INTEGRATING WATER RESOURCES AND POWER GENERATION: THE ENERGY-WATER NEXUS IN ILLINOIS

BY

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THESIS

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ABSTRACT

Thermoelectric power plants contribute 90 percent of the electricity generated in the United States. Steam condensation in the power generation cycle creates a need for cooling, often accomplished using large amounts of water. Negative consequences of power plant water demands, such as dialing down or shutting down, have become increasingly apparent during times of low water availability. Consequently, water constraints can translate into energy constraints. Projected future population growth and changing climate conditions might also increase the competition for water. These water constraints motivate a resource accounting analysis to both establish a baseline of current water requirements and simulate possible impacts from future water and energy management decisions. Furthermore, a potential future increase in the magnitude and duration of droughts and heat waves in the United States motivates a further scenario analysis on the possible impacts of drought and heat waves on power plant cooling operations. The analysis combined existing digital spatial datasets with engineering basic principles to synthesize a geographic information systems (GIS) model of current and projected water demand for thermoelectric power plants. Two potential future cases were evaluated based on their water use implications: 1) a shift in fuel from coal to natural gas, and 2) a shift in cooling technology from open-loop to closed-loop cooling.

The results show that a shift from coal-generated to natural gas-generated electricity could decrease statewide water consumption by 100 million m^3/yr (32%) and withdrawal by 7.9 billion m^3/yr (37%), on average. A shift from open-loop to closed-loop cooling technologies could decrease withdrawals by an average of 21 billion m^3/yr (96%), with the tradeoff of increasing statewide water consumption for power generation by 180 million m^3/yr (58%). Furthermore, an economic analysis was performed of retrofitting open-loop cooling systems to closed-loop cooling, revealing an annual cost between \$0.58

and \$1.3 billion to retrofit the 22 open-loop cooling plants in the analysis, translating to an effective water price between \$0.17 and \$0.68/m^3 saved, comparable to current municipal drinking water prices.

The tradeoffs associated with these unique water users yield interesting implications for integrated energy and water decision making and policy in Illinois and elsewhere. While there is evidence that a shift from coal-generated to natural gas-generated electricity is economically and politically motivated in the United States, a shift from open-loop to closed-loop cooling technologies is not economically motivated, thus policy would likely need to be the driver.

To my parents, for their love and support.

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LIST OF ABBREVIATIONS

BTA	Best Technology Available
CWA	Clean Water Act
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GIS	Geographic Information Systems
NPDES	National Pollutant Discharge Elimination System

LIST OF SYMBOLS

ft/s	Feet per second
m^3	Cubic meters
m/s	Meters per second
MW_e	Megawatt-electric
MWh	Megawatt-hour
MGD	Million gallons per day

CHAPTER 1

INTRODUCTION

Energy and water are closely related: energy is needed for water, and water is needed for energy. Water is needed for fuel mining and refining, energy crop irrigation, producing hydroelectric power, and cooling thermoelectric power plants. Energy is also needed to collect, treat, distribute, and heat water for municipal, industrial, and agricultural uses. Additionally, a large amount of energy is required to collect, treat, discharge, and reuse wastewater. This intrinsic relationship is commonly known as the energy-water nexus [1–13].

Despite the intrinsic relationship between energy and water, these sectors are largely regulated separately, with little consideration between sectors. Power plant siting is often determined by other factors such as land prices, proximity to fuel sources, rail lines, and power lines, with little consideration of water supply issues [1]. Furthermore, water supply planning often neglects the energy requirements associated with these systems [14]. As water and energy continue to become further constrained in the ever growing and warming world, sustainable development motivates a shift away from bifurcated planning and toward integrated planning. A better understanding of the intricate relationships between both sectors could support sustainable future planning at the local, state and federal levels.

The electric power sector in the United States is highly dependent on water for cooling, representing a significant branch of the energy-water nexus. Nearly all thermoelectric power plants — nuclear, coal, natural gas, biomass, geothermal, and solar thermal plants — require large amounts of cooling water [1–4, 7, 15]. In 2010, thermoelectric power plants were responsible for 38% of the national freshwater withdrawals [16]. As climate change is projected to increase the frequency and severity of droughts in the United States [17], water resources will likely become further constrained. Additionally, both water and energy will likely be in higher demand in the future as the U.S. population is projected to grow from 317 to 400 million by 2050 [18]. Competition is increasingly likely between power plants and other water users in water-stressed areas of the United States.

While the nexus between power generation and water demand is projected to face additional challenges in the future, power plant cooling technologies and fuel types can have a significant impact on the water intensity of electricity [1, 3, 19, 20]. For example, water demand in the thermoelectric power sector can be reduced by implementing advanced or alternative cooling technologies such as cooling towers or dry cooling [2, 21]. In addition to reducing water withdrawals, these alternative cooling technologies can lessen many of the environmental concerns associated with many current cooling systems [21]. Nuclear and coal-fired power plants are generally more water intensive than natural gas plants [2, 15], such that a fuel shift can reduce water demands.

The research presented in this thesis was guided by several research questions:

- What is the current relationship between water resources and thermoelectric power plants in Illinois?
- How might that relationship change with different fuel and/or cooling technology shifts?
- What economic or policy levers reduce strain on the energy-water nexus?

A baseline evaluation of current water and energy use is motivated by a demand for efficient resource management decisions. Additional background on the energy-water nexus is presented in Chapter 2. In Chapter 3, a methodology is outlined to develop a baseline of current water requirements for thermoelectric power plants, using the state of Illinois as test-bed. Scenario and economic analyses are also presented to simulate impacts of future energy and water decisions. The results of these analyses have implications on statewide and federal policies, as discussed in Chapter 4. Chapter 5 outlines future work of a methodology to estimate the possible effects of drought and heat waves on power plant cooling operations for 10 plants along the Illinois River, with conclusions presented in Chapter 6.

CHAPTER 2

BACKGROUND

Access to water is an important requirement for thermoelectric power plants. Power plants using a steam cycle generate 90 percent of the electricty in the United States; the remainder of the electricity is provided by hydroelectric and other renewable sources [22]. Coal-fired, natural gas-fired, and nuclear power plants represented 86% of the electricity generation in the United States in 2012 (see Figure 2.1). In a typical thermoelectric power plant, heat is created through the burning of fuel, from nuclear reactions, directly from the sun, or geothermal heat sources to boil highly purified water to generate steam. The high-pressure steam turns a steam turbine connected to a generator, which produces electricity. Steam exiting the turbine is condensed in a heat exchanger using water (or air) as the cooling fluid, and is then returned to the boiler to repeat the process. In wet cooling systems, the warmer cooling water is either directly returned to the source (open-loop) or recirculated (closed-loop).

Different types of cooling systems can have considerably different water requirements. To understand these implications, it is important to distinguish between the terms water *withdrawal* and water *consumption*. Water withdrawal is defined as water diverted from a surface water or groundwater source, while water consumption is water that is not directly returned to the original source (typically due to evaporation). Water withdrawal volumes are important for various reasons, as withdrawal rates from surface waters influence the amount of fish and aquatic life negatively affected by intake structures and thermal pollution. Power plants depending on groundwater for cooling place additional strain on aquifers with increased withdrawal rates. Furthermore, many states define water rights in terms of water withdrawal, meaning those volumes are not available for allocation to other high-value water users or environmental needs. Withdrawal volumes are critical for power generation because if the quantity demanded is not available, plants

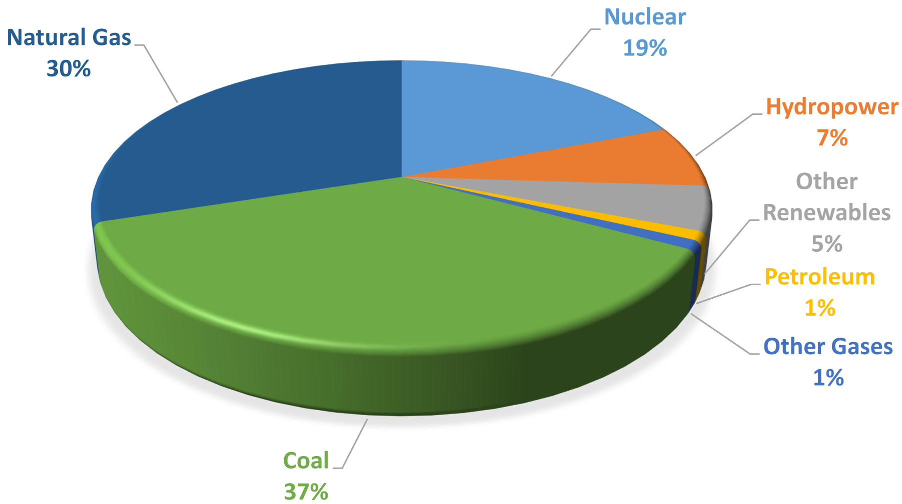

Figure 2.1: Electricity generation in the United States (2012) is dominated by natural gas, coal and nuclear fuels; all three fuels utilize a steam cycle [23].

might be forced to shut down or curtail operations. Water consumption is also important because water that is evaporated is not available for other uses in the same watershed. Different cooling technologies have vastly different withdrawal and consumption implications; concerns over the relative importance of water withdrawal versus consumption is often highly dependent on local characteristics [15, 24].

2.1 Cooling technologies

Thermoelectric power plants can utilize several different types of cooling systems, each one with various water and environmental implications: open-loop, closed-loop, dry cooling, and hybrid wet-dry cooling.

2.1.1 Open-loop cooling

Before 1970, the majority of U.S. thermoelectric power plants applied open-loop cooling methods due to the ease of implementation, high efficiency, and overall cost-effectiveness [25]. However, since the 1970s, the power industry has shifted away from this technology. The construction of open-loop cooling

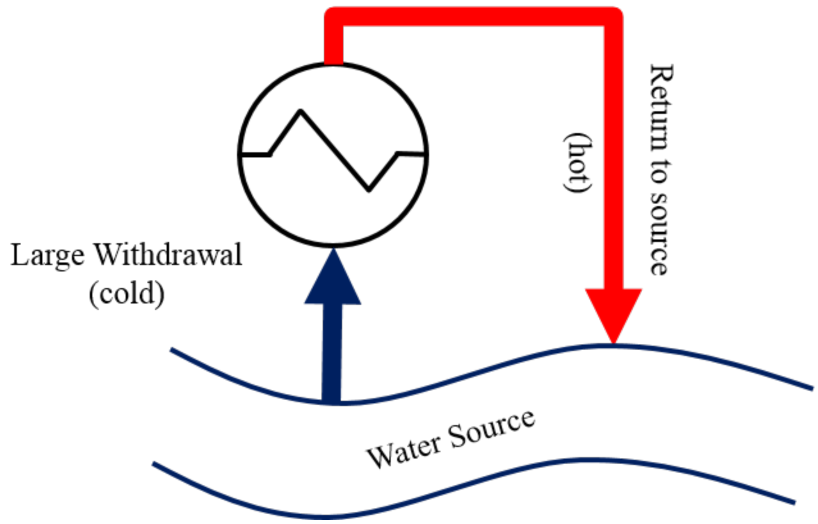

Figure 2.2: Open-loop cooling systems withdraw large amounts of water from the water source and return the heated water back to the water source.

systems peaked between 1955 and 1959, with only about 10 thermoelectric power plants having been built with open-loop cooling since 1980 [26, 27]. Open-loop cooling systems withdraw large amounts of water from a water source, and pump that water to a condenser where heat is transferred from the steam to the cooling water. The cooling water is subsequently discharged to the receiving water source at a higher temperature (see Figure 2.2). Despite its simplicity, this technology can have unintended and detrimental effects on the ecosystem of the water source, including impingement and entrainment of fish and aquatic life at the intake structure [28]. Impingement occurs when organisms become trapped against the intake screen as a result of the high flow rates, often resulting in asphyxiation, starvation, and/or death. Smaller organisms are subject to entrainment when aquatic life is sucked through the entire cooling system, including the pumps and condenser tubes, and discharged back to the source water. These small organisms are often the most fragile, typically fish eggs and larvae. Additionally, thermal pollution can be harmful to fish and aquatic life at the point of discharge. Thermal plumes decrease the dissolved oxygen in the receiving water and can cause significant changes to the ecosystem compositions and decrease biodiversity [29].

From a water use standpoint, open-loop cooling withdraws large amounts of water and returns most of the water back to the source. Therefore, a benefit of these systems is that little of this water is consumed. However, the hotter water does induce higher evaporation rates in the receiving water source (about 1% of withdrawals). This enhanced evaporation can still be a significant amount of consumption because open-loop cooling typically withdraws up to 40–80 times the volumes of recirculating cooling technologies [20]. In addition, open-loop cooling systems have the flexibility to use saline or seawater because the water is only used once and does not significantly evaporate in the cooling system, which can lead to scale, corrosion, and biofilm challenges.

2.1.2 Closed-loop cooling

As a result of regulations in the Clean Water Act in 1972, new power plants have shifted toward closed-loop cooling techniques, which recirculate water and minimize the environmental externalities. Closed-loop cooling is an alternative cooling technology that recirculates water through a cooling component, typically a wet cooling tower or cooling reservoir. Figure 2.3 illustrates the flow of cooling water for a typical power plant with a cooling tower, although the cooling tower could be replaced with a cooling pond. For cooling towers, some water is returned to the source in the form of blowdown in order to control the buildup of dissolved minerals in the recirculating water, while the remainder is consumed via evaporation. For this reason, recirculating systems largely do not use saline water. Due to the recirculating nature of closed-loop cooling, these systems withdraw less than 5% of the water withdrawn by open-loop systems [15]; however, most of the water is consumed via evaporation, such that on average, closed-loop cooling systems consume more water per megawatt-hour generated than similarly sized open-loop systems. Cooling reservoirs work by recirculating water within cooling ponds, also yielding slightly lower, but similar evaporation (consumption) rates as cooling towers.

Despite the additional water consumption, closed-loop cooling systems can significantly reduce the environmental damages associated with open-loop cooling. Decreased rates of impingement, entrainment, and thermal pollution are a direct result of the decreased withdrawal and discharge rates. However, the blowdown water discharged to the water source is typically returned at

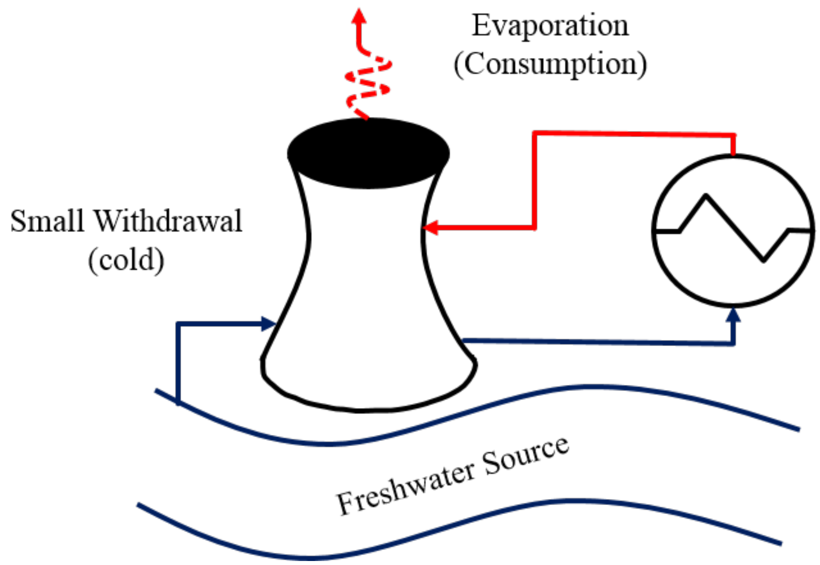

Figure 2.3: Closed-loop cooling systems withdraw smaller amounts of makeup water from the water source and recirculate the cooling through a closed-loop.

a lower quality due to the higher concentration of dissolved and suspended solids. In addition, visible water vapor (drift) leaving cooling towers creates a plume that can reduce the visibility and cause icing to downwind structures. Concerns with water-borne bacteria, such as Legionella (which can cause Legionnaires' disease), are also associated with drift from cooling towers. Cooling towers and cooling ponds both require significant real estate and are typically associated with a higher capital cost. Additionally, closed-loop systems tend to be more complex in nature than open-loop cooling systems and lower a plant's net energy production by 1.2%, on average [30].

2.1.3 Dry cooling

As an alternative to wet cooling, dry cooling is a cooling system that does not directly require cooling water. Dry cooling condenses steam by means of air convection using large fans (forced-draft) or hyperbolic towers (natural draft) to force air past small finned tubes in the condenser (see Figure 2.4). A large benefit of dry cooling systems is that they do not require water directly for cooling, thus making the power plant more resilient to water constraints. This flexibility allows for power plant siting in arid, water-constrained regions.

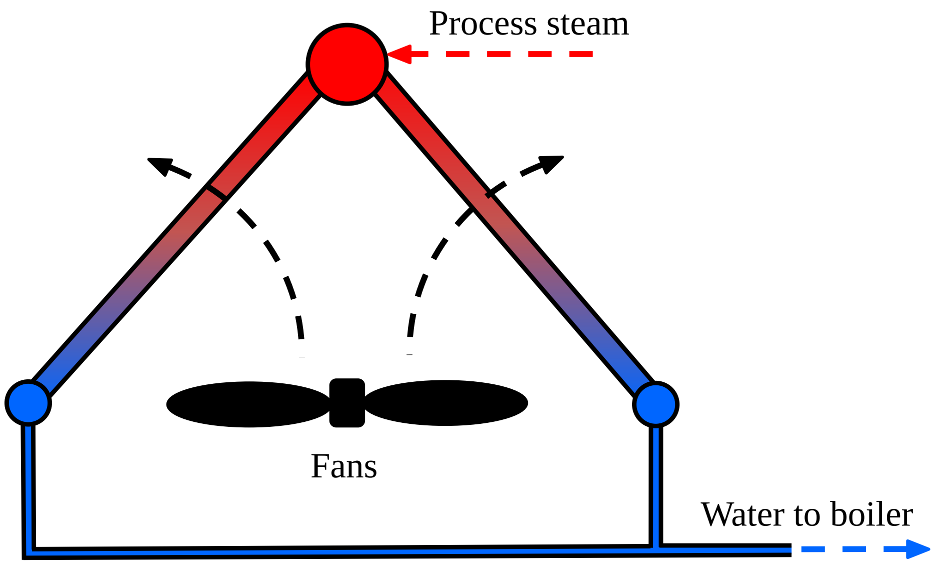

Figure 2.4: Dry cooling forces air pas finned tubes in order to condense steam (shown as a typical A–frame configuration).

However, the cooling efficiency of air is lower than water, thus dry systems incur a parasitic efficiency loss of 2-3%, on average, with some estimates of 15% efficiency loss in extreme circumstances. Furthermore, the cooling efficiency of dry cooling goes down as the ambient temperature rises, which can constrain power plants and further increase the parasitic efficiency loss during summer months [31]. Capital costs of dry cooling systems are also on the order of 1.5-8 times that of similarly sized wet-cooled systems [32], making them less economical.

2.1.4 Hybrid wet-dry cooling

Hybrid wet-dry cooling systems integrate both wet and dry cooling elements. While not largely implemented in the United States, these systems increase the flexibility of power plants. Hybrid systems can be operated in series or parallel, often with dry and wet cooling tower combinations such that cooling towers can be built to operate with only dry cooling, only wet cooling, or somewhere in between. This operational flexibility can help to mitigate the tradeoff of lower efficiency associated with dry cooling. Power plants can choose to use dry cooling during the cooler months, and wet cooling during hot summer days (often coinciding with high electricity prices), reducing the efficiency loss of the power plant during warmer weather while decreasing the overall water requirements. However, times of low water availability in a watershed often occur during the hot summer months when these plants have a higher water demand than when operating as a dry cooling system.

2.2 Cooling system comparison

In the United States, power plants implementing closed-loop cooling systems represent 53% of the electricity generating capacity [33]. Table 2.1 shows the number of cooling systems in the United States by primary energy source. Many new combined-cycle natural gas-fired power plants use closed-loop cooling systems, while many older coal and natural gas plants still utilize open-loop cooling. This trend results in the average age of closed-cycle cooling plants being 29 years, compared to 50 years for the average once-through cooling systems [33]. It is also worth noting that open-loop systems are more common in eastern states (with higher water availability, historically), and closed-loop systems are more prevalent in western states (with often constrained water availability). Dry and hybrid cooling systems are not widely used, representing only 3.3% and 0.3% of the systems in the United States, respectively.

Table 2.1: Many new combined-cycle natural gas power plants use closed-loop cooling systems, while many older coal and natural gas plants still implement open-loop cooling [25].

Primary Energy Source	Open-Loop (wet)	Closed-Loop (wet)	Dry Cooling	Hybrid Cooling	Total Cooling Systems
Coal	398	368	4	1	771
Natural Gas	197	422	51	4	674
Nuclear	50	44	0	0	94
Other*	74	41	1	0	116
Total	719	875	56	5	1,655

*“Other” consists of biomass, wood and wood-waste products, petroleum, and gases other than natural gas.

Water requirements on a m^3/MWh basis vary depending on fuel type, power generation technology, and cooling technology. Table 2.2 illustrates how the combination of fuel type and cooling technology can have a significant impact on water demands.

Table 2.2: Open-loop thermoelectric power plants withdraw more, and consume less, than closed-loop plants, on average. Coal and nuclear power plants have higher water requirements for cooling than natural-gas combined-cycle plants, while wind does not require any water for cooling. [15, 23].

	Open-Loop		Closed-Loop Reservoir		Closed-Loop Cooling Tower	
Primary Fuel	Withdrawal [m^3/MWh]	Consumption [m^3/MWh]	Withdrawal [m^3/MWh]	Consumption [m^3/MWh]	Withdrawal [m^3/MWh]	Consumption [m^3/MWh]
Coal	137.60	0.95	46.28	2.06	3.80	2.60
Nuclear	167.88	1.02	26.69	2.31	4.17	2.54
Natural Gas Combustion Turbine	negligible	negligible	negligible	negligible	negligible	negligible
Natural Gas Combined-Cycle	43.08	0.38	21.16	0.91	0.97	0.78
Wind	none	none	none	none	none	none
Photovoltaic Solar	none	none	none	none	none	none

2.3 Previous work

Similar work has been done in the energy-water nexus field and published in literature. Bartos & Chester also performed a statewide analysis in which the methodology can be applied to other states [10]. Similarly to the methodology described in this thesis, the analysis uses a bottom-up approach to estimate water and energy inputs in Arizona. A spatially explicit model of water-energy interdependencies in Arizona is developed in order to determine the extent to which conservation strategies provide water and energy benefits. It was found that water conservation policies have the potential to reduce electricity demand in Arizona.

Lubega & Farid approach the energy-water nexus from a systems modeling approach [12]. Bond graphs are used to develop models of the interrelationships between water and energy. When combined into an input-output model, it is possible to connect the dots between a region's energy and water consumption to the required water withdrawals. The set of algebraic equations developed can assist with integrated water and energy planning. While the methodology described in Section 3.1 does not consider all of the interrelationships between water and energy systems, it does describe a resource accounting analysis that can be used as inputs in a systems modeling approach to the energy-water nexus.

Cai et al. [8] perform a scenario analysis in order to evaluated water withdrawals for energy production from 2011 to 2030 based on energy strategy scenarios. The amount of water used for extraction, processing, and conversion of primary energy was used to estimate changes in water withdrawals and energy production for different scenarios. The results of the analysis have policy implications, as it was concluded that the projections of water withdrawal for energy production would aggravate China's water scarcity risk. Similarly, the scenario analysis results outlined in Chapter 3 have implications on statewide water and energy planning and management.

The methodology described in Chapter 3 is a unique method to quantify water withdrawal and consumption demands for thermoelectric power plants. The scenario analysis serves as a base case for potential shifts in water and energy planning. The results gathered by performing the methodology described could be used directly by water and energy policy makers, or as inputs to water and energy systems analysis models such as the model developed by Lubega & Farid [12].

CHAPTER 3

SCENARIO ANALYSIS OF WATER REQUIREMENTS FOR THERMOELECTRIC POWER GENERATION

3.1 Methodology

A further study of the energy-water nexus is presented, integrating baseline resource accounting and scenario and economic analyses, illustrated in the state of Illinois. Illinois, a net electricity exporter, was used as a test bed for this analysis because the state generates the majority of its electricity from coal-fired and nuclear plants, both highly water-intensive electricity fuels, as discussed in Chapter 2. While coal and nuclear plants represent only 61% of the statewide capacity, they were responsible for generating over 94% of the statewide electricity in 2012 [23]. The majority of these coal-fired and nuclear power plants in Illinois utilize open-loop cooling, representing a high demand on water resources within the state. The general approach presented here is highly transferable and applicable in other areas with sufficient data and significant overlap in energy and water resources.

3.1.1 Baseline

The Energy Information Administration (EIA) provides monthly water withdrawal and consumption values for electricity generators within the United States. The analysis uses self-reported data values to determine a baseline for power plant water withdrawal and consumption rates in Illinois [23]. However, it was observed that a variety of gaps and inconsistencies exist within the reported data. For instance, consumption rates were not reported for many power plants, and several power plants reported electricity generation and listed a cooling system type, yet no cooling rates were provided. Furthermore, some power plants failed to report any cooling system or cooling rates. These data gaps were identified and filled using best estimates according to literature rates based on empirical data [15]. Each electricity generator was individually analyzed and evaluated to determine water requirements, with withdrawal and consumption values estimated based on literature rates where data were absent. These literature rates were based on the fuel type, cooling technology, and annual generation of each power plant, as reported in Macknick et al. [15] to estimate water withdrawal and consumption with quantified uncertainty.

Thermoelectric power plants with a total steam capacity greater than or equal to 100 MW are required to report monthly cooling data [34]. To evaluate the most representative sample, several plants were identified that were below the capacity threshold and were included in the analysis. Since cooling types were not reported for these utilities, satelilite imagery was used to estimate a cooling system type, with once-through cooling assumed as a conservative default. Cogeneration plants below 100 MW were excluded from the analysis due to lack of data availability on the cooling operations of these plants. Furthermore, utilities with a primary fuel type of solar, wind, distillate fuel oil, hydroelectric, and landfill gas were excluded from the analysis as these fuels do not require cooling water.

The individual evaluation of each electricity generator in Illinois resulted in 28 power plants being included in the analysis (see table of power plants in Appendix); however, only 12 of these power plants (all using closed-loop cooling) reported water consumption values. Note that 206 generators operate in Illinois, but many were excluded due to lack of cooling operations, as mentioned. Based on literature [20], once-through cooling operations consume approximately 1% of the amount of water withdrawn through enhanced evaporation downstream. Given the extremely high intake rates associated with open-loop systems, water consumption rates can be non-negligible. In the baseline analysis, literature rates were used to approximate the consumption for the 16 power plants that did not report any consumption.

Lastly, many power plants reported multiple cooling systems in their monthly data, such that data categorization was ambiguous. Therefore, withdrawal and consumption rates were calculated for each cooling system, compared to reported literature, and the cooling system was re-categorized according to the closest match, when appropriate. In many cases, power plants reported as recirculating cooling with cooling ponds were recategorized as once-through cooling systems based on withdrawal rates for two reasons: 1) pond-cooled systems can be operated similarly to closed-loop systems, open-loop systems, or a hybrid of these systems [34], and 2) U.S. Environmental Protection Agency regulations focus on withdrawal rates due to impingement and entrainment concerns [28].

3.1.2 Scenario Analysis

After the withdrawal and consumption rates were estimated for each power plant, two potential future cases were evaluated based on their water implications: 1) a fuel shift from coal to natural gas (Case 1), and 2) a cooling technology shift from open-loop to closed-loop cooling (Case 2).

For Case 1, all 18 coal-fired power plants in the analysis were modeled to use natural gas. Similarly to the method used to fill in data gaps in the baseline analysis, a fuel shift was estimated to have withdrawal and consumption rates based on natural gas power plants as reported in literature [15]. Case 1 is interesting and pertinent because natural gas is operationally less water intensive since natural gas combined-cycle power plants utilize both a gas turbine and a steam turbine, resulting in a lower demand for cooling water per unit generation. Furthermore, there is evidence supporting a shift from coal to natural gas in the United States due to market economics, a recent increase in hydraulic fracturing, and environmental factors, among others [35]. High penetration of renewable energy is predicted to reduce water requirements as well [36]; however, the analysis focuses on natural gas as a viable and robust transition fuel.

In Case 2, a shift in cooling system technology from open-loop to closed-loop cooling was simulated. The Case 2 scenario represents another approach to reducing electricity-related water withdrawals as closed-loop cooling systems require vastly less water withdrawals than open-loop cooling, with the tradeoff of increasing water consumption. Despite the increase in water consumption, the shift from open-loop to closed-loop technology could be beneficial [37]. As mentioned previously, closed-loop cooling systems can significantly reduce the environmental damages in the form of decreased rates of impingement, entrainment, and thermal pollution. For Case 2, the retrofit of the 22 power plants in the analysis currently utilizing open-loop cooling to use closed-loop cooling was modeled. The analysis models this retrofit with cooling towers as the likeliest scenario, using best estimates from literature to approximate closed-loop withdrawal and consumption rates [15]. In the Case 2 scenario, the water withdrawal and consumption tradeoffs associated with alternative cooling were quantified, as introduced in literature [21, 38]

3.1.3 Economic Analysis

Expanding on Case 2, an economic analysis was performed to approximate the cost of retrofitting all 22 open-loop plants in the analysis to closed-loop cooling towers. The cost to retrofit was directly compared to the associated water savings to investigate whether the water cost savings alone would motivate a cooling technology shift.

The total annual cooling cost (C_a, US\$/yr) was calculated as the sum of the annualized capital cost and the annual operations and maintenance costs:

$$C_a = \underbrace{\left[\frac{i(1+i)^t}{(1+i)^t - 1}\right] C_c N}_{\text{Annualized Capital Cost}} + \underbrace{C_{O\&M} G}_{\text{Annual O\&M Cost}} \tag{3.1}$$

where i is the annual interest rate, t is the cooling system expected lifetime (yr), C_c is the capital cost of a retrofit (US\$/megawatt-electric(MW$_e$)), N is the nameplate capacity of the power plant (MW$_e$), $C_{O\&M}$ is the annual operations and maintenance cost (US\$/MWh) and G is the annual generation of the power plant (MWh/yr).

High and low capital costs to retrofit (C_c) were estimated using cost factors as reported in Stillwell & Webber [32]. The factors used were on a U.S. dollar per MW$_e$ of plant capacity basis, which were multiplied by the capacity of each power plant (N) to estimate a total cost to retrofit. The total capital cost to retrofit was annualized by assuming an expected lifetime (t) of 30 years at an annual interest rate (i) of 5 %. The annual operations and maintenance cost ($C_{O\&M}$) was assumed to be \$2.36/MWh, as reported in Stillwell & Webber [32].

The annual cooling cost (C_a) was divided by the average annual water saved by retrofitting to determine an effective "water price." This "water price" represents the minimum price at which water would be purchased, or conversely, at which it could be sold in a functioning water market, necessary to motivate a retrofit based solely upon water cost savings.

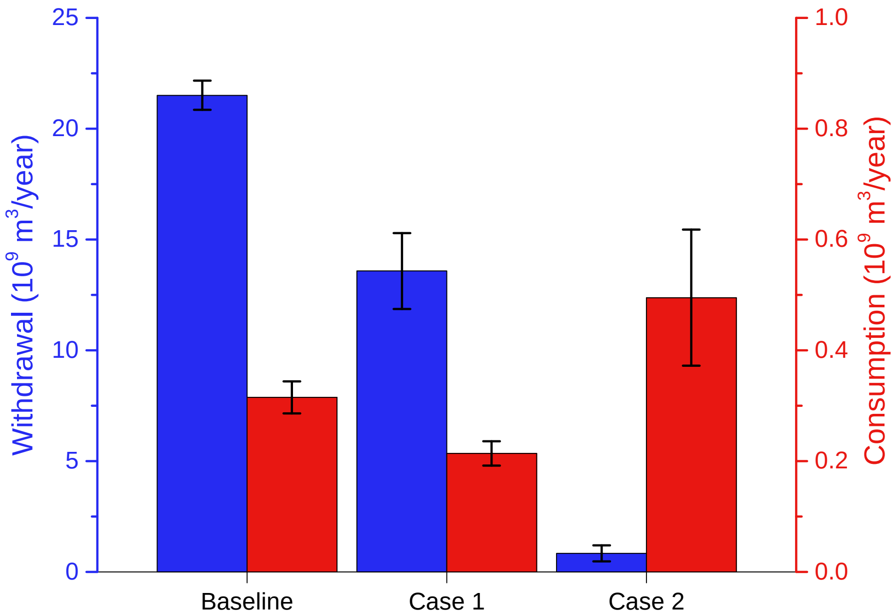

Figure 3.1: The scenario analysis results show that water withdrawals and consumption can be reduced by shifting from coal to natural gas (Case 1). The cooling technology shift from open-loop to closed-loop cooling (Case 2) reduces water withdrawals compared to the baseline with the tradeoff of increasing consumption for power generation in Illinois.

3.2 Results

The results show that water withdrawals can be conserved in both scenarios analyzed (Cases 1 and 2), as illustrated in Figure 3.1. The blue bars represent the total annual water withdrawal for all 28 thermoelectric power plants included in the analysis, while the red bars represent the total annual water consumption. Where cooling rates were not reported, minimum and maximum rates from Macknick et al. were used to fill these data gaps [15], with the error bars representing these maximum and minimum rates. That is, the error bars reflect the uncertainty in the empirical rates from literature, and do not include uncertainty in the self-reported cooling data.

As a baseline, the results suggest that thermoelectric power plants in Illinois withdraw between 20.8 and 22.2 billion m^3/yr, and consume between 287 and 345 million m^3/yr for power generation (see baseline case in Figure

3.1). These water withdrawal values of 20.8-22.2 billion m^3/yr based on EIA data are reasonably consistent (although notably higher) with U.S. Geological Survey withdrawal values for thermoelectric power generation in Illinois at 14.8 billion m^3/yr [16].

The scenario analysis results demonstrate that a shift from coal-generated to natural gas-generated electricity could decrease statewide water consumption and withdrawal by 100 million m^3/yr (32% decrease) and 7.9 billion m^3/yr (37% decrease), respectively, on average. These water withdrawal and consumption savings only represent decreased water demands at the power plant, not the entire fuel lifecycle. Notably, if natural gas came from a hydraulic fracturing operation, more water would be associated with fuel mining compared to traditional natural gas [39]; however, Grubert et al. [40] showed a coal to natural gas shift could still reduce overall water consumption, even when accounting for natural gas from hydraulic fracturing. Furthermore, the results demonstrate that a shift from open-loop to closed-loop cooling technologies could decrease withdrawals by an average of 21 billion m^3/yr (96 percent decrease), with the tradeoff of increasing statewide water consumption for power generation by 180 million m^3/yr (58 percent increase). The scenario analysis results are shown in Cases 1 and 2 in Figure 3.1.

Geographic information systems (GIS) was used to display the annual water withdrawal and consumption rates for power generation in the state of Illinois (see Figure 3.2). Each data point on the maps represents a thermoelectric power plant, while the size of the point represents the relative water rates (withdrawal in blue, consumption in red). The baseline case along with the two cases from the scenario analysis are plotted against each other in order to easily compare changes in water requirements from case to case. For example, the southernmost power plant in Figure 3.2 (Joppa Generating Station, 1100-MW coal power plant) illustrates that both the withdrawal and consumption decrease from the baseline to Case 1, indicating decreasing water requirements from a fuel shift from coal to natural gas. Furthermore, the power plant currently uses open-loop cooling, such that withdrawal dramatically decreases while the consumption slightly increases in Case 2, compared to the baseline. The six Illinois nuclear power plants are shown as larger data points (due to their high generation) that do not decrease in withdrawal from the baseline to Case 1. The water withdrawal rates for those six nuclear plants in Illinois represent open-loop cooling operations, meaning a reduction in withdrawals from these large plants can only be observed via a shift in cooling technology (Case 2).

The results of the economic analysis, shown in Table 3.1, indicate an up-front capital investment of \$3.4 and \$14 billion is needed to retrofit all 22 open-loop plants in the analysis to closed-loop cooling. When considering operation and maintenance costs, the total annual cooling cost (C_a) would be between \$0.58 and \$1.3 billion per year using Equation 3.1. Given that a statewide conversion to closed-loop cooling would save 20.7 billion m^3 of water withdrawn per year, the price of water necessary to motivate a retrofit would be between \$0.17 and \$0.68/m^3 (see Table 3.1 for a summary of the economic results), which is comparable to current U.S. drinking water rates [41].

Table 3.1: The economic results show that the price of water necessary to motivate a retrofit would be between \$0.17 and \$0.68 per m^3.

Ecomomic consideration	Value
Number of open-loop cooled power plants	22
Total capacity of power plants (MW)	24,800
Capital cost investment (10^9 US\$)	\$3.4–\$14
O&M cost investment (10^9 US\$/yr)	\$0.36
Total annual cost investment (10^9 US\$/yr)	\$0.58–\$1.3
Volume of annual water withdrawals conserved (10^9 m^3)	21
Equivalent cost of water (US\$/m^3)	\$0.17–\$0.68

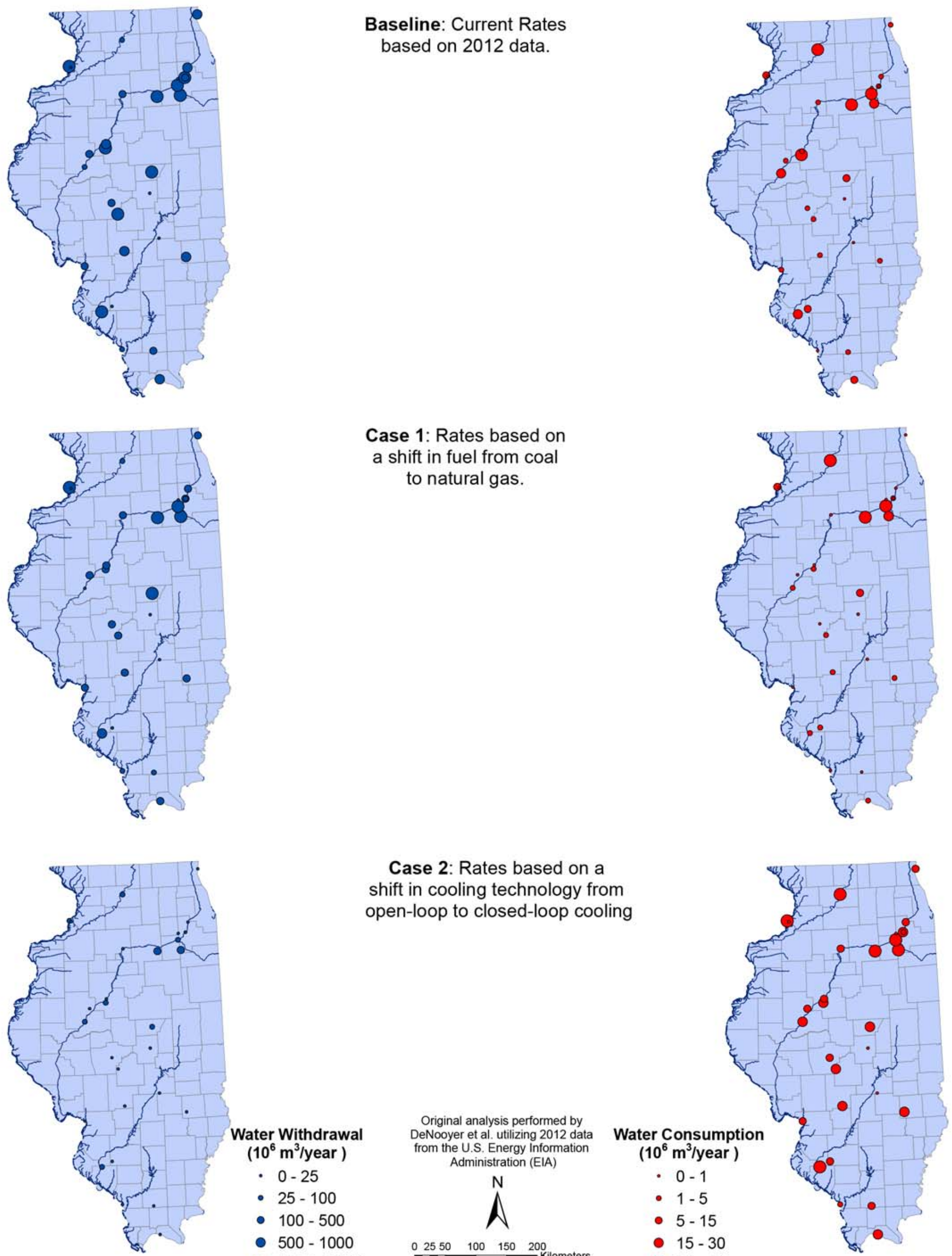

Figure 3.2: Withdrawal and consumption rates vary over different scenarios. Data points represent thermoelectric power plants, while the size of the point represents the relative water requirements.

CHAPTER 4

POLICY IMPLICATIONS

The results of the baseline and scenario analyses presented in Chapter 3 confirm that power plants in Illinois represent a high demand on water resources within the state, representing over 80% of total water withdrawals [16]. Furthermore, the scenario analysis shows that water withdrawals can be reduced both in a shift in fuel from coal to natural gas and a shift in cooling technology from open- to closed-loop cooling.

Given recent economic conditions in the United States, a shift from coal to natural gas is occurring based on market economics. This trend is projected to continue based on the EPA's proposed Clean Power Plan in which states are urged to reduce carbon pollution from power plants. Since natural gas is considered a "cleaner" fuel and emits less greenhouse gases than coal, a shift in fuel could partially fulfill federal plans to cut emissions. Evidence of this shift can be seen in Illinois as NRG Energy Inc. is planning to convert a coal-fired power plant in Joliet to generate electricity via natural gas [42].

While market economics are currently motivating a shift in fuel from coal to natural gas, a shift in cooling technology from open- to closed-loop cooling is not currently motivated by economics [29], as was quantified in the economic analysis in Section 3.1.3. In the majority of cases, the cost to retrofit open-loop power plants to cooling towers outweighs the direct environmental and water saving benefits. Therefore, in order to experience a shift from open-loop to closed-loop cooling, policy would most likely be the driver, using the Clean Water Act, Article 316(b).

4.1 History of Article 316(b)

The Federal Water Pollution Control Act Amendments (Clean Water Act) were enacted in 1972, and further amended in 1977. These amendments seek to "restore and maintain the chemical, physical, and biological integrity of the nation's waters [43]." Article 316(a) governs the thermal pollution of point sources. Section 316(b) states, "Any standard established pursuant to section 301 or section 306 of this Act and applicable to a point source shall require that the location, design, construction, and capacity of cooing water intake structures reflect the best technology available (BTA) for minimizing adverse environmental impact [43]." The EPA is the authority responsible for implementing Article 316(b), which they implement through the issuing of National Pollutant Discharge Elimination System (NPDES) permits. Most states assumed the responsibility for implementing an approved permitting program. Article 316(b) is the only federal law specifically regulating cooling water intake structures, yet the language used in 1972 tends to be vague when considering implementation and enforcement. Enforcement of the rule requires a continuously evolving definition of "best technology available." Therefore, the EPA has traversed through numerous amendments and clarifications to the rule since the enactment.

In 1976, EPA published a final rule implementing Section 316(b) based on BTA; however, the rule was remanded in 1977 by the Court of Appeals for the Fourth Circuit as a result of utilities challenging the ruling. The Court of Appeals cited failure to comply with the Administrative Procedures Act by not properly publicizing the rule's supporting documentation, despite the EPA's publication of a draft guidance report entitled, *Guidance Document for Evaluating the Adverse Impact of Cooling Water Intake Structures of the Aquatic Environment* [44]. This report details the adverse environmental effects caused by cooling water intake structures, including impact assessment and monitoring program details. This document served as the basis for implementation of Section 316(b) for the next 22 years until 1999, by regional and state permitting authorities. Compliance with this rule varied from state to state during this time, with many authorities choosing to implement the federal regulations based on site-specific circumstances.

In 1993, Hudson Riverkeeper led a group of environmental organizations in suing the EPA, claiming the EPA failed to implement article 316(b), therefore creating an inconsistent application of the CWA. EPA agreed to issue rules to implement the regulation, and the rules would follow a three-phase rulemaking procedure.

Issued in 2001, Phase I of the new rules outlined a best technology available approach for new facilities [45]. The final rule establishes national technology-based performance requirements applicable to the location, design, construction, and capacity of cooling water intake structures at new facilities [46]. New facilities affected by Phase I were those with a design intake flow of greater than 2 MGD (7,570.8 m^3/day) and that use at least 25% of water withdrawn for cooling purposes. Facilities can comply in two ways: 1) restrict the facility's intake flow to a level similar to a closed-loop system, limiting the intake velocity to 0.5 ft/s (0.152 m/s), or 2) demonstrate achieving impingement and entrainment reductions comparable to closed-loop cooling technologies by using other technologies or restoration. Phase I was subsequently challenged by industry groups (highlighted by Hudson Riverkeeper), but was upheld by the Court of Appeals with one exception: restoration was deemed incompatible with the intent of the CWA because it mitigated adverse environmental effects as opposed to minimizing them in the first place [47].

Issued in 2004, Phase II of the new rules outlined a BTA approach for existing facilities [48]. The rule applied to "large" facilities with a cooling intake of 50 MGD or greater. Performance standards were established for impingement and entrainment reductions over a hypothetical baseline value, requiring 80 to 90 percent reduction in impingement mortality and 60 to 90 percent reduction in entrainment. The baseline value is assumed to be equal to that of a hypothetical once-through cooling system with a standard 3/8-inch mesh water screen, but no further controls for minimizing impingement and entrainment [48]. Affected facilities could demonstrate compliance by following one of five alternatives [49]:

1. Demonstrate the facility has already reduced its flow commensurate with a closed-cycle recirculating system, or that it has reduced its design intake velocity to 0.5 ft/s or less.

2. Demonstrate that the existing cooling water intake structure configuration, operational measures, and/or restoration measures meet the performance standards set forth by the regulations.

3. Demonstrate that the facility has installed and properly implemented selected cooling water intake structure configurations, operational measures, and/or restoration measures that will, in combination with any

existing design, meet the performance standards set forth by the regulations.

4. Demonstrate that the facility installed and operates an approved cooling technology.

5. Demonstrate that the cost of compliance would be significantly greater than the costs considered by the EPA for a similar facility to meet the performance standards, or that the compliance costs would be significantly greater than the benefits of meeting the performance standards. Thus, a site-specific determination of BTA would be appropriate, where the design approaches performance levels that are as close as practicable to the performance standards set forth by the regulations without resulting in significantly greater costs.

In summary, an existing Phase II facility would need to demonstrate environmental damages similar to that of closed-loop cooling, or demonstrate that a site-specific determination of BTA is appropriate through the use of a cost-cost or cost-benefit test [47].

Similarly to Phase I, the EPA was sued over the regulations set forth in Phase II by industry and environmental petitioners (highlighted again by Hudson Riverkeeper); however, several key components were remanded. First, the Court of Appeals for the Second Circuit found that the BTA determination was inconsistent, stating that the EPA had improperly used a cost-benefit methodology to support the final BTA analysis. It was determined that cost may be used as a consideration, but not the principal basis, for determining the BTA. Secondly, the court disagreed with the EPA using ranges for performance standards (80 to 90 percent reduction in impingement mortality 60 to 90 percent reduction in entrainment). The EPA concluded that the ranges were necessary to consider variable technology performances. The court noted that by omitting a single numeric standard and not including a requirement for the facility to maximize the performance of the technology, the rule could incentivize facilities to only meet the lower end of the standards. Lastly, the EPA again included restoration as an option to comply, and again it was rejected as incompatible with the CWA [47]. Even though the court did not remand the rule in its entirety, Phase II was suspended by the EPA in July, 2007 [50].

Despite the suspension of Phase II, Phase III was issued by the EPA on June 1, 2006. Phase III establishes categorical requirements for new offshore oil and gas extraction facilitates that have a design intake flow threshold of greater than 2 MGD and that withdraw at least 25% of the water exclusively for cooling purposes [46]. Facilities affected by this ruling must comply with similar standards to those outlined in Phase I [45].

In November 2010, the EPA signed a settlement agreement with Hudson Riverkeeper promising to propose new standards for existing Phase II facilities. The agreement was for EPA to propose these standards by March 14, 2011; however, the agreement was modified five separate times, each time extending the date for the final rule. The EPA signed a final ruling on the Phase II power plants on May 19, 2014 [28]. The details of this final ruling are discussed in Section 4.2.

4.2 Policy implications of final ruling for existing power plants

The final ruling for existing facilities provides further regulation for facilities to determine the "best technology available." Implemented through the NPDES permitting system, "the regulations apply to the location, design, construction, and capacity of cooling water intake structures at regulated facilities and provide requirements that reflect the best technology available for minimizing adverse environmental impact [28]." Facilities subject to the regulations are those with a design intake flow greater than 2 MGD. If a facility requires an NPDES permit, but the design intake flow of the cooling system is less than the 2 MGD threshold, the permit is subject to permit conditions developed by the NPDES Permit Director on a case-by-case basis using best professional judgment.

Furthermore, EPA concluded that the best technology available for minimizing impingement mortality was "modified traveling screens." The impingement mortality reductions that the modified traveling screens provide serves as the basis for determining whether the cooling system is in compliance with the regulations. The EPA also identified four technologies (closed-loop recirculating systems, reduced design intake velocity, reduced actual intake velocity, and existing offshore velocity caps) that reduce impingement mortality at the same level as or better than modified traveling screens. Therefore, in general, closed-loop systems will comply with the BTA Impingement Mortality Standard. The final ruling also gives power to the NPDES Permit Director to require additional measures to protect against impingement if it is determined that modified traveling screens are insufficient.

While the EPA recognizes retrofitting to closed-loop cooling as an option for compliance, the EPA does not intend for facilities to install closed-loop cooling technologies solely for the purpose of meeting the impingement requirements. In fact, the EPA expects that all facilities could comply with the requirements without having to retrofit. Considering the extremely high costs for power plants to retrofit to closed-loop cooling, power plants may choose to comply with impingement standards without retrofitting. Facilities are given the option to demonstrate compliance through other innovative measures by performing a two-year study which includes collecting biological data to make site-specific adjustments to screens or combinations of technologies. Facilities that choose this route for compliance are required to conduct periodic monitoring to demonstrate that the performance is as good as, or better than, the standards set by the EPA.

On the other hand, EPA could not identify one technology as the national BTA for entrainment for existing facilities. When looking at a number of factors, closed-loop cooling was determined as the only high performing technology candidate for BTA for entrainment. Other technologies exist which have the potential to reduce entrainment to the BTA standard; however, these technologies are not uniformly high performing and are often dependent on site-specific factors. Nevertheless, EPA does not mandate closed-loop cooling as the basis for BTA for entrainment. Instead, the EPA established a detailed framework for the permitting authority to determine BTA on a site-specific basis based on the following key elements: land availability, air emissions, and remaining useful plant life [28].

4.3 Implications of final ruling on water requirements for power generation

Decreasing the reliance of the electricity sector on water resources is an important piece for managing the intricate relationships between energy and water. As illustrated in the baseline analysis results (Section 3.2), thermoelectric power plant cooling in Illinois represents a significant demand on water resources within the state. This analysis could be applied to other states to get a more accurate picture of energy's demand on water resources. Gaining a better understanding of the energy-water nexus on local, statewide and national scales is the first step to efficiently managing these constrained resources.

Future resources management can utilize policy levers which promote efficient use of water and energy. As shown in the Case 1 scenario analysis in Chapter 3, water withdrawal and consumption rates from thermoelectric power plant cooling can be decreased by shifting from coal to natural gas generated electricity. Furthermore, there is evidence that this shift is occurring as a result of policy and current economics. Water withdrawals can also be greatly decreased through a shift in cooling technology from open-loop to closed loop, with the tradeoff of increasing water consumption (Case 2). However, given high retrofit costs, this shift is not currently motivated by economics.

Thus, for a shift in cooling technology to occur, policy will most likely be the driver. The Clean Water Act Article 316(b) is the current policy which governs the intake structures for power plant cooling systems. If a national shift from open- to closed-loop cooling at existing power plants were to occur, Article 316(b) would be the likeliest platform for promoting this shift through a closed-loop cooling mandate. However, as the regulations are currently stated, the EPA leaves implementation and interpretation of the BTA for minimizing impingement and entrainment up to state permitting authorities.

CHAPTER 5

FUTURE WORK

As global climate change is projected to increase the frequency and severity of droughts in the United States [17], power plants may be become increasingly vulnerable due to their significant demand on water resources for cooling. Droughts and heat waves can pose risks to power plants by increasing the temperature of the intake water, and decreasing the water availability. Increased intake water temperatures might make it more difficult for power plants to remove enough heat in the condenser to remain below the maximum discharge temperature thresholds set by the EPA. Decreased water availability might increase the competition for water with other high-value water users, potentially limiting the amount of water available for cooling operations. Increased water temperatures and lower water levels can put power plants at risk of derating. Furthermore, the effects of drought and heat waves can reduce the power plant's efficiency in two ways: 1) reduced heat transfer rates in the condenser, or 2) increased pumping rates, applying a larger parasitic load to the power plant due to the additional electricity required to run the water pumps. Recent droughts and heat waves have exposed the vulnerability of some power plants. In 2012, many parts of Illinois experienced an extreme drought, forcing multiple power plants to request temporary permission to discharge cooling water at temperatures higher than permitted by the EPA [51]. Furthermore, the drought in 2012 resulted in the water levels of the Illinois and Kankakee Rivers dropping to flows below the withdrawal limits of some power plants [52].

Illinois power plants' recent vulnerability to the effects of drought and heat waves in 2012 motivates a further research question for future work: *How will future drought and heat waves affect power plant operations?* The future analysis will be applied to 10 power plants along the Illinois River. The methodology expands on an analysis performed by Cook et al [53]. In the analysis, Cook et al. develop a methodology for creating a multiple linear regression model of average monthly intake temperatures for power plants in the Upper Mississippi River Basin. The model considers monthly ambient air temperatures, wind speeds, historical intake temperatures, and historical effluent temperatures. Using energy balance equations in a thermodynamic model, the change in cooling water temperature at the plant was calculated. When used in tandem, the regression and thermodynamic models determine the effluent temperature of 43 power plants in the study area between the years 2010-2012. The models estimated the intake temperature within 2.2 °C, and the effluent temperature within 5.0 °C of the reported values.

The future work analysis will use the methodology from Cook et al. [53] to estimate the intake and effluent temperatures for 10 power plants along the Illinois River from the years 2010-2013 using a multiple linear regression model. The energy balance equations will be used to determine the change in cooling water flow as a function of inlet temperature. From there, various drought/heat wave scenarios will be applied to the model to predict how power plant operations would change with increased inlet temperatures and decreased intake rates. A power plant would be determined to be at risk of derating if the estimated effluent temperatures are higher than the maximum allowable effluent temperatures permitted through the NPDES permits. Additionally, it will be determined through energy balance equations how much each plant would be required to derate as a result of increased water temperatures.

CHAPTER 6

CONCLUSION

Given the current water requirements for thermoelectric power generation in the United States, primary fuel and cooling system alternatives for power generation can have a significant impact on the energy-water nexus. Illinois was an interesting test-bed for the analysis because Illinois depends on power from many older power plants currently using open-loop cooling, and the majority of the electricity generated within the state is from nuclear and coal power plants, both highly water-intensive fuel sources. However, the same methodology could be expanded to other states within the United States, or elsewhere. For instance, the methodology could be applied to western states where, historically, water availability is further constrained.

This research analysis was motivated by three main research questions, with the following findings:

- *What is the current relationship between water resources and thermoelectric power plants in Illinois?* The baseline analysis showed that power plants in Illinois represent a substantial demand on water resources within the state, corresponding to a significant branch of the energy-water nexus.

- *How might that relationship change with different fuel and/or cooling technology shifts?* A shift from coal-generated to natural gas-generated electricity (Case 1) could decrease statewide water consumption by 100 million m^3/yr (32%) and withdrawal by 7.9 billion m^3/yr (37%), on average. A shift from open-loop to closed-loop cooling technologies (Case 2) could decrease withdrawals by an average of 21 billion m^3/yr (96%), with the tradeoff of increasing statewide water consumption for power generation by 180 million m^3/yr (58%).

- *What economic or policy levers reduce strain on the energy-water nexus?* While there is evidence that Case 1 is happening given current market prices, policy would likely be the driver for Case 2. The economic analysis revealed that a shift in cooling technology from open-loop to closed-loop cooling is not currently motivated by water cost savings, given current water prices. The current policy which governs power plant cooling systems is the Clean Water Act Article 316(b), which relies on the best technology available for cooling systems, amidst rule changes.

Continuing strain on both energy and water resources is evident in generation of electric power. As described in this analysis, the electric power sector can serve as a suitable area for mitigating water resource challenges. Scenario analyses integrating water resources and power generation can help guide sustainable resources management and planning.

APPENDIX A

DATABASE OF WATER REQUIREMENTS FOR ILLINOIS THERMOELECTRIC POWER PLANTS

Table A.1: Database of water requirements for Illinois thermoelectric power plants [15, 23].

Power Plant	Primary Fuel	Capacity MW	Generation GWh/yr	Baseline Withdrawal [10^6 m^3/yr]	Baseline Consumption [10^6 m^3/yr]	Case 1 Withdrawal [10^6 m^3/yr]	Case 1 Consumption [10^6 m^3/yr]	Case 2 Withdrawal [10^6 m^3/yr]	Case 2 Consumption [10^6 m^3/yr]
Archer Daniels Midland Decatur	Coal	1,118	335	0.7	0.2	0.9	0.9	0.7	0.2
Baldwin Energy Complex	Coal	12,286	1,894.1	1,555.7	24.3	639.5	2.8	39.5	36.7
Braidwood Generation Station	Nuclear	18,806	2,354	2,560	29.1	2,560.6	29.1	121.0	50.8
Byron Generating Station	Nuclear	18,318	2,346.0	73.9	47.9	73.9	47.9	73.9	47.9
Clinton Power Station	Nuclear	9,374	1078.0	1107.0	9.0	1107.0	9.0	60.3	25.3
Coffeen	Coal	5,060	1,005.4	559.2	4.0	263.4	1.1	16.3	15.1
Cordova Energy	Natural Gas	5	611.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dallman	Coal	1,954	667.7	314.4	4.1	101.7	0.4	6.3	5.8
Dresden Generating Station	Nuclear	14,802	1,750.0	1,989.6	33.5	1,989.6	33.5	95.3	40.0
Duck Creek	Coal	2,818	441.0	373.4	2.2	146.7	0.6	9.1	8.4
E D Edwards	Coal	4,402	780.3	508.8	3.5	229.1	1.0	14.2	13.2
Grand Tower	Natural Gas	1,236	647.3	64.3	0.3	64.3	0.3	1.0	1.0
Havana	Coal	2,698	488.0	27.0	16.8	2.2	2.2	27.0	16.8
Hennepin Power Station	Coal	2,145	306.3	363.1	1.7	111.6	0.5	6.9	6.4
Holland Energy Facility	Natural Gas	1,022	702.1	1.0	0.8	1.0	0.8	1.0	0.8
Joliet 29	Coal	5,137	1,320.0	1,320.1	4.1	267.4	1.2	16.5	15.4
Joliet 9	Coal	907	360.4	362.7	0.7	47.2	0.2	2.9	2.7
Joppa Steam	Coal	6,489	1,099.8	859.7	5.1	337.8	1.5	20.9	19.4
Kendall County Generation Facility	Natural Gas	4,981	1256.0	0.3	0.3	0.3	0.3	0.3	0.3
Kincaid Generation LLC	Coal	5,143	1319.0	1057.7	4.1	267.7	1.2	16.5	15.4
LaSalle Generating Station	Nuclear	19,595	2,313.0	2,504.0	56.6	2504.0	56.6	126.1	52.9
Marion	Coal	1,740	422.0	230.5	1.4	90.5	0.4	5.6	5.2
Newton	Coal	5,521	1,234.8	686.0	4.4	287.4	1.3	17.8	16.5
Powerton	Coal	8,167	1,785.6	1,514.7	31.9	425.1	1.9	26.3	24.4
Prarie State Generating Station	Coal	3,264	1,766.0	8.4	7.8	2.7	2.7	8.4	7.8
Quad Cities Generating Station	Nuclear	15,506	1,819.0	1,574.3	14.7	1,574.3	14.7	99.8	41.9
Waukegan	Coal	3,315	793.7	684.7	2.6	172.5	0.8	10.7	9.9
Will County	Coal	3,240	897.6	838.7	2.6	168.7	0.7	10.4	9.7
Wood River	Coal	2,745	500.1	365.1	2.2	142.9	0.6	8.8	8.2
Total	-	181,831	32,293.4	21,505.4	315.5	13579.9	214.0	843.5	498.0

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