)	0.193	0.193	0.191	0.177	0.069
Total Gen Cost (billion USD)	0.011	0.011	0.011	0.010	0.004
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Capacity Factor (%)	8.0	8.0	8.0	7.0	5.0
Average Heat Rate (MMBTU/MWh)	10	10	10	10	10
Average Water Consumption Intensity (gall/MWh)	502	501	499	481	236
Average Water Withdrawal Intensity (gall/MWh)	1,402	1,397	1,394	1,384	1,572
NG-RC-ST	*Baseline*	*WW*10	*WW*100	*WW*1000	*WW*10000
Generation (TWh)	0.193	0.203	0.260	0.906	0.505
Total Gen Cost (billion USD)	0.011	0.012	0.014	0.049	0.050
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.001	0.001
Capacity Factor (%)	8.0	9.0	10.0	37.0	22.0
Average Heat Rate (MMBTU/MWh)	10	10	10	10	10
Average Water Consumption Intensity (gall/MWh)	502	498	517	513	503
Average Water Withdrawal Intensity (gall/MWh)	1,402	1,439	1,409	1,422	1,520

Table C.24: Summary of Simulations: NG-OT-ST EGUs

NG-OT-ST	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	3.06	3.06	3.00	2.65	1.02
Total Gen Cost (billion USD)	0.184	0.184	0.181	0.162	0.053
Water Consumption (trillion gallons)	0.001	0.001	0.001	0.001	0.000
Water Withdrawals (trillion gallons)	0.116	0.116	0.114	0.101	0.038
Capacity Factor (%)	2	2	2	2	1
Average Heat Rate (MMBTU/MWh)	10.7	10.7	10.7	10.7	10.7
Average Water Consumption Intensity (gall/MWh)	432	431	421	395	347
Average Water Withdrawal Intensity (gall/MWh)	37,836	37,834	37,847	38,037	37,245
NG-OT-ST	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	3.06	2.39	0.755	5.54	9.24
Total Gen Cost (billion USD)	0.184	0.147	0.054	0.889	10.155
Water Consumption (trillion gallons)	0.001	0.001	0.000	0.003	0.005
Water Withdrawals (trillion gallons)	0.116	0.090	0.022	0.171	0.312
Capacity Factor (%)	2	2	1	4	8
Average Heat Rate (MMBTU/MWh)	10.7	10.7	10.7	10.7	10.6
Average Water Consumption Intensity (gall/MWh)	432	433	438	495	498
Average Water Withdrawal Intensity (gall/MWh)	37,836	37,526	29,131	30,935	33,814

Table C.25: Summary of Simulations: OCGT-NA-CT EGUs

OCGT-NA-CT	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	5.17	5.17	5.19	5.35	6.75
Total Gen Cost (billion USD)	0.311	0.324	0.325	0.334	0.386
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Capacity Factor (%)	8	8	8	8	11
Average Heat Rate (MMBTU/MWh)	10.1	10.1	10.1	10.1	10.1
Average Water Consumption Intensity (gall/MWh)	50	50	50	50	50
Average Water Withdrawal Intensity (gall/MWh)	50	50	50	50	50
OCGT-NA-CT	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	5.17	5.27	5.92	18.2	30.7
Total Gen Cost (billion USD)	0.311	0.329	0.359	0.998	1.65
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.001	0.002
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.001	0.002
Capacity Factor (%)	8	8	10	38	67
Average Heat Rate (MMBTU/MWh)	10.1	10.1	10.1	10.1	10.1
Average Water Consumption Intensity (gall/MWh)	50	50	50	50	50
Average Water Withdrawal Intensity (gall/MWh)	50	50	50	50	50

Table C.26: Summary of Simulations: NGIC-NA-CT EGUs

NGIC-NA-CT	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	0.433	0.434	0.434	0.447	0.561
Total Gen Cost (billion USD)	0.019	0.019	0.019	0.020	0.024
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Capacity Factor (%)	22	22	22	22	28
Average Heat Rate (MMBTU/MWh)	9.8	9.8	9.8	9.8	9.8
Average Water Consumption Intensity (gall/MWh)	50	50	50	50	50
Average Water Withdrawal Intensity (gall/MWh)	50	50	50	50	50
NGIC-NA-CT	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	0.433	0.423	0.352	0.920	1.50
Total Gen Cost (billion USD)	0.019	0.019	0.015	0.040	0.067
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Capacity Factor (%)	22	21	18	46	76
Average Heat Rate (MMBTU/MWh)	9.8	9.8	9.8	9.8	9.8
Average Water Consumption Intensity (gall/MWh)	50	50	50	50	50
Average Water Withdrawal Intensity (gall/MWh)	50	50	50	50	50

Table C.27: Summary of Simulations: HY-NA-HY EGUs

HY-NA-HY	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	1.47	1.47	1.47	1.47	1.47
Total Gen Cost (billion USD)	0	0	0	0	0
Water Consumption (trillion gallons)	0	0	0	0	0
Water Withdrawals (trillion gallons)	0	0	0	0	0
Capacity Factor (%)	29	29	29	29	29
Average Heat Rate (MMBTU/MWh)	0	0	0	0	0
Average Water Consumption Intensity (gall/MWh)	0	0	0	0	0
Average Water Withdrawal Intensity (gall/MWh)	0	0	0	0	0
HY-NA-HY	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	1.47	1.47	1.47	1.41	1.39
Total Gen Cost (billion USD)	0	0	0	0	0
Water Consumption (trillion gallons)	0	0	0	0	0
Water Withdrawals (trillion gallons)	0	0	0	0	0
Capacity Factor (%)	29	29	29	28	28
Average Heat Rate (MMBTU/MWh)	0	0	0	0	0
Average Water Consumption Intensity (gall/MWh)	0	0	0	0	0
Average Water Withdrawal Intensity (gall/MWh)	0	0	0	0	0

Table C.28: Summary of Simulations: WI-NA-WI EGUs

WI-NA-WI	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	24.7	24.7	24.7	24.7	24.7
Total Gen Cost (billion USD)	0	0	0	0	0
Water Consumption (trillion gallons)	0	0	0	0	0
Water Withdrawals (trillion gallons)	0	0	0	0	0
Capacity Factor (%)	28	28	28	28	28
Average Heat Rate (MMBTU/MWh)	0	0	0	0	0
Average Water Consumption Intensity (gall/MWh)	0	0	0	0	0
Average Water Withdrawal Intensity (gall/MWh)	0	0	0	0	0
WI-NA-WI	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	24.7	24.7	24.7	24.7	24.7
Total Gen Cost (billion USD)	0	0	0	0	0
Water Consumption (trillion gallons)	0	0	0	0	0
Water Withdrawals (trillion gallons)	0	0	0	0	0
Capacity Factor (%)	28	28	28	28	28
Average Heat Rate (MMBTU/MWh)	0	0	0	0	0
Average Water Consumption Intensity (gall/MWh)	0	0	0	0	0
Average Water Withdrawal Intensity (gall/MWh)	0	0	0	0	0

Table C.29: Summary of Simulations: BM EGUs

Biomass	*Baseline*	$WC10$	$WC100$	$WC1000$	$WC10000$
Generation (TWh)	0.224	0.224	0.224	0.226	0.295
Total Gen Cost (billion USD)	0.009	0.009	0.009	0.009	0.012
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Capacity Factor (%)	17	17	17	18	23
Average Heat Rate (MMBTU/MWh)	12.5	12.5	12.5	12.5	12.5
Average Water Consumption Intensity (gall/MWh)	109	109	109	109	109
Average Water Withdrawal Intensity (gall/MWh)	1,188	1,188	1,188	1,188	1,188
Biomass	*Baseline*	$WW10$	$WW100$	$WW1000$	$WW10000$
Generation (TWh)	0.224	0.225	0.265	0.750	0.534
Total Gen Cost (billion USD)	0.009	0.009	0.011	0.033	0.041
Water Consumption (trillion gallons)	0.000	0.000	0.000	0.000	0.000
Water Withdrawals (trillion gallons)	0.000	0.000	0.000	0.001	0.001
Capacity Factor (%)	17	18	21	58	41
Average Heat Rate (MMBTU/MWh)	12.5	12.5	12.5	12.5	12.5
Average Water Consumption Intensity (gall/MWh)	109	109	109	109	109
Average Water Withdrawal Intensity (gall/MWh)	1,188	1,188	1,188	1,188	1,188

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