THE EFFECT OF AMBIENT AIR AND WATER TEMPERATURE ON POWER PLANT EFFICIENCY

by

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Abstract

The performance of thermoelectric generators depends on a variety of factors, many of which are meticulously controlled through generator design or operational management. However, there are environmental factors that affect operations which cannot be controlled directly, such as air temperature and water temperature. Recent studies have suggested that a warming climate will have a significant impact on cooling water availability for generators, arising in part from cooling water regulations designed to protect aquatic ecosystems. Other work has shown the effect of either air or water temperature on the efficiency of specific generating technologies. The physical relationships between ambient temperatures, combustion, and cooling processes are well understood, but the implications of these relationships for real-time plant efficiency across power generating technologies have not been fully explored in the literature. This study develops empirical estimates for the impact of air temperature and water temperature on the efficiency of coal- and natural gas-fired power plants with once-through and recirculating cooling systems.

Using USGS and NOAA air and water temperature data and EPA records of power plant fuel consumption and power output, this master's project quantifies the impact of air and water temperature on power plant efficiency. Regression models developed here indicate that a 1° C increase in air temperature is correlated with a 0.01 percentage point decrease in plant efficiency and a 1° C increase in water temperature is correlated with a 0.02 percentage point decrease in plant efficiency, though these vary for by generating technology and cooling system type. These impacts are substantially smaller in magnitude than analogous effects quantified in previous studies.

Contents

I. Introduction

Thermoelectric power plants currently generate 91% of electricity in the US (EIA 2011). The capacity of these plants to generate electricity depends on their access to cooling water. In recent summers, very warm and dry weather patterns have caused a decrease in the availability and cooling capacity of water resources, particularly in the southeastern US (NETL 2009). State and federal regulations impose limits on cooling water withdrawal volumes and regulate the maximum temperature of discharged cooling water. When water availability decreases, or when ambient water temperatures are already at or near discharge temperature limits, plants must curtail generation or shut down entirely to avoid non-compliance. In a recent paper published in Nature's Climate Change journal, Vliet, et al. discuss the interaction between cooling water regulations and generating capacity for subsets of US and European thermoelectric power plants; plants are grouped according to cooling system, and two climate scenarios are analyzed.[1] Using a suite of climate, hydrological, and water temperature models, the study finds that the capacity of 29 US plants with once-through cooling systems will fall by over 50% during 15 days each year under the extreme climate scenario, compared to just 11 days per year under the control scenario. The 8 European plants studied will experience the same capacity reduction 50 days per year under the extreme climate scenario and 31 days per year under the control scenario (Vliet, et al. 2012).

While Vliet et al. focus on the effect of the interaction of water resource policies and climate scenarios on thermoelectric plant output, other work has studied different generating technologies to find the magnitude of the physical relationship between ambient temperatures and plant output and efficiency. Natural gas combustion turbine efficiency is particularly sensitive to changes in ambient air temperature. Using data from a combined cycle plant,

[1] Vliet, et al. use the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emissions Scenarios* (SRES) A2 and B1 global emissions scenarios for their analysis.

Daycock shows that in order to keep power output constant, an increase of 33° C requires an additional 750-1500 Btu/kWh, depending on the plant's operating mode. (Daycock 2004)

Furthermore, observations of 160 MW and 265 MW Siemens natural gas combustion turbines in the United Arab Emirates showed that an increase in air temperature of 1° C led to a 0.1% decrease in turbine efficiency and a 1.47 MW power output reduction (Zubaidy 2011). Figure shows that over a range of 58° C the combustion turbine's heat rate varies from its design heat rate by approximately +/- 5%, which corresponds to an efficiency variation of approximately +/- 2% around the design efficiency. Several other studies look at this relationship for gas turbines and find comparable relationships between air temperature and efficiency (e.g. Jabboury and Darwish 1990, Ponce Arrieta and Lora 2004). The efficiency range resulting from air temperature changes for natural gas combustion turbines is large enough that many turbine designs include air condensers upstream of the compressor inlet to reduce the temperature of air entering the turbine which increases efficiency.

To study ambient temperatures and nuclear power plants Dumayaz and Sogut use a thermodynamic model of a pressurized-water nuclear plant. They find that for every 1° C increase in cooling water temperature there is a corresponding 0.12% loss of efficiency and 0.45% loss of power output. This relationship may help determine where to construct a nuclear reactor. In Turkey, for instance, the utility may site a new plant on either the Mediterranean Sea or the Black Sea. Since the Black Sea's average annual temperature is 6.5—7° C colder than the Mediterranean, siting the plant on the Black Sea could yield efficiency gains of 0.78—0.84% (Dumayaz 2006).

The research presented here fills a gap in the literature by using empirical data to simultaneously assess the impacts of air and water

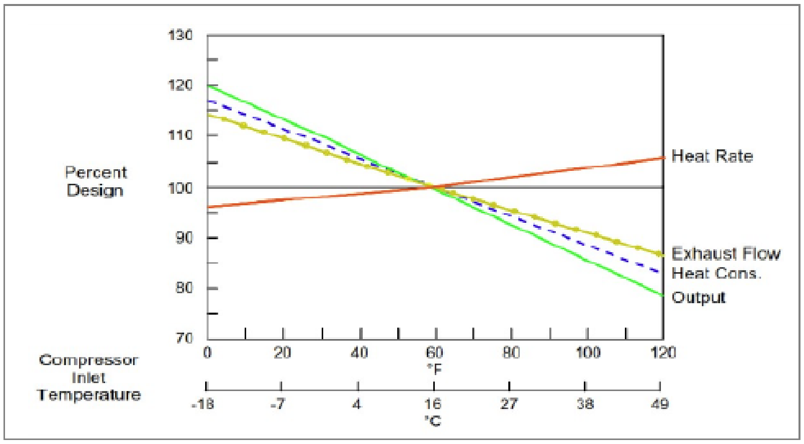

Figure 1. Effects of ambient temperatures on GE gas turbine performance characteristics. (Brooks 2000)

temperatures on a variety of generation technologies. There are four important differences between the current research and previous studies. First, previous work examines air temperatures or water temperatures individually rather than quantifying each environmental variable using a common methodology. Second, this work examines the differential effects of air and water temperatures across a variety of power generating technologies, comparing different fuel types and cooling systems. We analyze 16 plants grouped into 4 categories based on fuel type (natural gas and coal) and cooling system (once-through systems and recirculating systems) to examine the relative temperature impacts on efficiency for each technology combination. Third, this work focuses on fossil fuel-fired steam generators rather than combustion turbines or nuclear generators. Finally, we use empirical data rather than physical or technological models and compare results to the relationships found in the Integrated Environment Control Model (IECM) to estimate the magnitude of each temperature-efficiency relationships.

The relationships found between temperatures and efficiency are smaller than relationships previously reported by approximately one order of magnitude. For instance, we find that a 1° C increase in air temperature is correlated with a change in plant efficiency of +0.02 to -0.03 percentage points and a 1° C increase in water temperature is correlated with a change in plant efficiency of +0.02 to -0.06 percentage points. Previous work on water temperature and efficiency has found a 0.12% decrease in efficiency for every 1° C temperature increase. Possible explanations for the discrepancies between our work and previous results are offered in the Discussion section. As shown below, the relationship we calculate between air temperature and plant efficiency is similar to the relationship implied by the IECM model, but results from studies of combustion turbines and air temperature have found relationships an order of magnitude greater.

This paper is divided into 7 sections. Following the introduction, we describe the physical relationships between ambient temperatures and plant efficiencies in section two. In the third section data sources, data collection, and data selection processes are described. Section four outlines the methodology used. Section five presents the results and section six is a discussion of the results with practical implications. Section 7 is a conclusion.

II. Relationships between Ambient Temperatures and Efficiency

During the production of electricity, steam generators require oxygen during combustion and water during the cooling process. Ambient air is drawn into the combustion chamber to provide oxygen which is consumed in an exothermic combustion reaction whose heat is used to convert water to pressurized steam. The steam drives a turbine and generates electricity. Once the steam has expended its useful energy, it is cooled (typically using water, though not always), re-condensing it into water to be boiled again.

The steam generator interacts with the environment at two stages. One is at the intake of ambient air in the combustion process, and the second is when cooling water is drawn in for cooling. Water may be obtained from various natural sources. Out of these two interactions, three relationships are expected between ambient temperatures and power plant efficiency: two of which relate air temperature and the efficiency of the combustion process, and the third relates water temperature and plant efficiency.

Air Temperature and Efficiency

First, the temperatures of combustion for utility-scale generators typically reach 540° C or more (Tsiklauri 2004), depending on the boiler technology. Oxygen in the air is used for combustion and enters the plant at ambient temperatures usually below 50° C. Energy is expended raising the temperature of the incoming air to the combustion temperature. Air entering the boiler at 40° C requires relatively less energy to increase its temperature to 540° C than air entering the boiler at -10° C. Therefore, warmer air is expected to provide an efficiency boost to a steam boiler.

Second, given a gas with constant mass, a temperature increase causes volumetric expansion and a decrease in density. Consequently, the same volume of air will contain less oxygen at higher temperature. Given a constant flow rate (volume of air per unit time) for a boiler's air intake system, an increase in temperature will decrease the rate of oxygen supplied to the boiler. Lower levels of oxygen decrease the boiler's efficiency. This magnitude of this effect is large enough that many natural gas combustion turbines use condensers to cool incoming air. This effect of air temperature on efficiency has the opposite direction of the first effect. Part of this analysis is aimed at quantifying the overall effect of air temperature on efficiency, and whether the magnitude of this effect is correlated with different fuel types or cooling systems.

Water Temperature and Efficiency

The third relationship relates water temperature and efficiency, and can be explained using the Carnot equation for heat engine efficiency (see Figure and Equation 1). The equation indicates that the Carnot efficiency of a heat engine is related to the temperature differential between the heat source (T_H) and the heat sink(T_C). Given a heat source with constant temperature, as the temperature of the heat sink increases, the Carnot efficiency will decrease.

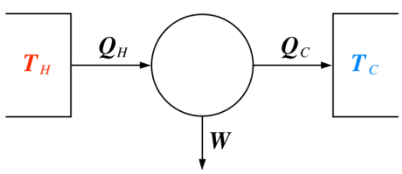

Figure 2. Diagram of a heat engine

$$\eta_C \leq 1 - \frac{T_C}{T_H}$$

Equation 1. Carnot efficiency for a heat engine.

III. Data Collection and Selection

Power Plant Data and Record Selection

EPA tracks hourly and daily electricity generation through its Clean Air Markets Division (CAMD) for all power generators subject to emissions reporting requirements under EPA's Acid Rain Program, NOx Programs, or the Clean Air Interstate Rule (CAIR). Plant operators subject to these air programs are required to report emissions, fuel consumption, and generating data, which are included in the available dataset. (For the data source, see EPA 2013 in the References section). The parameters relevant to this study are:

1. Time of operation in each hour (h). A value of 1 indicates the plant was fully operational for the hour of record, and a value of 0.5 indicates the plant only operated for 30 minutes in the hour.
2. Heat input (q). This value is reported in million Btu (mmBtu) per hour.
3. Generation (g). The amount of electricity produced in the given hour is reported in megawatt-hours (MWh).
4. Plant efficiency (η) is calculated by converting the plant's generation to mmBtu and dividing by heat input, according to Equation 2:

$$\eta = \frac{g * 3.412\ \frac{mmBtu}{MWh}}{q} \qquad Equation\ 2$$

Plant efficiency (η) is the dependent variable for the regression models. Here we describe which records are included in the regression analysis.

First, only hours during which the plant was operating for the full hour (h = 1) are included. During hours of partial operation the efficiency could be affected by the plant's efficiency while ramping up or down. Furthermore, in most cases, hourly values were registered as either 0, 0.25, 0.5, 0.75, or 1 (corresponding to 0, 15, 30, 45, and 60 minutes). However, it seems unlikely that a plant's operations would be limited to 15 minute increments, suggesting lack of precision in these particular records. In fact, there are numerous instances during hours of partial operation where calculated efficiency is very close to or above 100% which is physically unlikely, but no explanation for these efficiency levels is discernible from the data. For simplicity, hours of partial operation are excluded from our analysis.

After excluding hours of partial operation there are still hours where efficiency is above 100%. All of these records are excluded.

Efficiency varies significantly with power output. In order to control for power output, records are selected based on the mode of each unit's power output. In addition, this step removes many instances in the dataset where efficiency is inexplicably high or low. Although this filtering criterion removes a lot of available information, large numbers of records remain data for each unit. Table 3 (see Appendix) **Error! Reference source not found.**shows the number of records for each plant. For one generating unit, the mode of power output is 0 MW. For this unit, we exclude hours with output of 0 MW and use the mode of the remaining records for analysis.

Finally, in the remaining data there are still anomalous efficiencies as high as 60%, 70% or 80%. We found no explanation for these anomalies so we take a conservative approach regarding which records to include. We exclude efficiency outliers defined as those beyond one interquartile spread above or below the interquartile range, a common definition of outliers in statistics.

Water Temperature Data

Two federal agencies maintain data on water temperature. The United States Geological Survey (USGS) maintains monitors primarily in streams, rivers, and lakes around the country. These monitors track a variety of water conditions, including flows, water levels, chemical properties, and temperatures. The National Oceanic and Atmospheric Administration (NOAA) maintains buoys and fixed monitoring stations deployed primarily along the US coastline and in the Great Lakes. These buoys collect air and water temperature information as well as other climatic data. (USGS 2012 and NOAA 2012)

Ideally, water temperature data would be collected precisely at the plant's cooling water intake valve. However, it was challenging to find monitors located on the same water body and within several miles of power stations, and impossible to find temperature monitors located in the immediate vicinity of power plant intake structures. For each plant we identify monitors satisfying three conditions:

1. The monitor is located in the body of water from which the plant withdraws its cooling water.
2. The monitor is close enough to the plant's intake structure that relative changes in water temperature at the monitor location are likely to reflect the relative change in water

temperature at the plant's intake structure. (However, this condition may not be satisfied for all plants, which is discussed in subsequent sections.)

3. Hourly data is available for the two year period coinciding with the hourly plant data collected from EPA.

The distance between the power plant and the water monitor varies from 2.1 to 50.9 miles.

One shortcoming of this research is the lack of water temperature data with close proximity to the power plants. As the distance between the plant's intake structure and the water monitor increases, the likelihood of thermal pollution between monitor and plant increases, reducing the relevance of the data and the explanatory power of our results. We did not undertake any analysis of the potential thermal sources affecting the quality of water temperature data.

Finally, water temperature data is obtained only for plants with a once-through cooling system, and caution is taken to ensure that these plants do not store cooling water in cooling ponds whose temperatures would not necessarily be correlated with data from monitoring stations.

Air Temperature and Dew Point Data

Air temperature and dew point data is collected and distributed by the National Climate Data Center (NCDC), a division of NOAA. Using NCDC's Climate Data Online application, we identify the weather station closest to each power plant. As with available water data, these data do not reflect local temperatures at power plants. Distances between monitoring stations and power plants

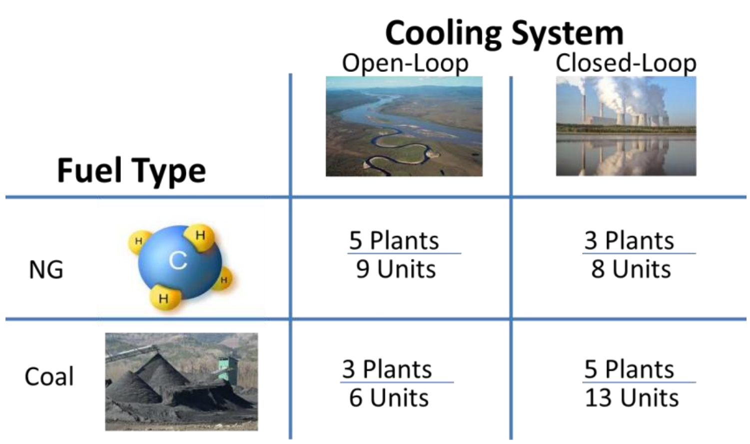

Figure 1. Plant and unit breakdown by fuel type and cooling system.

range from 2.0 to 58.6 miles. Potentially confounding air temperature factors are briefly described in the Discussion section.

Eight coal-fired plants and 8 natural gas-fired plants are analyzed in this study. The natural gas plants are either steam plants or combined cycle plants. Natural gas combustion turbines are excluded in order to reduce the variability between the coal and natural gas generators studied. In fact of the 8 natural gas plants used, 6 exclusively use boilers for generation while the other 2 are combined cycle plants. Of the 8 coal plants, 5 are cooled by once-through cooling systems, and 3 are cooled by recirculating systems. Of the 8 natural gas plants, 3 are cooled by once-through cooling systems, and 5 are cooled by recirculating systems. Figure 1 shows the breakdown of generating units among the four plant categories.

Figure 6 (see Appendix) shows a map of the plants' locations.

IV. Methods

Two methods are used to quantify the relationship between ambient conditions and power plant efficiency. First, plant efficiency and environmental data (air temperature, water temperature, and dew point) are used to build regression models for each generating unit. Regression models provide an empirical estimate of the magnitude and direction of each environmental variable's impact on efficiency. Second, the IECM,[2] is included to provide a theoretical comparison for the regression results.

Regression modeling

In this analysis, 37 regression models are built, one for each unit. Each model is constructed to describe the effect of the environmental variables on the unit's efficiency. Each model includes either 1, 2, or 3 environmental variables. Dew point data is not available for all locations, so it is excluded from some models. In addition, after running each regression with all available data,

[2] Version 8.0.2

some of the environmental variables were determined to be not statistically significant in explaining the efficiency of the respective units; these variables were removed from the final model. Throughout this analysis, statistically significant figures imply regression coefficients with p-values less than 0.05.

The reason for developing separate models for each unit[3] is that environmental data comes from a variety of sources which are likely to have varying degrees of accuracy. The assumption implied by these models is that temperature data from air and water monitors reflect the power plant's local air and water temperatures, or at least that relative temperatures are consistent between the monitors and power plants. There is reason to doubt this assumption, but we do not investigate which monitors are "accurate" proxies of actual plant data. In a combined model, inaccurate data would be mixed with accurate data; without knowing which monitoring data is accurate, we keep each unit's data separate and look at the temperature effects for each unit individually.

To illustrate the variation in data, we describe two plant sites and their proximity to water monitoring stations. The Humboldt Bay plant in Northern California is cooled by water from the Pacific Ocean. The closest available water temperature data is collected from a NOAA buoy in the Humboldt Bay 4 miles from the plant. However, the Port Jefferson plant is located on Staten Island and is cooled by water from the Arthur Kill, which is a narrow strait separating Staten Island from New Jersey. Water temperature data for the Port Jefferson plant is collected from a buoy in the New York Harbor, also about 4 miles away. However, the two cooling water sources for these two plants are very different in size, shape, and in commercial activity in the water body. It might be expected that water temperatures between Port Jefferson and the water monitor are affected by many local sources of thermal pollution, such as boat traffic or other industrial discharges, whereas, there are fewer sources of thermal discharge in Humboldt Bay, California. Rather than attempting to mitigate confounding sources of thermal pollution, or simply excluding the New York plant, we analyze each plant individually, and exclude variables based on their statistical significance in each model.

[3] Nested and fixed effects regression models were also considered for this analysis.

Several regressions were run before arriving at the final model. In the first set of regressions, a model is built for each of the 37 units. For plants with once-through cooling systems, efficiency is regressed against air temperature, water temperature and dew point. Whereas regression models for plants with recirculating systems only incorporate air temperature and dew point. From these models, regression diagnostics revealed significant temporal correlation in the error terms (for example, Figure), which is caused by a strong relationship between the efficiency in consecutive hours (i.e. efficiency in hour *t* is highly correlated with efficiency in hour *t – 1*). For many of the units, the explanatory power in this first set of models is weak based on adjusted R^2 values (see **Error! Reference source not found.** in the Appendix for a list of R^2 values from this model) Adjusted R^2 values range from below 0.01 to 0.59. To improve this model, a one-hour lagged efficiency variable is added to control for the correlation between efficiency in hour *t - 1* and the efficiency in hour *t*. This adjustment improves the distribution of error terms (see Figure) and also increases the model's explanatory power for all units (see **Error! Reference source not found.** for models' R^2 values before and after the lagged variable is included). One implication is that the previous hour's efficiency is highly correlated to the current hour's efficiency.

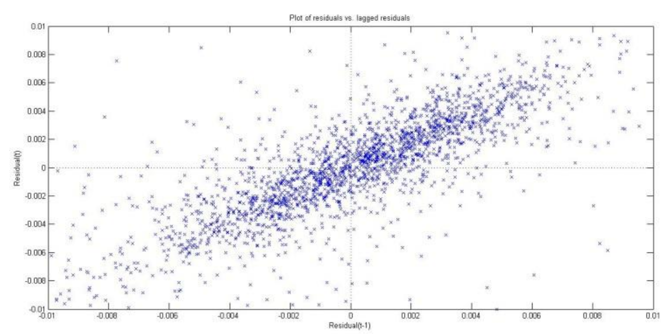

Figure 3a. Model Residuals in hour t vs residuals in hour t-1, without lag term for Unit 1 of the Arthur Kill plant.

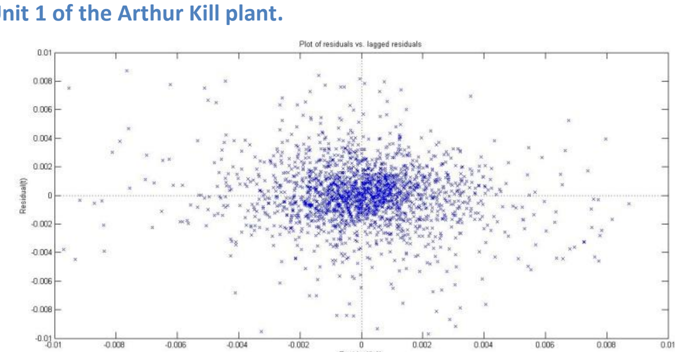

Figure 3b. Model Residuals for Arthur Kill Unit 1in hour t vs residuals in hour t-1, with lag term included.

Next, variables with insignificant coefficients are removed from each model. Table 1 (in the Results section) shows the number plants for which each of the environmental variables is significant in the regression.

For all generating units, *i*, the initial regression model takes the form

$$\eta_{t,i} = \beta_i + (\alpha_{1,i} * n_{t-1,i}) + (\alpha_{2,i} * A_i) + (\alpha_{3,i} * W_i) + (\alpha_{4,i} * D_i)$$

where,

$\eta_{t,i} = efficiency\ of\ plant\ i\ in\ hour\ t$

$\beta_i = intercept$

$\alpha_{1,i} = coefficient\ on\ the\ lagged\ efficiency\ variable$

$\eta_{t-1,i} = lagged\ efficiency;\ the\ efficiency\ of\ plant\ i\ in\ hour\ t-1$

$\alpha_{2,i} = coefficient\ of\ air\ temperature\ for\ plant\ i$

$A_i = air\ temperature\ at\ plant\ i$

$\alpha_{3,i} = coefficient\ of\ water\ temperature\ for\ plant\ i$

$W_i = water\ temperature\ at\ plant\ i$

$\alpha_{3,i} = coefficient\ of\ dew\ point\ for\ plant\ i$

$D_i = dew\ point\ at\ plant\ i$

However, for each unit, terms are removed from the final regression model depending on the significance of the independent variable.

Modeling Using the IECM

The IECM allows users to design a power plant using a wide variety of technical, operating, emissions technology, ambient, and financial specifications. As mentioned above, the relevant parameters for this study are:

1. Fuel type
2. Cooling system
3. Air temperature
4. Water temperature

Eight coal combustion and 2 natural gas combined cycle plants are modeled. Four of the coal plants are modeled with a once-through cooling system and 4 with a recirculating system. For each type of cooling system, we set the coal plant's capacity to 100, 200, 500, and 1000 MW to analyze the effect of plant size on the temperature-efficiency relationship. The IECM model does not allow the user to determine the size of the combustion turbine, so it is not possible to control the NG plant size in the same way,[4] so we only model two NG plants, one for each cooling system.

IECM allows the user to change the ambient air temperature, but not the ambient water temperature. For each plant, the ambient air temperature is set to 15°F, 36.25°F, 57.5°F, 78.25°F and 100° and the associated efficiencies are recorded to capture the IECM model's predicted effect of air temperature on plant efficiency.

In setting the plant size, the IECM natural gas plant can include one of two turbine models (GE 7FB and GE 7FA) and 1, 2, 3, 4, or 5 turbines. We use one GE 7FB, whose gross power output of 454.3 MW and net output is 264.4 MW. Changing the number of turbines does not affect the net efficiency of the plant. For the NG portion of IECM modeling we do not vary plant size.

V. Results

First, we summarize the effects predicted by the multivariate regression model developed from actual plant data; second, we discuss results from the IECM model.

Regression Modeling

For each generating unit, the regression coefficient estimates the correlation between a one-unit increase in the environmental variable (i.e. degree Celsius or dew point) and change in the unit's efficiency, in terms of percentage points gained or lost. For example, if a unit whose water temperature coefficient, α_3 is -0.01, that unit experiences an efficiency loss of 0.01 percentage points for every 1° C increase in water temperature, all else being equal. More specifically, if a

[4] The parameters controlling the capacity of the NG plant are the gas turbine model (GE 7FA or GE 7FB) and the number of turbines used in the plant. The two turbine models are roughly the same size, and varying the number of units has no impact on the plant's efficiency.

coal plant with a once-through cooling system is generating electricity with 35.00% efficiency and its cooling water temperature increases from 20° C to 21° C, its efficiency will drop to 34.99%.

Plant type and statistical significance of environmental variables

Table 1 and Table 4 (see Appendix) show which environmental variables are significant for each power plant category. Table 1 shows the number of plants where efficiency is statistically correlated ($p < 0.05$) to each of the independent environmental variables. Overall, air temperature is found to be significantly correlated with efficiency for 17 out of 37 units; water temperature is significant for 12 out of 16 units, and dew point is significant for 14 out of 29 units.

Table 1. Number of plants where efficiency is significantly affected by ambient variables.

		Air Temp		Water Temp		Dew Point	
Fuel Type	Cooling System	Number of Units Where Data is Available	Air Temp Significant in Regression on Efficiency	Number of Units Where Data is Available	Water Temp Significant in Regression on Efficiency	Number of Units Where Data is Available	Dew Point Significant in Regression on Efficiency
Coal	Recirculating	13	5	N/A	N/A	13	7
Coal	Once through	7	4	7	6	4	3
NG	Recirculating	8	5	N/A	N/A	8	4
NG	Once through	9	4	9	6	4	0
	Totals	**37**	**18**	**16**	**12**	**29**	**14**

Table 4 (see Appendix) summarizes which combinations of environmental variables are statistically significant for the units within each plant category. For example, there are 9 units powered by natural gas with once-through cooling systems. Among these 9 units, efficiency is correlated with air and water temperature at 2 units; however for 2 other units, efficiency is only correlated with air temperature (it is not correlated with any other environmental variables); and for 5 units, efficiency is only correlated with water temperature. Dew point is not significantly correlated with efficiency for any of the once-through natural gas plants.

Size and direction of temperature effects

The range of temperature coefficients for each of the models is indicated by the blue lines in Figure 2; each line is associated with a power plant category. Light blue represents air temperature coefficients and dark blue represents water temperature coefficients; the diamonds show the mean of the coefficients within each power plant category.

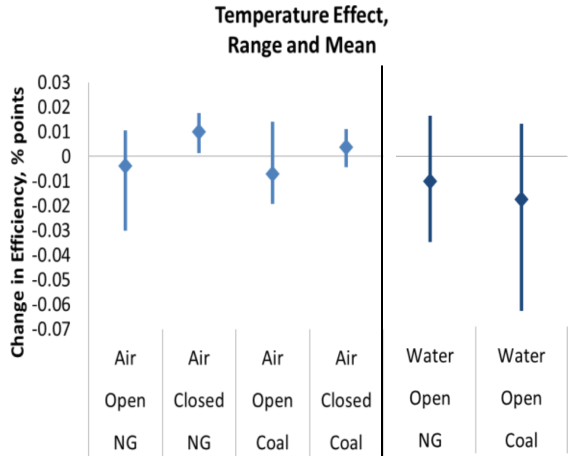

Figure 2. Effect of air and water temperatures on efficiency. Units are percentage change in efficiency per 1° C increase in temperature.
Open = open-loop, once-through cooling system
Closed = Closed-loop, recirculating cooling system

Quantitatively, figures from this graph can be used to estimate the overall impact of air and water temperatures on power plant efficiency. The mean air temperature effect on efficiency for open-loop coal plants is -0.007 percentage points for every 1° C increase in air temperature. Likewise, the mean water temperature effect for open-loop coal plants is -0.017. Multiplying these values by the variation of air and water temperatures over the course of a year generates an estimate of the temperature-related movement in plant efficiency. Average daily temperatures for 2007-2008 in York, Pennsylvania have a 41° C range (lowest daily average is -11° C and highest daily average is 30° C). Average daily water temperatures in York span 29° C (lowest daily average is 0° C and highest daily average is 29° C). Using Equation 3, the temperature-related efficiency variation of an open-loop coal plant in York, given 2 years of available data, is estimated to be 0.78 percentage points.

$$\eta_V = \alpha_2^* * A_R + \alpha_3^* * W_R \qquad \textit{Equation 3}$$

However, it is clear from Figure 2 that the effect of air temperature on efficiency is ambiguous. Some plants' efficiencies increase slightly with increasing air temperatures; other plants' efficiencies decline slightly with air temperature. This result is not surprising given the two physical relationships (described in section II) between air temperatures and efficiencies whose effects oppose each other. Moreover, nearly half of the plants analyzed did not exhibit any correlation between air temperature and plant efficiency.

Although the overall effect of air temperature on plant efficiency is uncertain and fairly small, there appears to be a correlation between the cooling system and the direction of efficiency. The efficiency of natural gas and coal plants with closed-loop cooling systems both tend to exhibit a positive correlation with air temperature, but the efficiency of open-loop systems tends to exhibit a negative correlation. This result was not expected based on the analysis of temperature and efficiency relationships. (However, one possible explanation is presented in the Discussion.)

Furthermore, the air temperature-efficiency relationship for open loop plants is mirrored in the water temperature-efficiency relationship, suggesting that these two variables are covariates which could weaken the regression modeling results. Two arguments refute this. First, there are 14 once-through generating units whose efficiency is statistically impacted by air and water temperature. However, only 4 of those units are affected by both air and water temperature, while the other 10 units are only affected by one variable or the other. Efficiencies at 7 plants are statistically correlated only with water temperature; at 3 plants efficiency is only correlated with air temperature; and at 1 plant efficiency is statistically correlated with both air temperature and dew point.

Second, the same regression was run with an interaction term between air and water temperatures. For nearly all the units' regressions, the coefficient on the interaction term was insignificant, or the models' power to explain the dependent variable (measured by the adjusted R^2) decreased dramatically with the interaction term, both of which indicate that the relationship between air and water temperature is not weakening the model. One additional concern which has not been tested is the possibility that even though air and water temperatures are not strong covariates at hour *t*, there may be a more significant relationship between air and water temperatures when a time lag is introduced.

Regarding water temperature and plant efficiency, the data show a clearer trend that increasing water temperatures are correlated with decreasing plant efficiencies for both coal and natural gas plants. This relationship is predicted by Carnot's equation.

Though dew point is included in the regression models, we do not describe in detail its impact on plant efficiency. For the majority of units, dew point is not a significant indicator of efficiency. Furthermore, of the 13 units where dew point is statistically significant, the regression coefficient on dew point for 8 of these units is an order of magnitude smaller than that of air or water temperature. Thus, if included in Figure 2, the range of dew points would be nearly invisible and not discernible from zero.

IECM Model

Coal Plants

Figure 3 shows the relationship between air temperature and plant net efficiency for four plants modeled using IECM. The 1000 MW plant is slightly more efficient than the 100 MW plant: at any given temperature, the 1000 MW plant's net efficiency is 0.03 percentage points higher than the 100 MW plant. Figure 3 shows that once-through plants have a higher net efficiency than recirculating plants. However, the gross efficiency of each plant is constant for both cooling types; the difference is caused by parasitic power consumption required to run the cooling tower.

According to IECM modeling results, there is a direct linear relationship between ambient air temperatures and efficiency for coal plants: as the temperature increases by 1° C, the plant's net efficiency increases 0.02 percentage points, when other variables are held constant. This relationship holds across cooling system types and plant sizes. The IECM model allows for the user to adjust temperatures within the range -9.4° C (15° F) to 37.8° C (100° F). When the ambient temperature is 37.8° C, the coal plant's net efficiency (for all plant sizes and cooling types) is 0.8 percentage points higher than when temperature is -9.4° C.

A 1000 MW coal plant operating in an environment whose temperature remains at 26° C for 24 hours will consume 7,425.6 short tons of coal, whereas the same plant operating at 0° C will consume 7,519.2 tons of coal, or 93.6 more tons over the same time period. In other words, for every 1° C increase in ambient air temperature the coal plant requires 3.5 fewer tons of coal to maintain a constant power output.

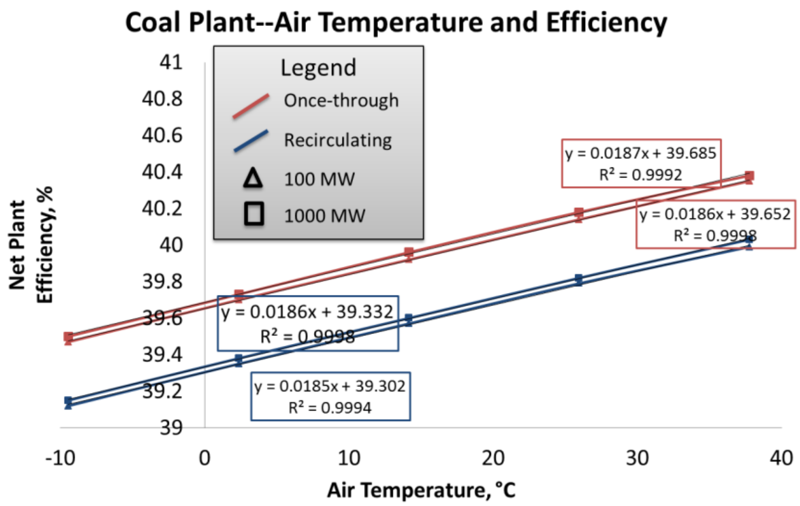

Figure 3. IECM Relationship between air temperature and coal plant efficiency for 4 different plants.

Natural Gas Plants

According to IECM results, the air temperature-efficiency relationship for natural gas plants is fundamentally different than for coal plants in both direction and shape of the effect. Instead of air temperatures boosting efficiency, increases in air temperatures reduce natural gas efficiency. Instead of a linear relationship between air temperature and efficiency, we observe a slightly decreasing slope in the curve as temperature increases. However, for simplicity, we assume a linear relationship across the range of temperatures modeled and present these results. This result is shown in Figure 4.

An increase of 1° C causes a decrease in net NG plant efficiency of 0.006 percentage points when the plant has a once-through cooling system, and 0.07 percentage points when the plant has a wet cooling tower. When air temperature at a once-through NG plant is -9.4° C efficiency is 50.55%. When air temperature increases to 37.8° C, efficiency decreases to 50.25%. For a recirculating plant the efficiency decrease over the same temperature range is from 50.26% to 49.91%.

Besides this slight change in efficiency, another notable relationship is observed between temperature and operation of the NGCC plant. As temperatures increase, the energy input into the plant, in mmBtu, decreased significantly. At -9.4° C (15° F) the plant's energy input is 1946 mmBtu/hour, but when the temperature is 37.8° C (100° F), the energy input drops to 1742 mmBtu. Overall, this is a 10.5% decrease in the energy input. Although the change in plant efficiency is very small, this drop in energy input leads to a significant drop in electrical output, from 288.3 MW (Net electrical output) to 256.3 MW over the same temperature range, which is an 11.1% reduction. This result corresponds to the well-documented effect described in the introduction: holding air volume constant, warmer air has a lower mass of O_2; when a combustion turbine's air compression system has a constant rate of air volume intake, the combustible O_2 levels per unit time decrease, decreasing the rate of combustion, meaning lower energy input, in mmBtu/hour.

Compared to a plant operating at a constant temperature of -9.4° C over a 24 hour period, the same plant operating at 37.8° C would consume nearly 5000 fewer mmBtu (46,704 mmBtu compared to 41,8008 mmBtu), and generate 761 fewer MWh of electricity (6,919 MWh compared to 6,158 MWh).

This work does not examine the empirical relationship between temperatures and fuel consumption or electrical output; we focus only on plant efficiency.

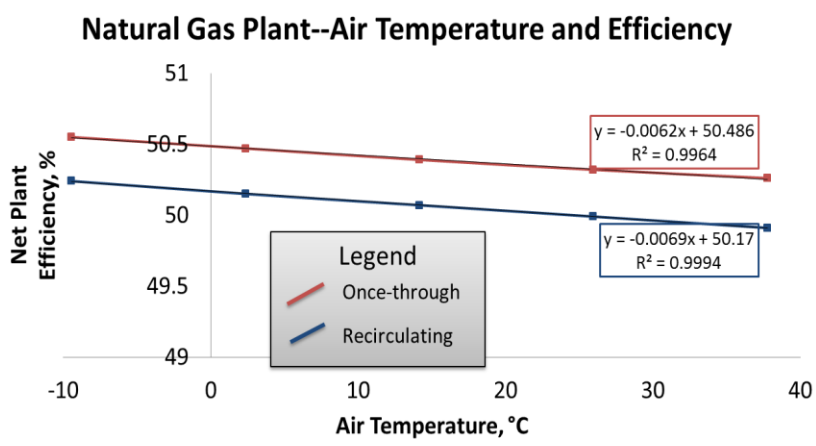

Figure 4. IECM relationship between air temperature and plant efficiency for once-through and recirculating plants.

VI. Discussion

Comparing Regression modeling and IECM results

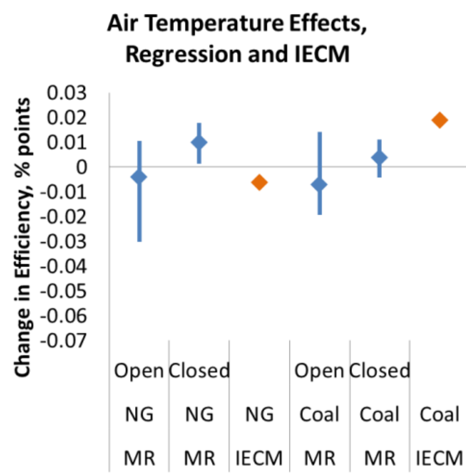

Figure 5. Comparison of regression results and IECM results. MR stands for multiple regression.

The IECM model predicts that increasing air temperatures have different effects on coal-fired boilers and NG combined cycle plants. As Figure 5 shows, increasing air temperature at a coal plant increases its efficiency; however increasing temperature at a NG combined cycle plant decreases efficiency. This may be explained using the analysis of the expected relationships between air temperatures and plant efficiency: increased air temperatures make a boiler more efficient because less energy is required to heat warmer air to the combustion temperature. However, combustion becomes less efficient with warmer air because the air is less dense and contributes less oxygen. The IECM model predicts that for a coal plant the former effect dominates, whereas for a NG combined cycle plant the latter effect dominates. This result is corroborated by available literature which shows that NG combustion turbines are less efficient when the air is warmer.

However, this result is not supported by the regression results presented here. There is virtually no difference between the air temperature coefficients of natural gas and coal plants from this regression. One possible explanation is that out of 8 NG-fired plants in this analysis, 6 are boilers and 2 are NG combined cycle plants. However, the 2 NGCC combined cycle plants in our dataset both show very small positive relationships between air temperature and efficiency, and the only plants with negative air temperature-efficiency relationships are the NG boilers.

Instead of showing varying effects of air temperatures on plant efficiency based on plant fuel type, the regression analysis suggests varying effects of air temperatures on efficiency based on the type of cooling system. This result is not predicted by the relationships we describe in section

II, in fact, it is difficult to imagine how different cooling systems could interact with air temperatures to have opposing effects on plant efficiency.

One possible explanation has to do with how the different cooling systems deal with thermal waste. Once-through cooling systems dispose of excess heat fairly rapidly. Cooling water enters the plant, removes heat from the steam, and is discharged back into the water body, carrying with it waste heat. However, for recirculating systems, cooling water enters the plant, removes heat from the steam, but then recirculates through the cooling system, getting hotter and hotter. Cooling towers are usually incorporated into recirculating cooling systems to allow the built-up waste heat to escape to the environment in the form of water vapor. Overall, plants with recirculating systems retain much more of the waste heat than those with once-through cooling systems, but perhaps more importantly, heat from recirculating systems is released much closer to the plant itself. Rather than discharging heat into the river and carried downstream, the heat is released into the plant's immediate vicinity in the form of water vapor. Perhaps there is a temperature feedback loop at plants with recirculating systems, where released heat increases the local temperature. The extra heat released from cooling towers is unlikely to appear in our data set since monitors are not onsite. However, discharging excess heat through the cooling towers may be more efficient when ambient temperatures are lower, whereas when ambient temperatures are higher, more of the discharged heat remains closer to the plant. Assuming warmer air increases efficiency, this feedback loop between ambient temperatures and temperatures in the plant's immediate vicinity would lead to even greater efficiency at plants with recirculating cooling systems than those with once-through cooling systems.

Explanation of insignificant environmental variables

There are a couple physical rationales to explain why in some instances the dependent variables may not be significant predictors of the independent variable. First, the water and air temperature monitors are not close to the power plants themselves. Though we would expect the relative temperature changes at the monitoring stations to reflect temperature changes at the plants, there could be thermal inputs to the water or air between the monitors and the plants that is not measured by the temperature monitors. These heat sources which could be other power plants or factories, heat island effects from urban centers or other concrete surfaces, local weather conditions, or even heat created by the power plants themselves would introduce variation in temperature not captured by this data. Potentially confounding heat sources are not examined in this analysis.

Second, there may be unexplored, unidentified factors related to the plants' operating characteristics which reduce the plants' sensitivity to air or water temperatures.

For reference, Table 2 (see appendix) shows the plants' locations, distances between monitors and plants, and the raw p-values for each regression coefficient (before removing the insignificant variables).

We do observe that statistical significance of the dependent variables is generally consistent across generating units within a particular plant. For example, for the Mercer plant's regression, coefficients of air temperature are statistically significant for both units 1 and 2 ($p < 0.01$); whereas at the Danskammer plant, the coefficients for both units 1 and 2 are not statistically significant ($p = 0.88$ and 0.94, respectively). This result suggests either consistently poor data quality for the Danskammer plant and consistently better data quality for the Mercer plant or that an unmeasured variable is far more important than temperature in determining the efficiency of the Danskammer plant, but which is not impacting the Mercer plant.

However, there are four instances where the statistical significance for the same parameter at the same plant is dramatically different between the plant's generating units. The water temperature for unit 1 of the Haynes plant is not statistically significant ($p = 0.40$) but for unit 2 of the same plant water temperature is significant ($p < 0.01$). Also at the Haynes plant, air temperature is statistically significant for unit 1 ($p < 0.01$) but not for unit 2 ($p= 0.48$). Similar discrepancies can be seen for the air temperature's significance levels between Port Jefferson's units 1 and 2 as well as for the water temperature significance between Danskammer's units 1 and 2. These results are odd. One confounding feature of the Haynes and Port Jefferson plants is that can be co-fired using oil. Typically, oil is used to ramp up a plant to its desired capacity, and it is possible that oil may be used as fuel during additional periods. However, the EPA data does not indicate which fuel is used in a given hour. If available, this data would have offered important insight since different fuel types in dual-fueled boilers could have a much larger impact on the unit's efficiency than would any changes in air or water temperatures.

Comparison with previous studies

The paper by Vliet et al. published in Nature describes a more substantial impact of a changing climate on power plant operations than is suggested by results presented here. This impact is the result of increased variation in both cooling water availability and temperature, which causes plants to shut down or curtail generation to avoid surpassing regulatory limits. Their work also points out that as cooling capacity decreases with increasing water temperature, power output will necessarily decrease as well. Reduced power output is likely to affect power plant efficiency. Our work attempts to isolate the effect of ambient temperatures on efficiency by eliminating variation in power output. We do however observe strong correlations between power output and efficiency showing that a decrease in power output is associated with a decrease in plant efficiency. Although efficiency impacts are merely implied by the scenarios described by Vliet, et al., they are not explicitly quantified. This goal of this work has been to quantify the relationship between temperatures and power plant efficiency.

There is some discrepancy between our results and the temperature impacts on efficiency found in the literature. Previous studies find that a 1° C air temperature increase leads an efficiency decrease of over 0.1 percentage points for natural gas combustion turbines, whereas the regression analysis presented here suggests a range of effects from -0.03 (decrease) to +0.02 (increase) percentage points per degree Celsius. This difference is most likely a result of different generation technologies studied. Natural gas turbines are particularly sensitive to air temperature compared to thermal steam generation plants. Furthermore, our results are consistent with estimates of the air temperature-efficiency effect implied by the IECM model.

Looking at water temperature and the efficiency of a pressurized-water nuclear reactor, Dumayaz found that a 1° C water temperature increase is correlated with an efficiency decrease of 0.12

percentage points. Our regression analysis suggests a range of efficiency changes from -0.06 (decrease) to +0.02 (increase). The nuclear plant may be more sensitive to cooling water temperature changes because the temperature inside the reactor (T_H in Carnot's equation) is 325° C (World Nuclear Association 2013) which is much lower than the 540° C temperatures inside coal and natural gas boilers (Tsiklari 2004). Analysis of the Carnot equation shows that a 1° C change in cooling water temperature (T_C) will have a larger effect on Carnot efficiency when T_H is lower.

Alternatively, it is possible that the temperature signal is reduced when regressed against efficiency as a result of thermal noise occurring between the air and water temperature monitors and the actual power plant. This is discussed above in the "Explanation of insignificant environmental variables" subsection.

Relevance of results

Variation explained by temperature changes compared to overall variation of power plants

Each power plant in this study operates at a range of efficiencies throughout the year. The regression results indicate that air and water temperatures are not the only factors that vary with efficiency. In fact, it appears that a large portion of the variation in plant efficiency cannot be explained by the relationship between ambient temperatures and efficiency. Holding power output constant, the efficiency variation over the course of a year for a generating unit is as low as 1.5 percentage points and as high as 9.0 percentage points. The average efficiency variation for the units studied is 3.9 percentage points.

In the Results section, the efficiency variation due to ambient temperature changes is estimated to be 0.78 percentage points for the open-loop coal plant in York, PA. The total observed efficiency variations for the three units of this York plant are 4.0, 6.0, and 6.0 percentage points. Therefore, the change in efficiency due to temperature changes throughout the course of a year explains only a fraction of the overall changes in efficiency.

Notably, assuming that plant efficiency varies by 0.12 percentage points per 1° C change in water temperature (Dumayaz), a 25° C water temperature range would lead to a 3% efficiency range, which is more consistent with the actual efficiency range experienced by the plants in this study.

Implications of 5° C increase for plant efficiency, fuel consumption, fuel cost, and emissions

Although the effect of temperature changes on power plant efficiency is small in percentage terms, this effect is noticeable in terms of fuel costs. Here we look at the potential impact of a 5° C increase in air and water temperatures on fuel costs for an 800 MW coal plant. For simplicity, we assume the plant has an average annual efficiency of 40%, a capacity factor of 70%, and that the 5° C increase in air and water temperatures applies to all hours of the year.[5]

The hypothetical plant consumes 1,743,532 short tons of coal each year. Using the average air and water temperature parameters ($\propto_2$ = -0.007 for air and $\propto_3$ = -0.017 for water), the decrease in efficiency associated with a 5° C temperature increase will be 0.12 percentage points. To maintain its power output of 800 MW, the plant requires 5,246 additional short tons of coal. Using the 2011 average coal price of $32.56 per short ton (EIA 2012), this decrease in efficiency represents an increased cost of $170,821 per year.

Finally, using EIA emission factors (Hong and Slatick 1994), 5,246 tons of bituminous coal represents 12,925 tons of CO_2 emissions.

VII. Conclusion

This study analyzes empirical data from thermoelectric power plants and temperature monitoring stations. Using multivariate regression, relationships between power plant efficiency and air and water temperatures are estimated for a variety of power plant types. For natural gas and coal plants with an open-loop cooling system a 1° C increase in air temperatures is correlated with a mean change in plant efficiency of -0.004 and -0.007 percentage points, respectively. For natural

[5] This assumption is particularly unrealistic but is used for illustration.

gas and coal plants with a recirculating cooling system, a 1° C increase in air temperature is correlated with a mean change in plant efficiency of 0.009 and 0.004 percentage points, respectively. A 1° C increase in water temperatures is correlated with a mean efficiency change of -0.01 and -0.02 percentage points for natural gas and coal plants.

These relationships are smaller in magnitude than reported by previous studies, which is likely a result of different methodologies, different technologies analyzed, and possibly due to data sources used in this study. Furthermore, regression results obtained in this study suggest that the variation in power plant efficiency is only partially explained by the variation in air and water temperatures.

Future iterations of this work may benefit from analyzing in greater detail the operating parameters at one or two power plants, confirming the accuracy of ambient temperature and plant efficiency data, or using another analytic method to compare this data. The conclusions we present contrasts with recent reports published in leading journals stating the dramatic impact of climate change on the power sector.

In the context of climate change, the effects quantified here pose relatively small risks to the power sector, especially given the gradual nature of global temperature changes. The temperature variation experienced by power plants over the course of a year, or even the course of a day is more dramatic than the expected change in temperatures over the next hundred years. However, any loss of efficiency will be experienced by all thermoelectric generators which account for the vast majority of power generation across the US and around the world. By calculating the magnitude of the relationship between ambient temperatures and plant efficiency, the current work helps determine the relative importance of the risk of rising temperatures for the power sector among the myriad risks created by a changing global climate.

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Appendix

Table 2. Distance between plant and temperature monitors, with regression model p-values. P-values above 0.05 (with red highlighting in this table) are often considered not statistically significant. These variables are omitted from the final model.

Plant Name and Unit	Plant City and State	Fuel	Cooling Syste	Distance to Water Monitor (mile	p-value for Water Temp coefficie	Distance to Air Monitor (mile	p-Value for Air Temp coefficie
Apache1	Cochise, AZ	Coal	Closed	n/a	n/a	54.5	0.000
Apache2	Cochise, AZ	Coal	Closed	n/a	n/a	54.5	0.000
Baldwin1	Baldwin, IL	Coal	Closed	n/a	n/a	9.2	0.145
Baldwin2	Baldwin, IL	Coal	Closed	n/a	n/a	9.2	0.088
Baldwin3	Baldwin, IL	Coal	Closed	n/a	n/a	9.2	0.187
Bowen1	Euharlee, GA	Coal	Closed	n/a	n/a	4.3	0.520
Bowen2	Euharlee, GA	Coal	Closed	n/a	n/a	4.3	0.000
Bowen3	Euharlee, GA	Coal	Closed	n/a	n/a	4.3	0.003
Bowen4	Euharlee, GA	Coal	Closed	n/a	n/a	4.3	0.000
Columbia1	Dekorra, WI	Coal	Closed	n/a	n/a	18.2	0.958
Columbia2	Dekorra, WI	Coal	Closed	n/a	n/a	18.2	0.461
Hayden1	Hayden, CO	Coal	Closed	n/a	n/a	2.4	0.000
Hayden2	Hayden, CO	Coal	Closed	n/a	n/a	2.4	0.000
Brunner1	York, PA	Coal	Open	50.9	0.030	50.9	0.001
Brunner2	York, PA	Coal	Open	50.9	0.011	50.9	0.000
Brunner3	York, PA	Coal	Open	50.9	0.008	50.9	0.075
Danskammer1	Newburgh, NY	Coal	Open	5.1	0.009	5.3	0.881
Danskammer2	Newburgh, NY	Coal	Open	5.1	0.709	5.3	0.936
Mercer1	Mercer, NJ	Coal	Open	3.5	0.000	7.6	0.000
Mercer2	Mercer, NJ	Coal	Open	3.5	0.000	7.6	0.001
Gadsby1	;alt Lake City, UT	NG	Closed	n/a	n/a	2.0	0.819
Gadsby2	;alt Lake City, UT	NG	Closed	n/a	n/a	2.0	0.121
HAFranklin1	Lee, AL	NG	Closed	n/a	n/a	11.1	0.000
HAFranklin2	Lee, AL	NG	Closed	n/a	n/a	11.1	0.000
HAFranklin3	Lee, AL	NG	Closed	n/a	n/a	11.1	0.000
HAFranklin4	Lee, AL	NG	Closed	n/a	n/a	11.1	0.000
Malburg1	Los Angeles, CA	NG	Closed	n/a	n/a	4.2	0.017
Malburg2	Los Angeles, CA	NG	Closed	n/a	n/a	4.2	0.054
ArthurKill1	Richmond, NY	NG	Open	4.7	0.000	4.2	0.000
ArthurKill2	Richmond, NY	NG	Open	4.7	0.000	4.2	0.007
Haynes1	Los Angeles, CA	NG	Open	10.5	0.402	4.5	0.000
Haynes2	Los Angeles, CA	NG	Open	10.5	0.000	4.5	0.482
Humboldt1	Humboldt, CA	NG	Open	2.1	0.000	17.4	0.798
Humboldt2	Humboldt, CA	NG	Open	2.1	0.000	17.4	0.280
PortJeff1	Long Island, NY	NG	Open	16.5	0.197	58.6	0.824
PortJeff2	Long Island, NY	NG	Open	16.5	0.137	58.6	0.013
Potrero1	an Francisco, CA	NG	Open	5.1	0.000	5.2	0.327

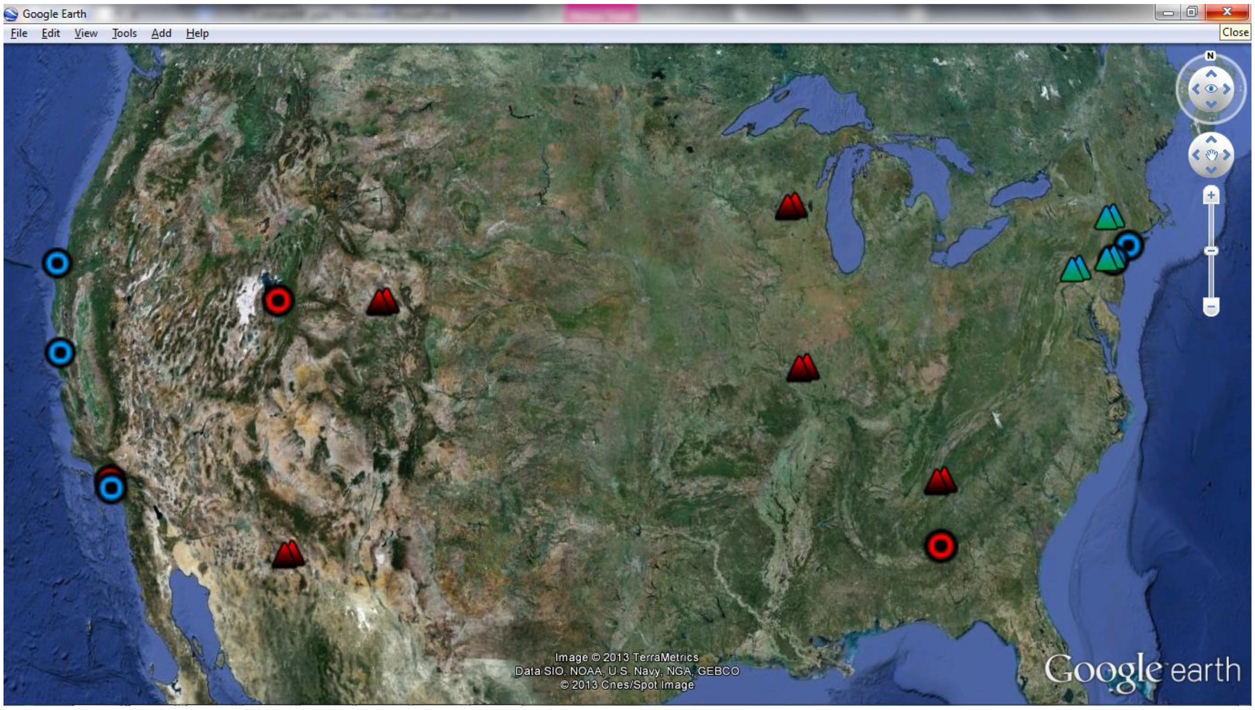

Figure 6.

Coal, recirculating

Coal, open-loop

Natural gas, recirculating

Natural gas, open-loop

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Table 3. Comparison of adjusted R2 values with and without lag of dependent variable included in regression model.

Unit	Fuel	Cooling System	Number of Records	Adjusted R^2--With Lag	Adjusted R^2--No Lag
Apache1	Coal	Closed	3474	0.66	0.06
Apache2	Coal	Closed	5191	0.83	0.07
Baldwin1	Coal	Closed	516	0.55	0.07
Baldwin2	Coal	Closed	493	0.62	0.08
Baldwin3	Coal	Closed	394	0.74	0.03
Bowen1	Coal	Closed	1421	0.72	0.24
Bowen2	Coal	Closed	1970	0.75	0.01
Bowen3	Coal	Closed	2587	0.74	0.01
Bowen4	Coal	Closed	1871	0.74	0.12
Columbia1	Coal	Closed	604	0.44	0.02
Columbia2	Coal	Closed	522	0.73	0.01
Hayden1	Coal	Closed	1851	0.76	0.07
Hayden2	Coal	Closed	4076	0.75	0.07
Brunner1	Coal	Open	850	0.67	0.13
Brunner2	Coal	Open	929	0.75	0.21
Brunner3	Coal	Open	561	0.54	0.10
Danskamme	Coal	Open	1537	0.80	0.03
Danskamme	Coal	Open	838	0.81	0.11
Mercer1	Coal	Open	6830	0.85	n/a
Mercer2	Coal	Open	7226	0.90	n/a
Gadsby1	NG	Closed	434	0.36	0.01
Gadsby2	NG	Closed	588	0.51	0.01
HAFranklin1	NG	Closed	314	0.50	0.20
HAFranklin2	NG	Closed	306	0.46	0.29
HAFranklin3	NG	Closed	367	0.47	0.13
HAFranklin4	NG	Closed	339	0.43	0.04
Malburg1	NG	Closed	2914	0.69	0.01
Malburg2	NG	Closed	2957	0.81	0.01
ArthurKill1	NG	Open	2181	0.72	0.34
ArthurKill2	NG	Open	2118	0.86	0.59
Haynes1	NG	Open	2107	0.88	0.09
Haynes2	NG	Open	1830	0.54	0.20
Humboldt1	NG	Open	1202	0.67	0.17
Humboldt2	NG	Open	1031	0.37	0.09
PortJeff1	NG	Open	311	0.50	0.05
PortJeff2	NG	Open	261	0.43	0.02
Potrero1	NG	Open	9477	0.81	0.48

Table 4. Number of units whose regression equation includes each combination of variables.

Number of units			Regression Models Include:							
			No Significant Variables	1 Significant Variable			2 Significant Variables			All Variables Significant
Fuel Type	Cooling System	Number of Units		Only Air Temp	Only Water Temp	Only Dew Point	Air Temp and Dew Point	Air Temp and Water Temp	Water Temp and Dew Point	
Coal	Recirculating	13	4	2	n/a	2	5	n/a	n/a	n/a
Coal	Once through	7	0	0	2	0	1	2	0	2
NG	Recirculating	8	3	1	n/a	0	4	n/a	n/a	n/a
NG	Once through	9	0	2	5	0	0	2	0	0
	Totals	**37**	**7**	**5**	**7**	**2**	**10**	**4**	**0**	**2**