Energy, Water Use, and Drought

An Examination of the Cooling Systems Used by Natural Gas Power Plants

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Abstract

This paper seeks to understand the factors that go into the decision that a power plant makes when choosing a cooling system, as well as the adaptations that power plants make under drought conditions. I use a multinomial logit regression model to demonstrate that water use and drought conditions are important factors that plants consider in their cooling system choice. Additionally, I use a fixed effect panel data regression model to show that during droughts, power plants with water-intensive cooling systems are likely to generate a lower proportion of total energy demand than plants that use less water for cooling. The conclusions of this study indicate that as climate change continues to cause more drought throughout the US, plants will likely choose to implement cooling systems with lower water use.

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I. Introduction

In August of 2012, Chicago was home to intense heat and drought, forcing all water consumers in the city to diminish their use of water. This had an especially serious impact on the energy industry, the sector with the greatest water use across the US. Power plants use water to cool their generating equipment, which is a necessary portion of the energy generating process. Due to statewide regulations from the Illinois Envieronmental Protection Agency, plants must allow their discharge water to cool to a maximum of 90 degrees before returning to the river. Because of the higher temperatures, however, the IEPA feared that plants would be unable to continue generating electricity as the water would be unable to cool enough after cooling the plant's equipment. This would cause power plants to scale back production, to the point that brownouts would be a risk throughout the state. To this effect, the IEPA issued special exceptions to four coal-fired plants and four nuclear plants, allowing them to discharge up to 97 degree water into the rivers. Plants were able to maintain generation levels, at the expense of increasing risk to the ecosystems present in rivers and lakes (Meyers, 2012).

This case raises an interesting question: how do power plants plan for droughts that may occur during their operations? The purpose of this study is to investigate the rationale behind some of the decisions that power plants make, related to drought conditions. Specifically, our interest is in the choice of cooling systems that power plants employ to cool their water. There are a number of factors that vary across cooling systems and may make the difference in the final decisions that these firms make. One of these, water use, is the main variable of interest throughout this study. Therefore, we seek to understand the relationship between the water use of various cooling systems and the choice of cooling system that a power plant makes.

This relationship has become particularly relevant in the last several years, as droughts have become more frequent throughout the US as a result of climate change (Intergovernmental Panel on Climate Change, 2007). Droughts decrease the supply of water available to power plants for cooling, resulting in the scaling back of production for power plants with water intensive cooling systems, as seen in the 2012 case in Chicago. This causes firms to lose revenue and for costs to rise for consumers.

Van Vliet et al (2012) analyzed the specific effects that drought may have on electricity supply, accounting for climate change in their analysis. The researchers modeled the daily river flow and water temperature projections for Europe and the US over the course of the 21st century. The model produced daily simulations for the river flow and water temperatures based on two of the Intergovernmental Panel on Climate Change's scenarios in its Special Report on Emissions Scenarios (IPCC, 2000). These simulations describe possible outcomes over the next century for America as climate change continues, under the scenarios presented by the IPCC.

Based on their simulations, van Vliet et al find that it will become increasingly likely that flows will be below a certain threshold as climate change continues. Specifically, the authors estimate a 4-12% decrease in low flows in the US by the 2040s, with a 15-19% decrease by the 2080s. Additionally, an average water temperature increase is estimated to be 0.7-0.9°C by the 2040s and 1.4-2.4°C by the 2080s.

These findings are largely the basis for our research; if it is likely that the usable summer capacity for thermoelectric generating plants will diminish significantly, what role will this play in the determination of which cooling systems to use at the plants? In this sense, our study analyzes the economics of van Vliet et al's research. We will investigate how the situation changes when allowing power plants to adapt to new drought conditions, by determining the factors that go into a power plant's choice of cooling system.

II. Industry Background

Before discussing the water use associated with energy generation, it is important to understand the basics of how electricity is generated in thermoelectric plants.[3] These plants generate heat, often by combustion of a fossil fuel such as coal or natural gas, in order to convert water into steam. This steam then spins a turbine, which drives an electrical generator to produce electricity. The steam is then condensed and returned to the heat source to go through the process once again. All of this water is in a closed system, and requires very little additional water to make up for losses. The primary use of water is in the condensation process, when external water is required in order to cool the steam in the closed system so that it begin the process once again. *Cooling systems*, then, are the systems put in place to facilitate the condensation process. Our interest throughout this study is in how power plants make the decision of which cooling system to utilize (US Energy Information Administration, 2014).

While there are many types of thermoelectric power plants, in this study, we will narrow our focus to only natural gas power plants. These plants use the combustion of natural gas as their heat source for converting water into steam. By limiting the fuel types of power plants that we consider, we simplify the choice of cooling systems, which will allow us to make more meaningful observations about the factors that go into a plant's decision.

There are four major types of cooling systems that natural gas power generators use: once-through, recirculating, dry, and hybrid cooling systems (Natural Resources Defense Council, 2014). We will view each separately, from the perspective of how it works, the cost associated with building the system, and the water use required with the system.

First, we must explore the different ways that water can be used. There are

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[3] Thermoelectric plants are power plants that use steam to spin a turbine in order to generate electricity.

four terms we will rely on to describe water use, and each differs in important ways. Diversion occurs when the water is moved from a watercourse without immediate beneficial use (such as filling cooling pond, adding water to lake from which withdrawals can occur). Withdrawal is when water is removed from a body of water for beneficial use, such as cooling water. Consumption occurs when the water is removed from the source, then is evaporated into the atmosphere in the form of vapor. Discharge is when water is returned to a body of water (US Energy Information Administration Form 860, 2012). The following equation is an important relationship between each of these terms:

$$\textit{Withdrawal} = \textit{Discharge} + \textit{Consumption}$$

The main variable of interest throughout this analysis is water withdrawal, due to the fact that this value incorporates all water that is removed from a body of water for beneficial use. Withdrawal is also regulated in each state by a state-wide government agency, and is therefore the greatest concern for power plants themselves.

In 2010, water withdrawals due to thermoelectric power resulted in 45% of the total water use in the US, far greater than any other sector. The next highest water use was due to irrigation, accounting for 33% of all water use. Interestingly, total water use in 2010 was actually the lowest that it has been since before 1970, with withdrawals due to thermoelectric power the lowest that they have been over the same period. Table 1 demonstrates the trends in estimated water use in the United States since 1950 (Maupin, 2014).

Table 1: Trends in Estimated Water Use in the US, 1950-2010 (billion gallons per day) (Maupin, 2014)

	Year						
	1950	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**
Total withdrawals	180	270	370	430	404	413	355
Thermoelectric power	40	100	170	210	194	195	161

In 2010, thermoelectric power water withdrawals still accounted for almost half of the entire water use of the US (Maupin, 2014). This is a very high proportion, especially given relatively frequent droughts that have occurred in recent years in the western portion of the country. Tellinghuisen (2012) examines the impacts that drought can have on the energy sector in her paper, using droughts in Texas and Australia as case studies.

Before discussing the cases themselves, we must first understand the theoretical effects that drought can have on power plants. There are four major cooling systems that we are interested in: once-through (wet), recirculating (wet), dry (dry), and hybrid (wet/dry). We will briefly explore the details of each cooling system.

a. Once-Through

In once-through cooling systems, cool water is taken from a nearby water source, such as a river or lake, and used to cool the steam in the system. After running through the system, this heated water is then discharged back into the body of water from where it was taken. Due to regulations about the temperature of the water that returns to the water source, there is often a cooling pond, where the water is discharged, and cools to the point where it can be returned to the body of water. Eventually, the water is returned at a temperature within a certain range of the temperature at which it was withdrawn (this difference in temperatures is regulated at the state level and varies across states) (NRDC, 2014).

We are specifically interested in the water use required by once-through cooling systems. In this type of cooling system, the vast majority of water used is discharged (it is withdrawn and returned to the body of water), where a small percentage is consumed through evaporation in the cooling pond. There are ecological concerns with discharge water, as it raises the temperature of the water source, which can present issues for wildlife (NRDC, 2014). Meanwhile, the cost of once-through cooling systems is generally much lower than other cooling systems. This low cost is generally what has driven utility companies to employ once-through cooling systems in the past.

b. Recirculating

Recirculating cooling systems begin in the same way as once-through cooling systems, where water is initially withdrawn from a nearby water source, and runs through the system to cool the steam. However, instead of simply being put into a cooling pond to be returned to the water source, recirculating systems send the water to cooling towers. This water cools until it can be used again, when it is sent back to the power plant to cool the steam once again (NRDC, 2014).

Recirculating plants have a much higher consumption rate than once-through plants, since a significant portion of the water in the cooling towers evaporates into the atmosphere. However, recirculating plants require much less water to be withdrawn, as the system only needs to withdraw enough water to replenish the losses due to evaporation. The main environmental issues associated with recirculating plants are the potential for lower river levels, due to the consumption of water. This is widely considered to be a less significant environmental threat than the ecological issues caused by once-through power plants (NRDC, 2014). As for cost, recirculating systems are generally more expensive than once-through systems. The costs have become more competitive with once-through systems, especially with increased regulation for water discharges, driving more utility companies to choose recirculating plants.

c. Dry Cooling

The term dry cooling refers to cooling systems that do not rely on a water source to cool the steam in a generator. There are two main categories of dry cooling, direct and indirect systems.

In a direct dry cooling system, steam from the turbine runs through a heat exchanger, which cools down and condensates the steam into water. This water is then directed back to the generator, where it is used again. These cooling systems require very high capital costs and lower overall power plant performance, especially on hot days. They do, however, use a small fraction of water compared wet cooling systems.

In an indirect cooling system, the cooling water remains in a closed loop throughout the cooling process. The steam is cooled using convection, to the point that it condenses and can be run back through the generator. Again, these systems require very high capital costs, but they do not reduce the plant's performance significantly (NRDC, 2014).

d. Hybrid Cooling

Hybrid cooling is designed as a combination of wet and dry cooling. During cooler weather, hybrid cooling systems operate essentially the same as dry cooling systems. During hotter seasons, however, they supplement their systems with wet cooling in order to avoid the efficiency losses that occur under purely dry cooling (NRDC, 2014). Even when using partially wet cooling, hyrid systems use far less water than either recirculating or once-through systems, making hybrid cooling preferable in the presence of drought.

Hybrid systems are very similar to dry systems in cost, withdrawal, and consumption, and are much more rare. Currently, there are only a total of five hybrid cooling systems in operation in the US (EIA, 2014). Because of their rarity and the similarity that hybrid systems have with dry cooling systems, we will often group dry and hybrid cooling systems together during our analyses.

The vast majority of plants in the US rely on once-through and recirculating cooling systems, both of which are very water intensive. Macknick et al (2011) modeled the typical water withdrawal and consumption at each type of thermoelectric power plant, a result that is presented in Table 2 for natural gas power plants.

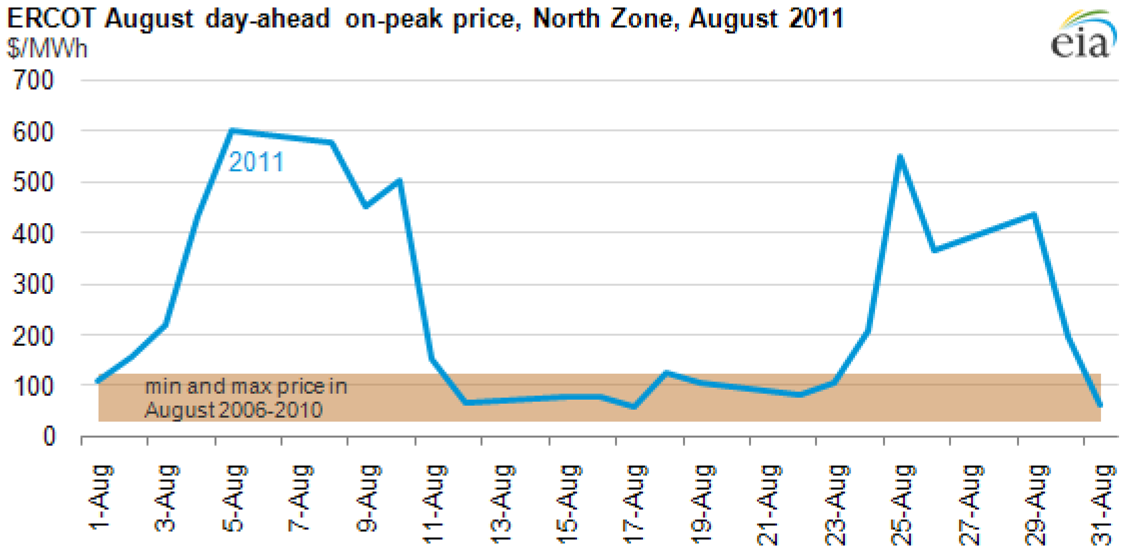
Table 2: Water Withdrawal Factors for Natural Gas Cooling Technologies (gal/MWh) (Macknick, 2011)

Fuel Type	Cooling	Technology	Median	Min	Max
Natural Gas	Recirculating	Combined Cycle	253	150	283
		Steam	1,203	950	1,460
		Combined Cycle with CCS	496	487	506
	Once-through	Combined Cycle	11,380	7,500	20,000
		Steam	35,000	10,000	60,000
	Dry	Combined Cycle	2	0	4

Due to the high water intensity of most cooling systems, droughts can have a significant negative impact on the power that a plant can produce. For once-through cooling systems, a drought can reduce the water levels and increase the temperature of the body of water from which the plant withdraws. This can decrease the effectiveness of the cooling, or even force the plant to stop withdrawing water entirely, causing potential brownouts. For recirculating cooling systems, droughts can shrink the size of the cooling reservoirs, thereby reducing the quantity of water available for cooling and potentially causing power plants to scale back their production (Tellinghuisen, 2014). We see this effect occurring in the example presented early in this paper, where the Illinois EPA was forced to issue special exceptions for power plants in Chicago to discharge hot water back into the water source in order to avoid brownouts (Meyers, 2012).

In another example, Tellinghuisen describes the effects of a drought in Texas in 2011, when sources of cooling water were at historic lows for almost 11,000

Figure 1: Texas Heat Wave, August 2011: Effects of an Electricity Supply Shortage in \$/MWh (EIA, 2011)



MW of generating capacity. Texas regulators projected that up to 3,000 MW of capacity may have been curtailed by May 2012, had the drought continued (Electric Reliability Council of Texas, 2011). Fortunately, the drought did end before that point, and there were not quite effects to that scale: a small power unit (24 MW) shut down entirely during the drought and a larger unit was forced to curtail generation at night in order to maintain enough water supplies to cool during peak hours of the day. Additionally, wholesale electricity prices skyrocketed in August of 2011, to the point that at some point during five separate days of the month, the wholesale hourly price hit the state's cost cap of \$3,000 per MWh. As a whole, the entire month of August saw power prices rise far beyond the normal August wholesale prices, as shown in Figure 1 (EIA, 2011).

In the introduction, we briefly discussed van Vliet's study on the effects of drought on electricity supply after accounting for climate change. This study also included an analysis of the effects on usable electricity capacity for plants that implement both once-through and recirculating cooling systems. For plants using once-through cooling systems, the usable capacity was projected to decrease by

12-16% by the 2040s, and for plants with recirculating cooling systems, the usable capacity will likely diminish by 4.4-5.9% by the 2040s. The study did not analyze the decrease in usable capacity for dry cooling systems, but because the water use associated with these cooling systems is extremely low, it sees unlikely that decreased water flows would not have a significant effect on the usable capacity of either of these cooling systems.

These findings demonstrate the effect that climate change may have on plants implementing any type of wet cooling system. In order to evaluate whether these effects are likely, however, we must investigate the economics of this research and answer the question of how power plants will adapt to avoid the reductions in their usable capacity.

III. Data

a. Description of Data

This study relied upon numerous data sources to provide accurate information on utility companies, power plants, cooling systems, and drought conditions. Two main data sources were used: the Energy Information Administration and the US Drought Monitor.

1. US Energy Information Administration

The EIA requires utility companies to submit yearly and months forms on all practices in order to continue running. The result is an abundance of data that is publicly available. For this study, Forms 923 and 860 were used as the main sources of data.

Form 860 is required by all electricity generators that have a nameplate capacity of at least one megawatt (MW) and are connected to the electricity grid. The form is submitted by utility companies once per year, detailing generator-level specific information about current and planned generators. The form also contains information about associated environmental equipment and, more specifically, cooling systems. The main information of interest in Form 860 is the type of cooling system that each electric generator utilizes, along with the year that the cooling system was built and the total cost to date of the cooling system.

Form 923 is, similarly, required by all electricity generators with capacity of one MW and connected to the grid. One main difference between Forms 923 and 860 is that Form 923 requires that plants report some data for each month of the year, even for plants in which the data is collected annually. We will use monthly reports of electricity generation on a plant level, along with water withdrawal, consumption, diversion, and discharge. Additionally, we will use the annual reported value of the total installed capacity of each plant.

2. US Drought Monitor

The US Drought Monitor is the result of a partnership between the National Drought Mitigation Center at the University of Nebraska-Lincoln, the US Department of Agriculture, and the National Oceanic and Atmospheric Administration. The collaboration tabulates drought conditions throughout the US each week to come up with a clear picture of drought across the entire country. We are specifically interested in weekly state-level data on droughts throughout the US, dating all the way back to 2000. Specifically, the data measures the percentage of a given state that is under a drought at any point during a specified week. While this is a somewhat crude measurement of whether a specific power plant is under a drought, it does provide a fairly accurate estimate of the drought conditions present for the region, therefore allowing us to investigate the relationships between drought conditions, water use, and cooling systems.

b. Descriptive Statistics

In order to adequately perform an analysis of the factors that are taken into account in the choice of cooling systems, there are a number of statistics that we must understand. Table 3 gives a basic overview of the data between 2010 and 2012, describing the averages of six variables that are relevant to our analysis. I will briefly describe each variable and how each varies across the three plants. In each of these tables, we look only at natural gas plants that are currently in operation in the US. There were a total of 1,714 natural gas plants in the US in 2012, although many of these are small plants that provide power to a small audience. We will limit our study to natural gas plants with a nameplate capacity of at least 100 MW that were in operation in 2012, giving us a total of 527 plants (US EIA, 2014). The data for these plants comes from EIA Forms 860 and 923, as previously discussed.

Table 3: Cooling System Summary Statistics

	(1) Once-Through	(2) Recirculating	(3) Dry/Hybrid
Cost (thousand dollars)	9046	12922	47052
Capacity (MW)	825	859	843
Capacity Factor	.231	.228	.188
Withdrawal (gallons per minute)	402	70	10
Consumption (gallons per minute)	1.6	4.9	1.0
N	170	337	20

Cost is one of the most difficult variables to work with throughout this analysis.[4] For now, however, it suffices to say that cost appears to behave as we would expect for natural gas plants using each of the three cooling systems. Once-through requires the lowest capital investment, while recirculating is approximately 30%

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[4] This is because our cost data is not normalized to present day dollars. Plants simply report to total real dollars to date that have been spent on construction and maintenance of their cooling systems. This is an issue, because a system costing the same number of real dollars 50 years ago and today are certainly of far different nominal value, but this distinction is not represented in the data. Because of potential maintenance costs throughout the years, it is impossible to accurately represent the nominal dollars spent on each cooling system based on the EIA data. Therefore, in each of our regressions, we do not include cost as a regressor, even though it is likely an important variable in the determination of which cooling systems to choose.

more expensive in capital cost. Meanwhile, dry and hybrid cooling systems are significantly more expensive, at more than five times the cost of once-through.

As for capacity and the capacity factor, there is a minimal amount of variation between the three types of plants. Each average capacity is between 820 and 860 MW, while average capacity factor for each cooling type over the three year period is between 18% and 24%. Power plants using recirculating cooling systems were slightly higher in average capacity and plants using dry/hybrid systems were lower in capacity factor but each set of plants was similar in both size and use.

Moving on to water use, *Withdrawal* and *Consumption* are both measured as rates with a unit of gallons per minute. As expected, once-through plants required far higher withdrawals than either recirculating or dry/hybrid plants. Recirculating plants came next in water withdrawals, with dry and hybrid plants in a distant third. As for consumption, recirculating plants consumed the most water, due to the use of cooling towers as a main cooling technology. Neither once-through nor dry/hybrid plants required much consumption. These water use statistics reflect our expectations, as described in the *Technical Details* section.

Figure 2 gives a summary of drought conditions in each state, in 2010 through 2013. For the purposes of this study, the term *drought* refers to a week that is abnormally dry, or put into a classification of "D0" by the US Drought Monitor. This classification is caused by short-term dryness leading to a slowing of planting and growth and will result in some lingering water deficits.[5] The measured variable in our study is the percentage of a state that was under drought in a given week, averaged throughout the year. Unsurprisingly, western states such as California, Nevada, Utah, New Mexico, and Texas were particularly prone to drought in 2012, due to the drought that occurred in that year. The extent of the drought is, however, somewhat surprising. For more than half of the US in the year 2012,

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[5] There is no current consensus on a definition of drought from a numerical standpoint. For more information on the different classifications of drought, see the US Drought Monitor's classification scheme in the References section.

Figure 2: State Drought Conditions, 2010 to 2012

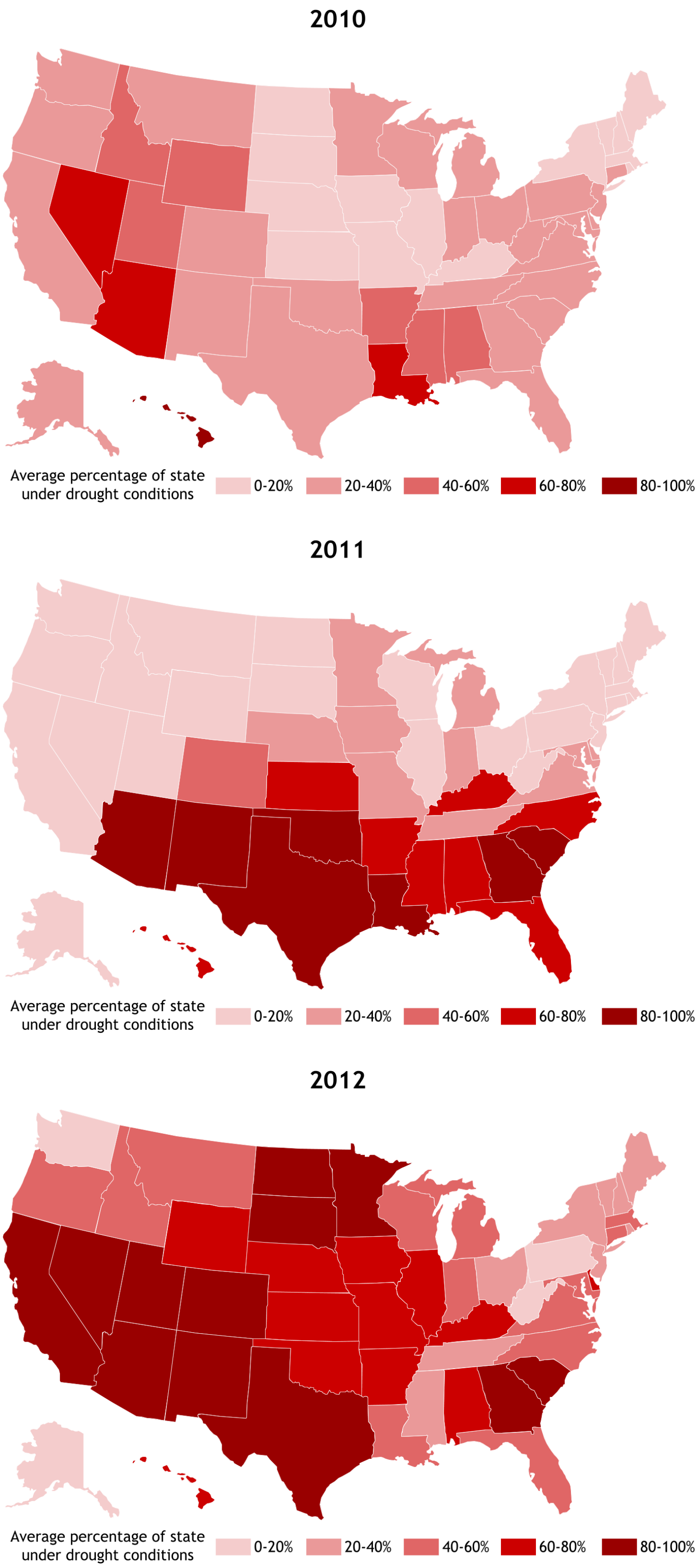
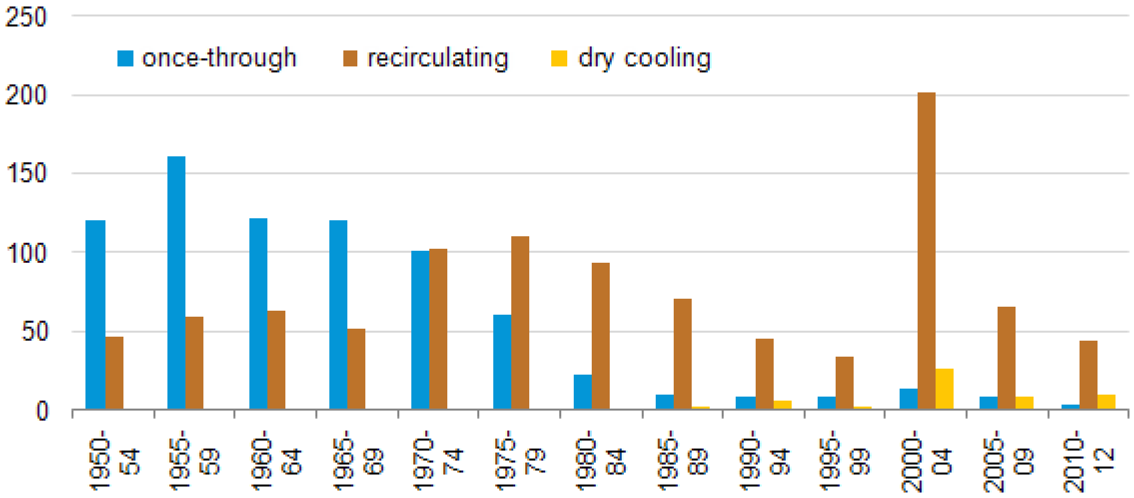


Figure 3: Vintage of Cooling Systems Operating Between 2007 and 2012 (EIA, 2014)



some form of drought was occurring in 2012, compared with under 30% in 2010.[6]

Figure 2 gives the number of cooling systems built in each year, which were in operation between 2007 and 2012. This figure demonstrates how recirculating cooling systems are being used much more than they previously were. It is important to note that power plants can retrofit once-through cooling systems to become recirculating systems. While this process can be costly, it significantly decreases the water use of the cooling system. Additionally, this figure shows the increased use of dry cooling since 1990, as the technology became more feasible and less costly.

IV. Research Design

In this analysis, we can think of the water use at power plants as having two major components: the first is discrete choice of cooling system, while the second is based in the operational decisions that determine water withdrawals. The discrete

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[6] All drought data used is a state-wide statistic. While this statistic give some idea of the likely drought conditions of a particular power plant, it does not necessarily accurately represent the true drought conditions of the plant. In the vast majority of cases, however, the drought conditions throughout a state will reflect the specific conditions at a specific plant, giving us a fairly accurate estimate of the drought conditions at the plant itself.

choice of cooling system is generally a decision made at the initial construction of the plant, and will only change with a major retrofit to the entire system. The operational decisions, however, will vary even over the course of a week, based on the plant's output, the temperature, and a number of other factors.

In this study, we use separate regression models to estimate each component of a plant's water use. We begin with our model for the variation within a given plant caused by decisions made on the operations of the plant. There are two main decisions that a plant make that interest us: the energy that a plant is willing to generate and the quantity of water that the plant deems necessary for cooling. This model will attempt to discern which (if any) action a plant chooses to take when facing increased drought conditions. Each portion of the model relies on a simple OLS regression of the following form:

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\begin{aligned}
Withdrawals_{i_t} &= \beta_0 + \beta_1 {*}\mathit{Drought} + \beta_2 {*} i + \beta_3 {*} t + \epsilon_{i_t} \\
NetGeneration_{i_t} &= \gamma_0 + \gamma_1 {*}\mathit{Drought} + \gamma_2 {*} i + \gamma_3 {*} t + \epsilon_{i_t}
\end{aligned}
$$

It is important to note that our design of this regression takes into account fixed plant and time effects. In the regression model, i represents the plant number, while t represents the time. Without these terms, there may have been correlation between the error term and the drought term, resulting in biased estimated of the effect of drought. By using the fixed plant and time effects, we control for unobservable plant-level characteristics that do not change over time, as well as changes over time that affect all plants equally.

In this regression, *Withdrawals* is a rate in the form of gallons per minute per kilowatt-hour. This variable is self-reported in EIA Form 860 on a monthly basis. Meanwhile, *Net Generation* measures a plant's monthly net generation, as reported in EIA Form 923. Finally, *Drought* represents the percentage of the power plant's state that was under some form of drought.[7] Because this data is given on a weekly basis, we average the values in each month to give a monthly drought statistic.

The analysis uses data from 2010-2012, giving us a total of 36 months of data on withdrawals, net generation, and drought for each plant. In this period, there was at least one major drought across the US (in the summer of 2012), ensuring that there will be sufficient variation in $Drought$ over the three-year period. Based on these regressions, we should be able to discern the operational decisions that a plant makes to respond to increased drought conditions.

The second model used in this study analyzes the discrete choice of cooling system on the basis of drought conditions and water withdrawals. This model uses a alternative specific conditional logit regression[8], which fits McFadden's choice model. The strength of this model is that it allows for multiple types of independent variables: those that stay constant for the same cooling system but vary across plants, those that vary across cooling system but remain constant for each plant, and those that vary across both cooling systems and plants.

In this model, our dependent variable, called *Choice*, determines the cooling system that is used at each plant. One independent variable is *Withdrawal*, which again measures the withdrawal rate of the plant in gallons per minute per kilowatt-hour. Additionally, *Drought* is a case-specific independent variable that measures the percentage of the power plant's state that was under some form of drought at the time of observation. In this model, we use data from 2010 through 2012 for each natural gas power plant.

The alternative specific conditional logit regression generates a likelihood function, to determine how the independent variable contribute to the choice in cooling

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[7] One limitation of the data is that we only use drought data between the years 2010 and 2012 for this analysis. We assume that regions that are drought-prone in this period will also have been historically more prone to drought.

[8] See Stata's manual in our References section for more details on this regression model.

system. Specifically, the model will describe how *Drought* affects the cooling system choice, accounting for the change in the withdrawal that occurs across different cooling systems. Once-through cooling systems will be treated as a base case, so that all interpretation of other cooling system types will determined relative to once-through cooling systems.

It is important to note that there are a number of factors that go into the the decision of which cooling system a plant may choose, some more limiting that others. Regulations regarding water withdrawals and discharge temperatures that vary from state to state may have different impacts in different states on how plants make their decision. These regulations may limit a plant to certain cooling systems, resulting in the plant having fewer choices to consider for their cooling system. Despite these potential limitations, we will assume that a power plant has the option of choosing each of the four cooling systems.[9]

V. Results

The results of the three regressions are shown in Tables 5 through 7. Tables 5 and 6 are dedicated to the analysis of within-plant effects of drought on water withdrawals. These regressions are divided among the two tables: Table 5 is dedicated to the model with *Withdrawals* as our dependent variable, while Table 6 is devoted to the regression with *Net Generation* as the dependent variable.

Each table follows the same format: the coefficients on *Drought* in Table 5 represent the variable β_1, as written in our model above, while the coefficients on *Drought* in Table 6 represent γ_1. These are the primary variables of interest, as they describe how power plants respond to changing drought conditions, either through altering their withdrawal rates or by scaling back their production.

In each of the three cooling systems, β_1 is not statistically significant, indicating

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[9] This is a fair assumption, as no states have specifically banned the use of a particular cooling system. Plants do have a legitimate choice among the four cooling systems, even if a state's regulations and drought conditions make a specific cooling system impractical to implement.

Table 4: Panel Regression of Drought on Withdrawal

	Once-Through		
	Withdrawal rate		
	Coefficient	Std. Err.	p-value
Drought	.592	.585	.311
Constant	39.4	31.8	.216
Observations	5447		

	Recirculating		
	Withdrawal rate		
	Coefficient	Std. Err.	p-value
Drought	-.026	.065	.689
Constant	6.63	4.12	.108
Observations	10240		

	Dry/Hybrid		
	Withdrawal rate		
	Coefficient	Std. Err.	p-value
Drought	-.0109	.00812	.181
Constant	1.45***	.402	.00036
Observations	466		

Table 5: Panel Regression of Drought on Net Generation

	Once-Through		
	NetGen		
	Coefficient	Std. Err.	p-value
Drought	4.47	28.4	.875
Constant	156000***	1540	0
Observations	5564		

	Recirculating		
	NetGen		
	Coefficient	Std. Err.	p-value
Drought	71.4**	23.2	.00214
Constant	164000***	1470	0
Observations	10700		

	Dry/Hybrid		
	NetGen		
	Coefficient	Std. Err.	p-value
Drought	286***	69.0	.0000406
Constant	96000***	3680	3.65e-97
Observations	545		

that plants are unlikely to alter their withdrawal rates on the basis of increased drought conditions. This may be because altering the withdrawal rate reduces the efficiency of the plant, thereby decreasing the plant's profits significantly.

Meanwhile, the differences between γ_1 in each type of cooling system are illuminating. At once-through plants, γ_1 is positive but insignificant, giving us little indication of whether or not plants with once-through cooling systems are likely to curb their production as drought conditions increase. However, for both recirculating and dry cooling plants, γ_1 is positive and significant. In fact, for plants with dry cooling, the coefficient is about four times the that of plants with recirculating.

There are a couple of important takeaways from these results: first, total net generation rises as drought conditions increase. This is likely due to increased temperatures that cause energy consumers to turn on their air conditioners and increase their energy use. Secondly, and more importantly for the purposes of this analysis, as drought conditions increase, a higher proportion of energy is generated by plants whose cooling systems use less water. This is evidenced by γ_1 being insignificant at plants using once-through (highest water use), and being significant and rapidly increasing in magnitude at plants that use less water for cooling. We can then infer that plants with lower water use are more willing to generate energy under drier conditions. Meanwhile, plants employing once-through systems find it more costly to continue to generate under drought conditions, giving them a lower proportion of total energy supply.

Table 7, meanwhile, is dedicated to the second regression in this study – an analysis of the choice of cooling system that a power plant makes. In this table, once-through is the base case, while recirculating systems are represented by 2, dry cooling systems are represented by 3 and hybrid cooling systems by 4. This table demonstrates the effect that an increase in drought conditions has on the choice of cooling system that a power plant makes. The most significant takeaway from this section is that an increase in drought conditions makes it significantly more likely (p = 2.81e-08) that a power plant will choose a recirculating cooling system (2) compared with a once through cooling system (1).

Table 6: Multinomial Logit Model Withdrawal

		(1) Choice	
	Coefficient	Std. Err.	p-value
CoolingSys			
withdrawal_per_kwh	-.0129	.120	.914
2			
Drought	.0331***	.00595	2.81e-08
Constant	-.732**	.274	.00748
3			
Drought	.0289	.0160	.0701
Constant	-3.59***	.775	3.64e-06
4			
Drought	-.000121	.0310	.997
Constant	-3.75**	1.29	.00352
Observations	2108		

The explanation for this result is fairly straightforward: an increase in drought conditions causes water resources to be less abundant in a given region, making water supplies vulnerable to high temperatures and any thermal pollution. This vulnerability can cause plants to be forced to scale back production or even shut down entirely to comply with regulations.Therefore, it is more cost effective where drought is prevalent for plants to choose recirculating cooling, which has higher capital costs than once-through but will prove to ultimately be more profitable in the long run.

For dry cooling systems, the coefficient is positive and significant at 90% confidence (p = 0.07), making it fairly likely that with greater drought conditions, a power plant will choose dry cooling over once-through. For hybrid plants, the coefficient is statistically insignificant (p = 0.997), likely due to the fact that there are too few hybrid plants in the data to determine significant results.

The result for dry cooling systems indicates that there is another significant factor outside of drought conditions that plays a role in a plant's decision to choose dry cooling – cost. Because the capital costs of dry cooling systems are so high, it is not necessarily clear that increased drought conditions will cause the choice of dry cooling over once-through. As the cost of dry cooling continues to become more competitive with other cooling systems, it is likely that more plants in regions with high drought intensity will choose dry cooling systems. At the moment, however, it is a rarity for natural gas plants because of the high cost.

As for hybrid cooling systems, there are not enough observations to make any significant observations from this analysis. Currently, it is simply a technology that is only used extremely rarely with natural gas power plants, resulting in insignificant results in this study.

VI. Conclusions

The results of this study indicated that concerns regarding water use are important factors in a power plant's choice of cooling system. Specifically, power plants in regions with higher drought prevalence were significantly more likely to choose recirculating cooling systems over once-through cooling systems. Similarly, it was likely that plants in these areas would have a higher probability of choosing dry cooling systems compared with once-through system. These results demonstrate that in the long run, the higher capital costs of recirculating and dry cooling systems can be outweighed by the increase in profit that occurs over the life of the plant as a result of decreasing the plant's water use.

While this discrete choice of cooling system was influenced by drought conditions, the operational decisions that determine the other component of a plant's water use were not affected by drought conditions in a very different way. In general, plants were not likely to change their withdrawal rate as a result of increased drought conditions. However, the proportion of energy produced by once-through plants declined as drought conditions increased, and recirculating and dry cooling plants saw significant increases in their net generations. This demonstrates that plants implementing recirculating and dry cooling systems were able to continue producing more energy as the drought conditions worsened, while once-through plants were forced to limit their generation due to higher temperatures and lower river flows.

Looking forward, it is likely that as climate change continues to cause more drought throughout the US, plants will continue to choose cooling systems that require lower amounts of water withdrawals. This is consistent with the trends that we have seen over the last forty years, as recirculating power plants have become more popular as a result of decreasing cost and lower water availability. Therefore, despite the expected lower water flows that are expected due to climate change, it seems likely that power plants will continue to adapt by implementing cooling systems that require less water, rather than simply curbing their generation or shutting down during droughts.

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