Power plant heat-rate efficiency as a regulatory mechanism: Implications for emission rates and levels

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Abstract

In August 2018, the U.S. Environmental Protection Agency (EPA) proposed a new policy – the Affordable Clean Energy rule – to reduce greenhouse gas (GHG) emissions from existing coal-fired electric generating units and power plants. The new rule establishes emissions guidelines, including heat-rate efficiency improvements, for states when developing plans to limit GHG emissions. Past studies have indicated that heat-rate efficiency improvements can increase electricity output, leading to a reduction in emissions rates and an increase in emissions levels – a rebound effect that can temper the emissions-reduction benefits of plant-level heat-rate efficiency. This study adds to the literature by examining data on the relationship of plant-level heat-rate efficiency on the rate and level of GHG emissions. We explored three different types of GHGs – carbon dioxide, methane, and nitrous oxide. Controlling for variation across operators, our results suggest that gains in heat-rate efficiency are associated with higher levels of all three pollutants. Specifically, we found that a ten percent increase in heat-rate efficiency led to an average seven-to-nine percent increase in the level of GHG emissions. Our analysis highlights the need to further study the full effects of heat-rate efficiency policies before such rules are enacted.

Keywords: Greenhouse gas emissions; heat-rate efficiency; thermal efficiency; electricity policy; rebound effect

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Highlights:

- Ten percent gain in thermal efficiency led to 8.7% increase in the level of CO_2 emissions.
- Ten percent gain in thermal efficiency led to 7.6% increase in methane emissions.
- Ten percent gain in thermal efficiency led to 7.3% increase in the nitrous oxide emissions.
- Improvements to thermal efficiency led to a decrease in the rate of GHG emissions.

1 Introduction

Will a regulatory framework targeting lower greenhouse gas (GHG) emission rates also reduce emission levels? A recently completed analysis from the U.S. EPA found that coal-fired power plants can reduce carbon dioxide emissions by making on-site efficiency upgrades or "heat rate improvements," which is claimed to reduce the amount of carbon released by a unit of electricity generated (U.S. Environmental Protection Agency, November 1 2018). However, skeptics suggest that efficiency improvements may reduce emissions rates, but such improvements generally lead to enhanced electricity output, which can increase emissions levels (Grant *et al.* , 2014). This is not a new argument – experts have debated about the relationship between energy efficiency and global climate change (formerly referred to as the "greenhouse effect") for the past several decades (Brookes, 1990; Keepin & Kats, 1988; Jones, 1989). In particular, Jones (1989) argues that efficiency improvements should be viewed as complementary to other energy technologies, not in competition with them. From a policy perspective, this idea implies that efficiency improvements alone may not be capable of reducing GHG emissions.

In August 2018, the U.S. Environmental Protection Agency (EPA) proposed the Affordable Clean Energy (ACE) rule (83 FR 44746), which would provide a regulatory framework for states to establish guidelines for regulating GHG emissions from coal-fired power plants (The Federal Register, August 31 2018).[1] The ACE rule focuses entirely on emission rates, proposing to direct states to establish emission rate standards for electricity generating units in their state, and to choose

[1]The ACE rule is intended to replace the Clean Power Plan (CPP) (80 FR 64662), proposed in 2015 but never fully implemented due to a stay by the U.S. Supreme Court (The Federal Register, October 23 2015). In October 2017, the EPA proposed repealing the CPP, arguing that the proposal exceeded the agency's administrative authority (82 FR 48035).

among a list of the "best system of emission reduction" (BSER) technologies to implement those standards by improving power plant efficiency.

The relevant measure of power plant efficiency is thermal efficiency or heat-rate efficiency – a measure of the efficiency of a power plant that converts a fuel (such as coal) into heat and then ultimately into electricity. More specifically, it is the amount of energy, measured in the British thermal units, used by an electrical generator (within a power plant) to generate one kilowatt-hour of electricity. By adopting heat-rate efficiency measures or technologies, a plant can reduce the per-unit costs of its energy inputs as well as reduce the amount of fuel used per unit of output. For example, cogeneration (or combined heat and power) is a technology in which electricity is generated, and the heat created during the production process is captured to be used for productive purposes. To avoid confusion between the terms thermal efficiency and heat-rate efficiency, we will use the latter term hereafter.

In addition to reducing emissions rates, increased heat-rate efficiency can reduce both the marginal cost and average cost of production. For that reason, more thermally efficient power plants may be dispatched more frequently, which would increase the capacity utilization in those plants.[2] Figure 1 is a binscatter plot that uses the plant-level data 2010-2016 employed in this analysis to show that more thermally efficient plants do have higher capacity utilization. If the cost-reduction effect is significant enough to lead to increased generation, GHG emission levels could increase. This form of a rebound effect, or Jevons effect (Jevons, 1866, Chapter 7), would cause rates and levels to diverge, potentially undermining the rate-based policy's ability to deliver stabilization or reduction in GHG emission levels. Divergent rates and levels, where the level effect is smaller than the rate ef-

[2]This logic holds both in vertically-integrated states, where least-cost operation guides dispatch, and restructured states participating in organized wholesale power markets, where security-constrained economic dispatch would lead to increased capacity utilization of more thermally efficient power plants that can submit lower offers into energy and ancillary service markets.

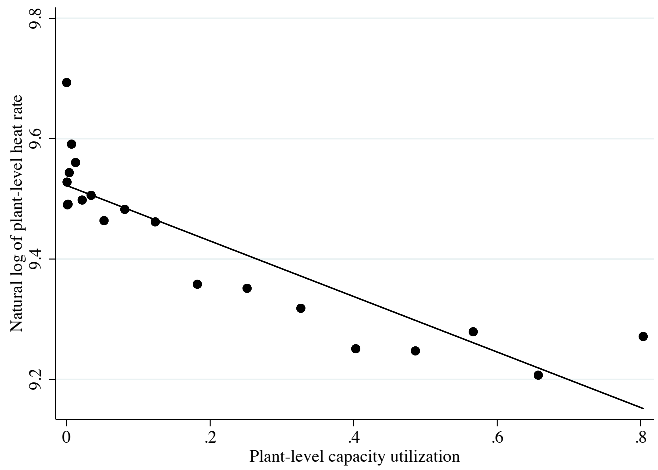


Figure 1: Plant-level heat rate plotted against capacity utilization

fect, temper the emissions reduction benefits of higher heat-rate efficiency (Gillingham *et al.* , 2013).

Our analysis focuses on emission rates and levels for three greenhouse gases – carbon dioxide, methane, and nitrous oxide. Carbon dioxide is the largest by volume, methane is the most potent (although with a shorter residence time in the carbon cycle), and nitrous oxide is the third largest GHG in the U.S. They have different physical and economic dynamics, so identifying the association between rates and levels for each GHG separately yields clearer insights for appropriate policy responses. For example, carbon dioxide and nitrous oxide emissions arise predominantly from combustion for electricity generation or transportation, while methane emissions arise more from flaring and leakage than they do from combustion.

The likely effect of improved power plant heat rates on GHG emission rates and levels under the ACE is an empirical question. At the margin, the energy efficiency effect and cost reduction effect have opposing consequences for the amount of electricity produced. This paper examines updated plant-level data on generation, fuel use, and emissions to establish what, if any, plant-level rebound effects have occurred in the past eight years, to create a better understanding of the possible unintended consequences of rate-based regulations.

One contribution of this work is the collection and combination of three separate data sources into one data set with multiple years of data since 2010. In part, our analysis updates prior work from Grant *et al.* (2014), who performed a cross-sectional analysis using 2010 emission data to show that plants with higher heat-rate efficiency and lower per-unit emission rates did have greater levels of GHG emissions.

Our fixed effects panel data approach, with time and plant-level fixed effects, uses updated plant-level data on generation and fuel use to estimate heat rates (conditional on various other determinants of plant-level emissions) over time. Our data include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions – all of which are greenhouse gases. Following Grant *et al.* (2014), we test the hypotheses that plant-level heat-rate efficiency is negatively associated with emission rates and positively associated with emission levels. These hypotheses capture the question of whether a rate-based power plant efficiency regulation, like that proposed in the ACE rule, would meet the policy objective of reducing greenhouse gas emissions.

We find mixed results for the relationship between heat rates and pollution emissions. Consistent with the policy objective of the ACE rule, we find that plant-level heat rates are negatively correlated with all three GHGs' emissions – that is, as plants experience heat rate efficiency gains, the *rate* of pollution emissions is declining. However, our results also suggest that plants that experience heat rate efficiency gains, on average, generate higher *levels* of GHG emissions, which is contrary to the objectives of the ACE rule. These findings support the earlier results from Grant *et al.* (2014). We model this relationship given three levels of fixed effects: state-level, plant-level, and operator-level. When we control for variation within plants (i.e., specify plant-level fixed effects), there is no longer a significant relationship between heat-rate efficiency and the level of emissions. We posit that the plant-level fixed effects model arguably suffers from the incidental parameters problem, leading to inconsistent parameter estimates; instead we appeal to the operator-level fixed effects model, which implies that heat-rate efficiency gains are positively correlated to the levels of all three GHG emission types. Based on our finding, we argue that more research is necessary to determine the full effects of heat rate policy rules on the level and rate of pollution emissions.

1.1 Background

Would reductions in emission rates at coal-fired power plants translate into reduced plant-level GHG emission levels? Increased heat-rate efficiency of a power plant can reduce emissions per unit of electricity generated (Hansel, 2014; U.S. Environmental Protection Agency, 2010; Tierney, 2014). By decreasing the marginal cost of generation, though, it can also increase total plant emissions if the decrease in marginal cost means that the plant is dispatched more frequently. Two recent regulatory rulings have both relied on rate-based greenhouse gas regulations.

The Obama Administration proposed the Clean Power Plan (CPP) in June 2014, using the regulatory authority granted to the EPA by Congress under the Clean Air Act.[3] One aspect of the CPP was state-specific emissions standards that used "adequately demonstrated" approaches to emissions reduction (Fowlie *et al.* , 2014). These standards would be tailored to the specific features of each state's

[3]The Supreme Court of the United States issued a stay of the CPP on February 9, 2016, until all lower courts had heard and ruled on legal challenges. In the ensuing period, the U.S. Presidential election led to a change of political party, resulting in policy changes at many federal administrative agencies including the EPA.

generation profile, and each state would be required to design a plan to meet the standard.

Compliance with the CPP would require meeting an emissions rate rather than reducing emissions levels by a specific amount, although states had the choice of translating the rate-based standard into a mass-based standard by using plant-level electricity generation forecasts to estimate future emissions levels.

Against the backdrop of the CPP and legal challenges to it, the Trump Administration proposed the Affordable Clean Energy (ACE) rule in October 2017 as an alternative to the CPP (Congressional Research Service, 2019). The ACE rule would provide guidelines to states using a definition of the best system of emission reduction (BSER) based on heat-rate efficiency improvements. The EPA would provide states and generation owners with a list of "candidate technologies" that satisfy BSER, with states able to choose among them when implementing the rule.[4]

While the CPP and the ACE proposals differ in scope and focus, both proposals rely on rate-based limits on greenhouse gas emissions (U.S. Environmental Protection Agency, 2018). For a given level of output, an emissions rate reduction would reduce emissions levels, but an increase in generation accompanying a shift to lower-carbon fuel sources could increase levels while decreasing rates. In analyzing the CPP, Fowlie *et al.* (2014) note that "The use of a ratio-based standard makes for a loose connection between meeting the required emissions-output ratio and achieving the Administration's forecasted emissions reductions" (p. 815). Rate-based regulations in other industries, such as low-carbon fuel standards, can lead to increased emissions levels (Holland *et al.* , 2009).

The CPP had a more diversified portfolio of activities that would have constituted compliance, and states could choose whether to use emission rates or emis-

[4]The ACE proposal also includes provisions that modify New Source Review restrictions on existing power plant modifications.

sion levels. This flexibility implied some tradeoffs, especially regarding inefficiencies due to wholesale power market balkanization if neighboring states did not coordinate on their chosen approach (Bushnell *et al.* , 2017). The ACE proposal's focus on emission rates and power plant heat rates seems to reduce some of those potential coordination costs. One substantial difference between the two proposals is the scope of compliance — ACE's measurement would include only on-premises energy efficiency improvements, while the CPP's focus was broader.

By the ACE proposal's underlying logic, improving heat-rate efficiency at coal-fired power plants would reduce their emission rates. The relevant heat-rate efficiency measure is a plant's heat rate, which is the amount of energy used to generate a kilowatt-hour (kWh) of electricity. Plants with higher heat-rate efficiency have lower heat rates because they use less fuel per generated kWh.

Grant *et al.* (2014) examined this question in the context of the Clean Power Plan, using cross-sectional plant-level data from 2010. They found that increased heat-rate efficiency had contradictory effects by decreasing carbon dioxide emissions rates while also increasing emissions levels. Their work motivates our analysis, in which we use multiple years of plant-level data on carbon dioxide, methane, and nitrous oxides.

2 Data and Methodology

2.1 Data

We constructed a data set including electric power generation facility characteristics and pollution emissions for the years 2011 through 2016. To construct the data set, we combined three separate samples: the U.S. Energy Information Administration's (EIA) 860 and 923 surveys, and the US. Environmental Protection Agency's

Greenhouse Gas Reporting Program (GHGRP). EIA survey 860 collects generator-level specific information about existing and planned generators and environmental equipment (U.S. Energy Information Administration, 2018a). Likewise, EIA survey 923 collects electric power data on electricity generation, fuel consumption, and fossil fuel stocks (among other information) (U.S. Energy Information Administration, 2018b). On the other hand, the EPA's GHGRP tracks facility-level emissions from the largest sources of greenhouse gas emissions in the U.S. (U.S. Environmental Protection Agency, 2017).

To collate the three separate surveys, we used power plants as the unit of analysis and matched the unique powerplant identifier from the EIA data to the EPA's facility identifier for the GHGRP data. After pooling the data across plants and years, we ended up with a quasi-balanced panel data set of approximately 11,118 observations. Our sample consists of 1,482 unique power plants over a six-year period. The sample comprises coal, natural gas, and petroleum (or fuel oil) plants. According to Muyskens *et al.* (March 28 2017), there were 1,793 natural gas-powered and 400 coal-powered electric plants in the U.S. as of the year 2017. Our sample has fewer plant-level observations because the U.S. EPA's GHGRP primarily includes plants that met the EPA's criterion of a "major source" polluter and were required to submit emissions reports (Grant *et al.* , 2014).

2.1.1 Dependent variables

We defined two different measures of pollution emissions that connect directly to the CPP and ACE proposals: the emissions level and the emissions rate. The EPA's GHGRP provided three types of pollutants – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (U.S. Environmental Protection Agency, 2017). Emission levels are defined as the metric tons of emissions (of CO_2, CH_4, or N_2O)

by plant and year. The emissions data (measured in both rates and levels) were highly skewed, so when using these data in our econometric analysis, we converted the emissions using a natural logarithmic transformation.

The emissions rate provides information about the pollution intensity of each plant's production. We operationalized the emission rate as a metric ton of pollution emitted per megawatt-hour (MWh) of net electricity generated:[5]

$$\text{Emissions rate}_{it} = \frac{\text{Pollution emissions}_{it}}{\text{Net electricity generated}_{it}}, \tag{1}$$

where i denotes a power plant and t denotes the year of observation. The emissions rate is a measure of emissions per unit of electricity generated that is independent of the overall scale and scope of a plant's total annual electricity generation.

To provide robust estimates of the relationship between emission levels (or rates) and heat-rate efficiency, we used the repeated years of observations to formulate a panel data set. Panel data enabled us to control for time-invariant factors, including plant, operator, state, and year fixed effects, that would affect emissions and efficiency through time. We also controlled for North American Electricity Reliability Corporation (NERC) specified regions.

2.1.2 Primary explanatory regressor

Our main regressor (or explanatory variable) of interest is plant-level heat-rate efficiency, operationalized as the plant's heat rate or the amount of energy used to generate a unit of electricity. The total fuel consumed is expressed in British thermal units (BTU), whereas net electricity generation is expressed in MWh:

[5] As in Grant *et al.* (2014), this measure of emission rate can also be interpreted as the pounds of pollution per kilowatt-hour of net generation after a small conversion (metric tons to pounds and megawatt-hours to kilowatt-hours) to the reported units of analysis.

$$\text{Heat rate}_{it} = \frac{\text{Total fuels consumed}_{it}}{\text{Net electricity generation}_{it}}. \quad (2)$$

The "total fuels consumed" in the numerator is defined by the EIA as the sum of all energy inputs (feedstocks) converted to BTUs.[6] Total fuels consumed is calculated by multiplying the total fuel quantities (used as inputs in production) by their average heat content (U.S. Energy Information Administration, 2018b). As with the levels of observed emissions, the calculated heat rate values were highly skewed, so we converted the heat rates using a natural logarithmic transformation.

2.1.3 Controls

To help ensure that the effect estimates of heat-rate efficiency (on the rates or level of emissions) are not biased, we controlled for several other plant-level characteristics. All of the control variables are outlined in rows fifteen through twenty-three of Table 1, including coal, natural gas, or petroleum as indicators (or binary variables) of particular feedstock. We also included total, summer, and winter capacity to control for the overall size of a given plant. Moreover, "CHP" denotes an indicator variable equal to unity if the plant utilizes a combined heat and power technology to generate electricity.[7] Lastly, the term "Ownership" consists of three indicator variables for different types of generator ownership (U.S. Energy Information Administration, 2018a). The binary variable "jointly owned" indicates that the generator is owned jointly by at least two separate parties (one of which may not have an ownership stake with the parent operator or utility). "Solely owned" indicates that the generator is wholly-owned by the operator or utility, while "third-

[6]This ratio will be converted to natural log form (explained further below) so that the estimated coefficient is easier to interpret.

[7]Combined heat and power has proven to be an economical option to reduce greenhouse gas emissions in the energy sector (Karbassi *et al.* , 2007).

party owned" pertains to generators wholly-owned by a third-party.

2.2 Methodological Approach

To derive robust estimates of the effect of the plant-level heat rate on emissions levels (or rates), we adopted a micro-panel estimation strategy using an unbalanced panel of 1,482 plants over a period of six years (2011-2016). The panel data model is expressed as:

$$\ln(p_{it}) = \beta \cdot \ln(h_{it}) + \mathbf{X}\boldsymbol{\delta} + \mathbf{M}_i'\boldsymbol{\gamma} + \mathbf{Y}_t'\boldsymbol{\eta} + \varepsilon_{it}, \tag{3}$$

where $\ln(p_{it})$ denotes the natural log of pollution emissions, and the term $\ln(h_{it})$ represents the natural log transform of the heat rate of plant i in year t. The term $\mathbf{X}$ denotes a vector of covariates including plant feedstock, plant-level production capacity, an indicator for combined heat and power, and a categorical variable for generator ownership type. $\mathbf{M}_i$ is a vector of plant-, state-, or operator-level fixed effects. $\mathbf{Y}_t$ is a vector of year binary variables, corresponding to the years 2012 to 2016. The parameters to be estimated are: $\beta, \boldsymbol{\delta}, \boldsymbol{\gamma}, \boldsymbol{\eta}$.[8]

Our primary interest lies in the estimated sign and magnitude of the coefficient, β, on the heat rate term. As in Grant *et al.* (2014), our two hypotheses are:

$H_1 : \beta_{rate} > 0$ (Emissions *rate* and heat rate are *positively* related);

$H_2 : \beta_{level} < 0$ (Emissions *level* and heat rate are *inversely* related).

[8]For the sake of exposition, we omitted the fixed effects coefficient estimates ($\boldsymbol{\gamma}$ and $\boldsymbol{\eta}$) from the tables of regressions results below, and can provide the full set of regression results upon request.

The term β_{rate} refers to the estimated heat-rate coefficient on the *rate* of emissions; whereas the term β_{level} denotes the estimated heat-rate coefficient on the *level* of emissions. We expect the emissions rate and heat rate to be positively correlated ("H_1") because more efficient plants have lower heat rates (i.e., less heat is expended for each kilowatt-hour of electricity produced). All other things begin equal, we expect that the rate of emissions is declining in increased efficiency; therefore, the rate of emissions and the heat-rate ratio move in the same direction.

Regarding the second hypothesis, less efficient plants have higher heat rates (i.e., more heat is expended for each kilowatt-hour of electricity produced), which are predicted to yield higher levels of pollution emissions, so the expected sign on the second hypothesis ("H_2") is negative.

The natural logarithm transformation of plant-level emissions and heat rate enables interpretation of the β coefficient (in that particular set of regressions) as an elasticity.[9]

Summary statistics are offered in Table 1.

3 Results and Discussion

Figures 2-3 illustrate the predicted effects of the observed plants' heat rates on their levels and rates of emissions. Emissions levels are displayed in 2a-2c, while emissions rates are provided in 3a-3c. All of the plots are conditional on the other

[9]Since we are applying a natural logarithm transformation to a ratio, these two specifications (excluding the other control variables) for the heat rate variable are roughly equivalent: $\ln(emissions) = \beta \ln(heat/MWh) + \varepsilon$, and $\ln(emissions) = \beta_1 ln(heat) - \beta_2 ln(MWh) + \varepsilon$. We tested the equivalence of the two coefficients in the latter specification by running a set of auxiliary regressions (not provided), and then conducted Wald post-estimation tests to determine if $\beta_1 = \beta_2$ (not provided). The Wald test results indicated a rejection of the hypothesis for all three pollutants. The rejection implies that a plant's total fuels consumed (the heat variable in the numerator) and the plant's net generation (the MWh produced in the denominator) are exerting separate effects on the level of emissions. However, these findings do not necessarily invalidate the choice of the heat rate ratio as an explanatory variable.

Table 1: Summary statistics: The number of observations, mean, standard deviation, minimum value, and maximum value for each variable

Variable	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
Carbon dioxide	11,118	249,243.70	735,002.4	0.1	1.2e+07
Carbon dioxide (natural log)	11,118	8.5620	3.7857	-2.3026	16.3127
Carbon dioxide rate	11,118	4.7931	19.55	6.16e-09	163.99
Carbon dioxide rate (natural log)	11,118	-2.8826	3.8819	-18.9050	5.0998
Methane	11,118	402.25	1,846.69	0	35,097
Methane (natural log)	11,118	2.0431	2.7331	-5.0878	10.4659
Methane rate	11,118	0.0071	0.0673	0	3.8231
Methane rate (natural log)	11,118	-7.2172	4.5971	-20.5955	1.3411
Nitrous oxide	11,118	892.81	3,688.47	0	61,471.44
Nitrous oxide (natural log)	11,118	2.3491	2.8974	-4.9116	11.0263
Nitrous oxide rate	11,118	0.0147	0.1157	0	5.9810
Nitrous oxide rate (natural log)	11,118	-6.5834	4.6488	-20.4193	1.7886
Heat rate	11,118	15,805.3	32,785.22	15.2141	1,484,118
Heat rate (natural log)	11,118	9.4297	0.5151	2.7222	14.2103
Coal (1=yes)	11,118	0.1822	0.3861	0	1
Nat gas (1=yes)	11,118	0.5596	0.4965	0	1
Petroleum (1=yes)	11,118	0.2063	0.4047	0	1
Total capacity	11,118	578.9693	642.8523	1	4,317.5
Summer capacity	11,118	516.6641	581.8041	0	3,695
Winter capacity	11,118	540.3824	600.9367	0	4,019
CHP	11,118	0.1924	0.3942	0	1
Solely Owned	11,118	0.8040	0.3970	0	1
Third-party owned	11,118	0.0915	0.2882	0	1

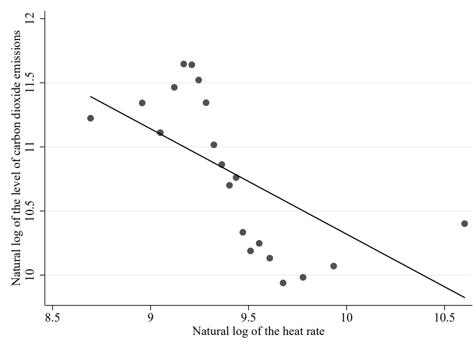
Notes: Variables that have been converted to natural logs are listed with the phrase "natural log" following the **variable name. Otherwise, all other variables are listed in levels.**

control variables (discussed in detail below). More specifically, the illustrations are based on non-parametric regressions, where the bins of emissions are represented by the circles and the line of fit (of the bivariate regression) is represented by the straight line. The figures were generated using the Stata program "binscatter," which uses a non-parametric method to plot the conditional expectation function that describes the average y-value for each x-value. The binned scatterplots were a useful way to visualize the relationship between emissions and heat rate, as the conventional scatterplots were too noisy to make any sense out of the line of fit. To generate the binned scatterplot, the program groups the x-axis variable into equal-sized bins, computes the mean of the x-axis and y-axis variables within each bin, and then plots each of these data points (Stepner, 2014). (For ease of exposition, we grouped each observation into one of twenty bins, the default setting for the program, within each figure). As with standard ordinary least squares regression analysis, the tighter the scatterpoints are to the regression line, the more precisely the slope is estimated, and vice versa.

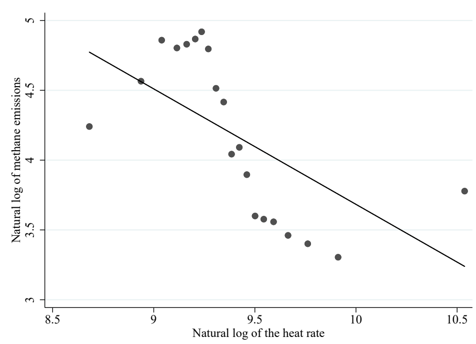
As illustrated in the figures, the natural log-transformed emission rates (Figure 3) appear to be more precisely estimated than the level of emissions (Figure 2). The keen reader will notice a non-linear relationship between the (natural log) level of emissions and (natural log) heat rates. Based on this observation, we explored regression models with a quadratic specification of the heat-rate ratio to determine if there is a non-linear relationship between plant-level heat rates and emissions.

3.1 Carbon dioxide emissions

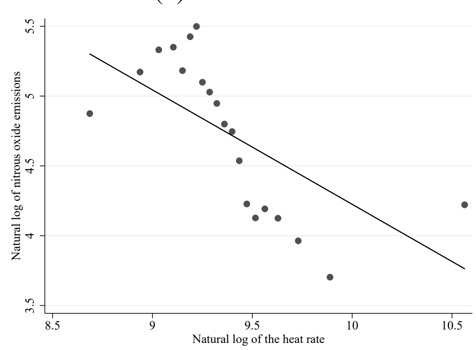
To analyze further the initial findings offered by the binned scatterplots, we also conducted multivariate regression analysis in Tables 2-7. Generally speaking, the results are consistent with the specification offered in equation (3). Table 2 illus-



(a) Carbon dioxide level

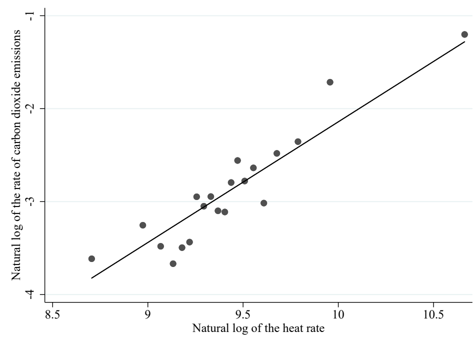


(b) Methane level

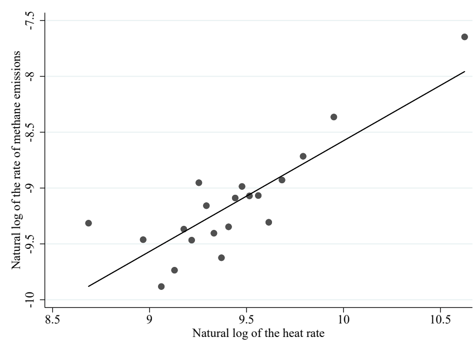


(c) Nitrous oxide level

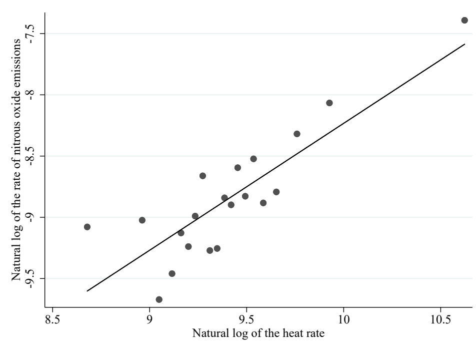
Figure 2: Binned scatterplot of emission levels against plant-level heat rates (conditional on all of the other explanatory variables)



(a) Carbon dioxide rate



(b) Methane rate



(c) Nitrous oxide rate

Figure 3: Binned scatterplot of the rate of emissions against plant-level heat rates (conditional on all of the other explanatory variables)

trates the relationship between the level of carbon dioxide emissions and the heat rates conditional on various plant-level characteristics, NERC, and year fixed effects. Whereas, Table 3 illustrates the correlation between the the rate of CO_2 emissions and heat rates.

3.1.1 The level of carbon dioxide emissions

Within Table 2, columns (1) - (6) illustrate the models with the level of emissions (transformed to natural logs) defined as the dependent variable. The specifications in columns (3) and (4) differ by using plant-level fixed effects instead of state-level fixed effects as defined in columns (1) and (2). Columns (5) and (6) differ still by using operator-level fixed effects – where the operator is defined as the parent company operating the plant. The plant-level (operator-level) fixed effects control for any unobserved heterogeneity within plants (operators), whereas the state-level fixed effects control for unobserved heterogeneity within states. Our empirical observations contained data on 50 states and the District of Columbia; 1,481 distinct plants; and, 923 unique operating companies – these are listed at the bottom of Table 2 depending on which unit is defined as the fixed effect term. The specifications in columns (1), (3), and (5) assume a linear relationship between heat rates and emissions, and the specifications in columns (2), (4), (6) offer a sensitivity analysis by using a quadratic specification of the heat rate term.

As predicted by our first hypothesis, the estimated coefficient on the (natural log transformed) plant-level heat rate is negative and highly statistically significant across the specifications in columns (1) and (2). The coefficient estimate in column (1) implies that a ten-percent decrease in heat rate leads to an approximate 4.7 percent increase in the level of carbon dioxide emissions. These findings suggest that as heat rates are decreasing (which implies an improvement in plant-level heat-rate efficiency as promulgated by the CPP or ACE rules), carbon dioxide emissions levels are increasing (not decreasing). The specification in column (2) suggest that the relationship between the heat rate and CO_2 emissions is non-linear.

The estimated coefficient on the heat rate is sensitive to the specification of fixed effects, as the results for columns (3) and (4) indicate. More specifically, when we include plant-level fixed effects, the results suggest no significant relationship between emissions and the heat-rate ratio. We posit that the insignificance with the plant-level effects is arguably due to a incidental parameters problem, wherein the large number of plants within our study is greatly increasing the number of variables within the model to be estimated (Greene, 2003).[10] Therefore, we also estimated the same regression equation but specified operator-level fixed effects, which greatly reduced the number of variables within the model. The estimate in column (5), our preferred specification, corroborates the finding in column (1). More specifically, the estimate for the heat-rate ratio coefficient implies that a ten percent gain in heat-rate efficiency is associated with an approximate 8.7 percent increase in carbon dioxide emissions.

In addition to the heat rate, the results in Table 2 suggest that coal and natural gas usage do not have a statistically significant effect on plant-level CO_2 emissions. The petroleum-use coefficient for specification (5) implies that if a plant uses petroleum as a feedstock, then it will lead to an approximate 52 percent ($100\times(\exp(-0.7369)-1)$) decrease in the level of carbon dioxide emissions.[11] It is possible that the statistically significant relationship between petroleum use and carbon emissions is an artifact of this empirical sample, wherein the level of

[10] Incidental parameters cannot be consistently estimated, and they may cause inconsistency in the maximum likelihood estimation of the remaining parameters.

[11] We applied an exponential transformation to the estimated coefficient on the indicator variable of ownership because the dependent variable (CO_2) is defined in natural logarithmic form (Halvorsen & Palmquist, 1980).

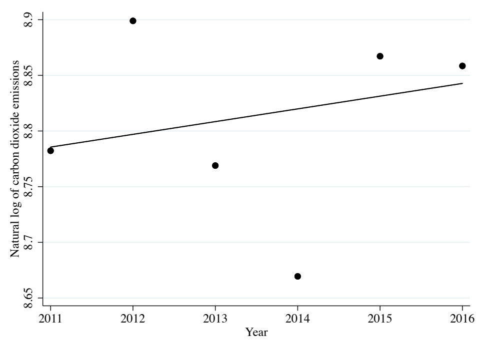
emissions fell, but the percentage of plants using petroleum (within our empirical sample) steadily rose during this period of observation. As predicted, total plant capacity has a small but statistically significant positive effect on the level of CO_2 emissions.

The combined heat and power (labeled as "CHP" in Table 2) coefficient implies that the utilization of cogeneration leads to a positive and highly statistically significant effect on the level of CO_2 emissions. Initially, this result seems non-intuitive as one would not necessarily expect that a more efficient form of electricity production would lead to an increase in the level of emissions. However, we think this finding is possibly an artifact of this empirical sample – in other words, both of these series are trending upward over this sample period as illustrated by Figure 4. Finally, the coefficients on ownership type are negative but not statistically significant for our preferred regression specification in column (5).

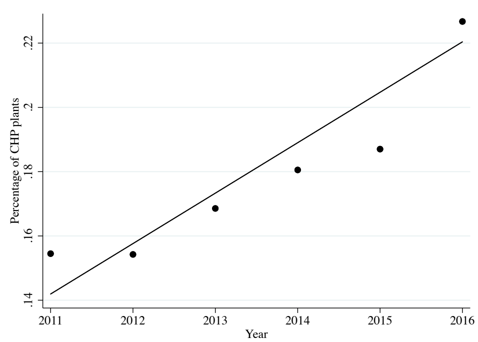
3.1.2 The rate of carbon dioxide emissions

Consistent with Grant *et al.* (2014) and as predicted by our hypothesis, the estimated coefficient on (the natural log of) the heat rate is positively related (and highly statistically significant) to the (natural log of the) rate of carbon dioxide emissions. The results for the regressions, using the rate of carbon dioxide emissions as the dependent variable, are offered in columns (1)-(6) of Table 3.[12] The positive correlation implies that as plants are becoming more thermally efficient (heat rates are shrinking), the rate of carbon dioxide emissions is declining. The coefficient for specification (1) suggests that for every ten percent increase in heat-

[12]Based on the binscatter plots in Figure 3, an outlier observation(s) appears in the upper right-hand quadrant of each diagram. Therefore, as a robustness check, we ran auxiliary regressions (not provided) in which we truncated the carbon dioxide observations to remove the outliers in the top five percent of the distribution. The truncation procedure had negligible effects on the estimated coefficients. We conducted the same procedure for the other two pollutants below and found similar results.



(a) Carbon dioxide levels by year



(b) CHP plants by year

Figure 4: Binned scatterplot of carbon dioxide emissions and combined heat and power plants by year (2011-2016)

Table 2: The relationship between power plant heat-rate efficiency and the level of carbon dioxide emissions (2011-2016)

	$\ln(CO_2)$					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	-0.4696***	-3.8541*	-0.0605	0.0851	-0.8651***	-2.3291
	(0.0731)	(1.6574)	(0.0905)	(0.6199)	(0.1068)	(1.6823)
ln(Heat rate)^2		0.1696*		-0.0074		0.0744
		(0.0808)		(0.0295)		(0.0790)
Coal (1=yes)	0.0619	0.0579	-0.3349*	-0.3347*	0.0069	0.0123
	(0.1821)	(0.1822)	(0.1528)	(0.1528)	(0.1716)	(0.1713)
Nat gas (1=yes)	0.2668	0.2392	-0.1080	-0.1080	-0.0272	-0.0282
	(0.1556)	(0.1572)	(0.1204)	(0.1204)	(0.1385)	(0.1386)
Petrol (1=yes)	-1.0322***	-1.0450***	-0.6157***	-0.6153***	-0.7369***	-0.7402***
	(0.1598)	(0.1602)	(0.1272)	(0.1273)	(0.1433)	(0.1433)
Total capacity	0.0019**	0.0019**	0.0032*	0.0032*	0.0019*	0.0019*
	(0.0006)	(0.0006)	(0.0016)	(0.0016)	(0.0008)	(0.0008)
Summer capacity	-0.0002	1.2e-4	-0.0008	-0.0008	0.0023*	0.0024*
	(0.0009)	(0.0009)	(0.0018)	(0.0018)	(0.011)	(0.0011)
Winter capacity	-0.0010	-0.0011	-0.0014	-0.0014	-0.0023*	-0.0035**
	(0.0008)	(0.0008)	(0.0012)	(0.0012)	(0.0011)	(0.0011)
CHP	1.3512***	1.3299***	0.1918	0.1918	0.6045**	0.6011**
	(0.0927)	(0.0931)	(0.2242)	(0.2242)	(0.2227)	(0.2224)
Solely owned (1=yes)	-0.3034*	-0.2924*	-0.0639	-0.0643	-0.0804	-0.0786
	(0.1221)	(0.1225)	(0.4950)	(0.4951)	(0.1903)	(0.1902)
Third-party owned (1=yes)	-0.5932***	-0.5851***	-0.3056	-0.3059	-0.3241	-0.3275
	(0.1618)	(0.1614)	(0.5209)	(0.5209)	(0.2814)	(0.2813)
Constant	15.8025***	32.5829***	9.2478***	8.533*	19.6518***	26.8613**
	(0.8983)	(8.4664)	(1.1589)	(3.344*)	(3.1247)	(8.9152)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,115	11,115	11,115	11,115	11,115	11,115
R^2	0.1807	0.1824	0.6473	0.6473	0.4626	0.4628
No. categories	51	51	1,481	1,481	923	923

Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following: $^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$.

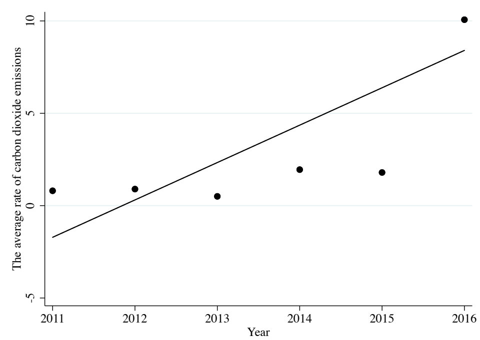
Table 3: The relationship between power plant heat-rate efficiency and the rate of carbon dioxide emissions (2011-2016)

	CO_2 rate					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	1.2756***	0.0287	1.3161***	-0.6337	1.1885***	-0.7859
	(0.0784)	(0.9489)	(0.1359)	(0.9614)	(0.1157)	(0.9619)
ln(Heat rate)^2		0.0654		0.0988*		0.1004*
		(0.0465)		(0.0467)		(0.0474)
Coal (1=yes)	-1.2374***	-1.2390***	-2.0707***	-2.0732***	-1.7793***	-1.7721***
	(0.2011)	(0.2010)	(0.1983)	(0.1984)	(0.2016)	(0.2015)
Nat gas (1=yes)	0.8730***	0.8622***	0.4237*	0.4237*	0.3579*	0.3565*
	(0.1774)	(0.1775)	(0.1676)	(0.1677)	(0.1749)	(0.1749)
Petrol (1=yes)	2.8041***	2.7992***	3.2169***	3.2125***	2.8475***	2.8430***
	(0.1801)	(0.1801)	(0.1745)	(0.1745)	(0.1783)	(0.1783)
Total capacity	0.0019**	0.0019**	0.0038*	0.0038*	0.0025**	0.0025**
	(0.0010)	(0.0007)	(0.0016)	(0.0016)	(0.1783)	(0.0008)
Summer capacity	0.0010	0.0010	-0.0012	-0.0012	0.0023*	0.0023*
	(0.0009)	(0.0009)	(0.0019)	(0.0019)	(0.0011)	(0.0011)
Winter capacity	-0.0037***	-0.0037***	-0.0015	-0.0015	-0.0054***	-0.0054***
	(0.0008)	(0.0008)	(0.0012)	(0.0012)	(0.0012)	(0.0012)
CHP	0.4265***	0.4183	0.1914	0.1903	-0.0336	-0.0383
	(0.0909)	(0.0904)	(0.2496)	(0.2496)	(0.2198)	(0.2196)
Solely owned (1=yes)	0.0071	0.0114	0.0108	0.0156	0.3277	0.3301
	(0.1224)	(0.1224)	(0.5153)	(0.5153)	(0.1870)	(0.1868)
Third-party owned (1=yes)	-0.2698	-0.2666	-0.2461	-0.2417	-0.1408	-0.1453
	(0.1618)	(0.1617)	(0.5315)	(0.5315)	(0.2821)	(0.2822)
Constant	-12.1053***	-5.6385	-15.9125**	-6.3448	-10.0875**	-0.3648
	(0.9813)	(4.8634)	(1.5528)	(5.0332)	(3.1410)	(5.7423)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,115	11,115	11,115	11,115	11,115	11,115
R^2	0.2320	0.2322	0.5990	0.5994	0.4501	0.4505
No. categories	51	51	1,481	1,481	923	923

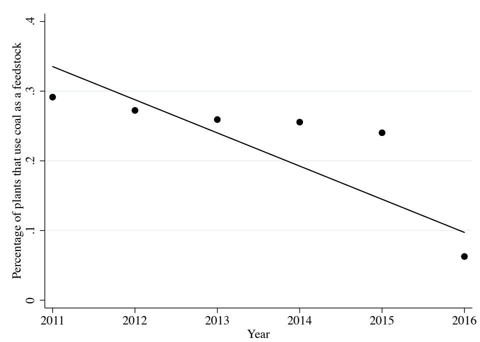
Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

rate efficiency, the rate of emissions declines by approximately 13 percent. Interestingly, the coefficient on the coal feedstock indicator is negative and highly statistically significant, implying that using coal as a feedstock will lead to a reduction in the rate of CO_2 emissions on average. Put differently, the coefficient estimate in column (5) suggests that if a plant (within the sample for this particular study) used coal, then its rate of emissions declined by about 83 percent ($100\times$(exp(-1.7793)-1)). We speculate that the coefficient on coal is an artifact of this empirical sample, as the rate of CO_2 emissions slightly increased during this period, whereas the number of plants using coal feedstocks has steadily declined over this period (illustrated in Figure 5).

According to the regression analysis in Table 3, natural gas (used as a feedstock) had a positive and statistically significant effect on the rate of CO_2 emissions. Specifically, the estimate in column (5) suggests that if a plant used natural gas as a feedstock, then its rate of CO_2 emissions increased by approximately 43 percent ($100\times$(exp(0.4237)-1)). Although natural gas combustion generates CO_2 emissions, we believe this result is partially an artifact of the data, where the number of natural gas generators and carbon dioxide emissions were both growing over this period (U.S. Energy Information Administration, December 18 2017). Our estimates suggest that burning petroleum fuel to generate electricity has a strong and highly statistically significant effect on the rate of CO_2 emissions. The relationship between petroleum use and the carbon emissions is consistent with our prior, as burning petroleum fuels accounted for 45 percent (compared to 26 and 29 percent from coal and natural gas, respectively) of U.S. energy-related CO_2 emissions in 2017 (U.S. Energy Information Administration, 2018d).



(a) Rate of carbon dioxide emissions by year



(b) Percentage of coal plants by year

Figure 5: Binned scatterplot of the rate of CO_2 emissions and coal plants by year (2011-2016)

Table 4: The relationship between power plant heat-rate efficiency and the level of methane emissions (2011-2016)

	$\ln(CH_4)$					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	-0.5777***	-3.1057*	-0.0924	0.6865	-0.7610***	-1.2540
	(0.0545)	(1.5278)	(0.0688)	(0.5038)	(0.0832)	(1.2126)
ln(Heat rate)^2		0.1267		-0.0395		0.0251
		(0.0744)		(0.0238)		(0.0588)
Coal (1=yes)	0.4469**	0.4439**	-0.0677	-0.0667	0.3148*	0.3167*
	(0.1349)	(0.1350)	(0.1096)	(0.1095)	(0.0123)	(0.1228)
Nat gas (1=yes)	-0.0272	-0.0477	-0.0784	-0.0784	-0.1829	-0.1833
	(0.1128)	(0.1149)	(0.0874)	(0.0874)	(0.0963)	(0.0963)
Petrol (1=yes)	-0.6759***	-0.6854***	-0.4345***	-0.4328***	-0.5331***	-0.5342***
	(0.1145)	(0.1150)	(0.0903)	(0.0903)	(0.0989)	(0.0990)
Total capacity	-0.0006	0.0006	0.0035**	0.0035**	0.0007	0.0007
	(0.0005)	(0.0005)	(0.0013)	(0.0013)	(0.0006)	(0.0006)
Summer capacity	0.0022**	0.0022**	-0.0023	-0.0023	0.0056***	0.0056***
	(0.0007)	(0.0007)	(0.0014)	(0.0014)	(0.0010)	(0.0010)
Winter capacity	-0.0021**	-0.0021**	-0.0011	-0.0011	-0.0056***	-0.0055***
	(0.0006)	(0.0006)	(0.0008)	(0.0008)	(0.0009)	(0.0009)
CHP	0.9218***	0.9058***	0.2110	0.2114	0.3227*	0.3215*
	(0.0643)	(0.0646)	(0.1299)	(0.1299)	(0.1435)	(0.1433)
Solely owned (1=yes)	-0.3914***	-0.3832***	0.0495	0.0496	-0.2375	-0.2368
	(0.0927)	(0.0932)	(0.3588)	(0.3589)	(0.1435)	(0.1433)
Third-party owned (1=yes)	-0.5626***	-0.5566***	-0.0321	-0.0339	-0.2233	-0.2244
	(0.1166)	(0.1164)	(0.3747)	(0.3748)	(0.1918)	(0.1917)
Constant	9.2667***	21.8005**	2.9308***	-0.8913	11.1856***	13.6138**
	(0.6224)	(7.7980)	(0.7937)	(2.6925)	(1.4220)	(6.3711)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,1115	11,115	11,115	11,115	11,115	11,115
R^2	0.1761	0.1779	0.6578	0.6579	0.4617	0.4617
No. categories	51	51	1,481	1,481	923	923

Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5: The relationship between power plant heat-rate efficiency and the rate of methane emissions (2011-2016)

	CH$_4$ rate					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	0.6224**	0.4846	1.0025***	0.3870	1.0045***	1.3301
	(0.0828)	(0.7636)	(0.1288)	(0.9520)	(0.1178)	(1.2800)
ln(Heat rate)^2		0.0069		0.0312		-0.1450
		(0.0372)		(0.0463)		(0.0636)
Coal (1=yes)	-0.3283	-0.3284	-0.8881***	-0.8889***	-0.0667**	-0.6676**
	(0.2390)	(0.2390)	(0.2240)	(0.2241)	(0.2428)	(0.2427)
Nat gas (1=yes)	-0.0640	-0.0651	0.3654*	0.3654*	-0.1069	-0.1067
	(0.2051)	(0.2054)	(0.1823)	(0.1823)	(0.2033)	(0.2034)
Petrol (1=yes)	2.5451***	2.5446***	2.6275***	2.6261***	2.3409***	2.3416***
	(0.2084)	(0.2084)	(0.1898)	(0.1899)	(0.2074)	(0.2075)
Total capacity	-0.0014	-0.0014	0.0052**	0.0052**	-0.0008	-0.0008
	(0.0008)	(0.0008)	(0.0020)	(0.0020)	(0.0010)	(0.0010)
Summer capacity	0.0045***	0.0045***	-0.0074**	-0.0074**	0.0057***	0.0057***
	(0.0011)	(0.0011)	(0.0024)	(0.0024)	(0.0015)	(0.0015)
Winter capacity	-0.0040***	-0.0040***	-0.0001	-0.0001	-0.0054***	-0.0054***
	(0.0011)	(0.0011)	(0.0016)	(0.0016)	(0.0014)	(0.0014)
CHP	-0.6856***	-0.6865***	0.1628	0.1625	-0.6402*	-0.6396*
	(0.1118)	(0.1117)	(0.3073)	(0.3074)	(0.2554)	(0.2554)
Solely owned (1=yes)	-0.1927	-0.1922	0.0231	0.0246	-0.0351	-0.0355
	(0.1481)	(0.1482)	(0.6344)	(0.6343)	(0.2287)	(0.2288)
Third-party owned (1=yes)	-0.1284	-0.1281	0.5681	0.5695	0.5149	-0.5156
	(0.1966)	(0.1967)	(0.6180)	(0.6180)	(0.3363)	(0.03363)
Constant	-18.2894***	-17.6063***	-17.4393***	-14.4191**	-22.0147***	-23.4196**
	(1.0148)	(3.9644)	(1.4997)	(4.9940)	(2.6251)	(.0001)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,1115	11,115	11,115	11,115	11,115	11,115
R^2	0.1656	0.1656	0.5244	0.5245	0.3615	0.3615
No. categories	51	51	1,481	1,481	923	923

Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following:
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.2 Methane emissions

In addition to carbon dioxide emissions, we also examined the relationship between plant-level heat-rate efficiency and methane emissions. The results are provided in Tables 4 and 5. Methane only accounts for approximately nine percent of total greenhouse gas emissions, but methane can trap up to 100 times the amount of heat (compared to CO_2) in the atmosphere with a five-year period (Nyman, 2014). According to Nyman (2014), methane primarily comes from industry (including electric power generation), natural gas and petroleum systems, and agriculture.

The layout and structure of the methane regressions are similar to those of Table 2 and 3. Therefore, for the sake of exposition, we only highlight the main findings from Tables 4 and 5. Similar to the results for carbon emissions, we find that the heat rate is negatively related to methane emissions in levels, implying that as plants are becoming more thermally efficient (on average), they are emitting higher levels of methane. The coefficient in column (5) (Table 4) suggests that a ten percent increase in heat rate efficiency led to a 7.6 percent increase in the level of methane emissions. Similar to the carbon regressions, however, we do not find consistent evidence of a correlation between plant-level heat-rate efficiency and the methane emissions rate – the exception applies to specifications (3) and (4), in which we find no statistically significant relationship. The specifications in columns (1) and (2) used state-level fixed effects, whereas columns (3) and (4) used plant-level fixed effects, and columns (5) and (6) exploit the operator-level fixed effects. Again, the regression equation with the plant-level fixed effects arguably suffers from the incidental parameters problem, so we prefer the specification with operator-level fixed effects offered in column (5).

The heat rate coefficient on the rate of emissions (Table 5) suggests that heat rate improvements are positively correlated with reductions in the rate of methane emissions. Specifically, the coefficient in column (5) of Table 5 implies that ten percent increase in heat rate efficiency is associated with a ten percent decrease in the rate of methane emissions. The specification with plant-level fixed effects, column (3), corroborates the findings for our preferred specification in column (5).

From Table 4, coal-fired electricity generation has a small but positive and significant effect on the level of methane emissions. Specifically, the coefficient in specification (5) implies that coal use increased methane emissions by approximately seven percent (100×(exp(0.4469)-1)). The direct combustion of coal is generally not considered to be a contributor, so this relatively small effect is consistent with our prior (U.S. Energy Information Administration, March 11 2011).

The estimated coefficients for natural gas use are not statistically significant (within Table 4), which may seem odd at first, but past research has shown that most natural gas plant methane emissions were caused by leakage, not combustion (Lavoie *et al.* , 2017). The petroleum use coefficients are negative for the levels (Table 4) and positive for the rate (Table 3b) of methane emissions (all are highly statistically significant). The coefficient on specification (5) in Table 4 implies that petroleum-fired electricity, on average, reduced the level of methane emissions by approximately 41 percent (100×(exp(-0.5331)-1)). That may seem like a large impact, but petroleum-fired electricity generation accounted for only 0.5 percent of total generation in the U.S. in 2017 (U.S. Energy Information Administration, 2018c). The inverse relationship between petroleum use and methane emissions may seem counter intuitive, but methane emissions are often linked with the petroleum refining process (Lavoie *et al.* , 2017) instead of the combustion process. Conversely, petroleum-fired generation is positively correlated (and highly statistically significant) with the rate of methane emissions according to columns (1) - (6) in Table 5.

3.3 Nitrous oxide emissions

For the sake of brevity, we only briefly highlight the main findings from the regressions associated with the level and rate of nitrous oxide emissions. As a greenhouse gas, nitrous oxide is the third largest contributor to global warming, and past projections have shown that emissions could double by 2050 (Davidson & Kanter, 2014).

The regression results for nitrous oxide emissions are offered in Tables 6 and 7. As with carbon dioxide and methane emissions, the specifications for nitrous oxide imply that an improvement in heat-rate efficiency would lead to an increase in emissions levels. Similar to our findings with the other two pollutants, when we specify power plant-level fixed effects, the relationship between heat rate efficiency and nitrous oxide emissions is no longer significant. The coefficient on heat rate efficiency in column (5) of Table 6 (our preferred specification) suggests that a ten-percent increase in heat-rate efficiency would lead to an approximate 7.3 percent increase in nitrous oxide emissions.

As with the other two pollutants, heat-rate efficiency had a statistically significant effect on N_2O emissions rates (and, this finding is robust to the specification of state, plant, and operator fixed effects). According to the U.S. Energy Information Administration (March 31 2011), the largest stationary contributor of N_2O emissions comes from coal combustion, so it was not surprising that the coefficient on coal use (Table 6 column (5)) was positively related to N_2O emissions levels. Likewise, N_2O emissions levels drop, on average, if a plant uses petroleum as a feedstock instead of coal.

Table 6: The relationship between power plant heat-rate efficiency and the level of nitrous oxide emissions

	$\ln(N_2O)$					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	-0.6291***	-2.9591*	-0.0699	0.6206	-0.7275***	-1.2076
	(0.0579)	(1.4872)	(0.0704)	(0.5113)	(0.0854)	(1.1620)
ln(Heat rate)^2		0.1168		-0.0350		0.0244
		(0.0724)		(0.0241)		(0.0564)
Coal (1=yes)	0.5992***	0.5964***	-0.0499	-0.0490	0.5059***	0.5077***
	(0.1443)	(0.1443)	(0.1199)	(0.1199)	(0.1340)	(0.1338)
Nat gas (1=yes)	-0.1253	-0.1442	-0.0197	-0.0197	-0.2118*	-0.2121*
	(0.1194)	(0.1212)	(0.0935)	(0.0935)	(0.1040)	(0.1040)
Petrol (1=yes)	-0.6552***	-0.6639***	-0.4973***	-0.4958***	-0.5108***	-0.5118***
	(0.1214)	(0.1218)	(0.0968)	(0.0967)	(0.1066)	(0.1066)
Total capacity	0.0009	0.0008	0.0040**	0.0040**	0.0009	0.0009
	(0.0006)	(0.0006)	(0.0014)	(0.0014)	(0.0007)	(0.0007)
Summer capacity	0.0028***	0.0029***	-0.0024	-0.0024	0.0061***	0.0061***
	(0.0008)	(0.0008)	(0.0015)	(0.0015)	(0.0011)	(0.0011)
Winter capacity	-0.0029***	-0.0029***	-0.0013	-0.0013	-0.0062***	-0.0062***
	(0.0007)	(0.0007)	(0.0001)	(0.0001)	(0.0010)	(0.0010)
CHP	0.7308***	0.7161***	0.1667	0.1670	0.1085	0.1074
	(0.0670)	(0.0671)	(0.1449)	(0.1450)	(0.1562)	(0.1561)
Solely owned (1=yes)	-0.3978***	-0.3902***	-0.0024	-0.0040	-0.3307*	-0.3301*
	(0.0989)	(0.0994)	(0.4067)	(0.4068)	(0.1554)	(0.1555)
Third-party owned (1=yes)	-0.5010***	-0.4954***	-0.0013	-0.0715	-0.2641	-0.2652
	(0.1253)	(0.1251)	(0.0001)	(0.4427)	(0.2187)	(0.2186)
Constant	11.2300***	22.7818***	3.2260***	-0.1620	12.5309***	14.8956*
	(0.6669)	(7.5944)	0.8272)	(2.7435)	(1.4771)	(6.1247)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,115	11,115	11,115	11,115	11,115	11,115
R^2	0.1718	0.1731	0.6556	0.6557	0.4566	0.4567
No. categories	51	51	1,481	1,481	923	923

Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following:
$^* p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$.

Table 7: The relationship between power plant heat-rate efficiency and the rate of nitrous oxide emissions

	N_2O rate					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Heat rate)	1.0807***	2.9724*	1.0160***	0.5356	1.3178***	2.5925
	(0.0853)	(1.5075)	(0.1250)	(0.9762)	(0.1234)	(1.8768)
ln(Heat rate)^2		-0.0948		0.0243		-0.0648
		(0.0733)		(0.0469)		(0.0913)
Coal (1=yes)	-0.7954**	-0.7931**	-1.1070***	-1.1077**	-0.9989***	-1.004***
	(0.2379)	(0.2379)	(0.2353)	(0.2353)	(0.2429)	(0.2427)
Nat gas (1=yes)	-0.4386*	-0.4232*	0.0269	0.0269	-0.4345*	-0.4336*
	(0.2038)	(0.2048)	(0.1903)	(0.1903)	(0.2003)	(0.2003)
Petrol (1=yes)	1.9423***	1.9494***	2.2934***	2.2924***	1.8078***	1.8107***
	(0.2065)	(0.2068)	(0.1964)	(0.1965)	(0.2027)	(0.2027)
Total capacity	-0.0005	-0.0005	0.0063**	0.0063**	0.0007	0.0007
	(0.0008)	(0.0008)	(0.0021)	(0.0021)	(0.0010)	(0.0010)
Summer capacity	0.0040***	0.0039**	-0.0086***	-0.0086***	0.0052**	0.0051**
	(0.0011)	(0.0011)	(0.0027)	(0.0027)	(0.0016)	(0.0016)
Winter capacity	-0.0044***	-0.0044***	-0.0005	-0.0005	-0.0066***	-0.0066***
	(0.0011)	(0.0011)	(0.0017)	(0.0017)	(0.0016)	(0.0016)
CHP	-1.0831***	-1.0712***	-0.3533	-0.3536	-1.3631***	-1.3601***
	(0.1114)	(0.1110)	(0.3230)	(0.3230)	(0.2642)	(0.2641)
Solely owned (1=yes)	-0.0292	-0.0353	0.7153	0.7165	0.0406	0.0390
	(0.1466)	(0.1470)	(0.6216)	(0.6216)	(0.2297)	(0.2298)
Third-party owned (1=yes)	-0.0330	-0.0376	1.1011	1.1022	0.7220*	0.7249*
	(0.1975)	(0.1976)	(0.6206)	(0.6216)	(0.3446)	(0.3445)
Constant	-10.8238***	-20.2031**	-14.8536***	-12.4965**	-12.0889***	-18.3657
	(1.0271)	(7.7262)	(1.4624)	(5.1507)	(2.6345)	(9.9483)
Fixed effects	State	State	Plant	Plant	Operator	Operator
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
NERC fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	11,115	11,115	11,115	11,115	11,115	11,115
R^2	0.1671	0.1674	0.5155	0.5155	0.3621	0.3622
No. categories	51	51	1,481	1,481	923	923

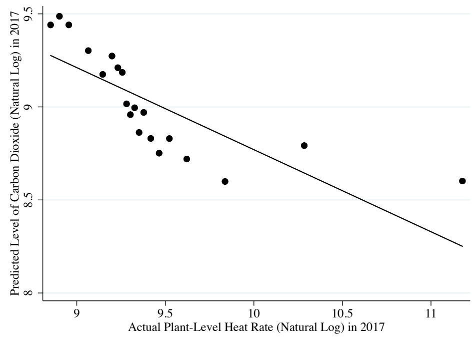
Notes: Huber-White robust standard errors in parentheses. Asterisk symbols denotes the following:
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.4 Predicted level of power-plant related GHG emissions in 2017

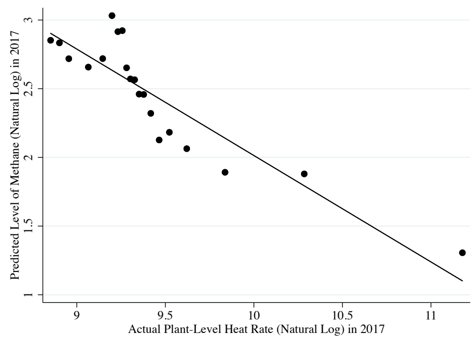
Unfortunately, the U.S. EPA's GHGRP did not provide the GHG emissions data for 2017. However, the U.S. EIA does provide the plant-level data (for EIA forms 923 and 860) for the year 2017. Therefore, we were able to predict the levels of emissions (for all three pollutants) based on the regressions results in Tables 2, 4, and 6. More specifically, we assumed that all plants that the EPA GHGRP reported as a "major source" polluter (emits 25,000 metric tones or more of CO_2 equivalent within a year) in the year 2016 also received the same designation in the year 2017. We chose the modeling specification outlined in column (5) of Tables 2, 4, and, 6, and based on those estimated coefficients we were able to predict emissions for the year 2017. Figure 6 displays the predicted emissions levels against plant-level heat rates using a bivariate regression within a binned scatterplot. As clearly demonstrated by the three sub-figures, the level of emissions appear to be negatively correlated with heat-rate efficiency – i.e., GHG emissions levels seem to be increasing with improvements to heat-rate efficiency.

4 Conclusion and Policy Implications

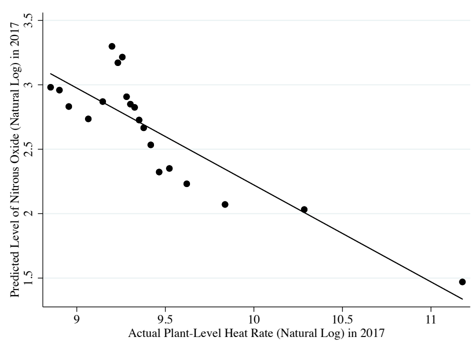
This analysis took advantage of plant-level data on electricity generation, fuel use, and emissions, which allowed us to use longitudinal data to identify changes to GHG emissions over time. We used the most recent data from the EPA and EIA to estimate the relationship among power plant heat rates, greenhouse gas emission rates, and greenhouse gas levels. When specifying fixed effects at the operator level, we found that more thermally efficient plants with lower heat rates generally have lower greenhouse gas emission rates, but higher total emissions levels. The level effect is not large enough to offset the rate effect, but it does attenuate the



(a) Carbon dioxide level



(b) Methane level



(c) Nitrous oxide level

Figure 6: Binned scatterplot of predicted emission levels against actual plant-level heat rates in 2017

emissions reduction benefits associated with reduced emissions rates. As such, our results are mostly consistent with the work of Grant *et al.* (2014). However, when we specified plant level fixed effects, the relationship between heat-rate efficiency and the level of emissions was no longer statistically significant.

One crucial factor determining plant-level GHG emission levels is whether a plant increases its generation output. Improved power plant heat rates can reduce both emission rates and per-unit costs by improving generation energy efficiency. Its output levels depend on whether it gets dispatched, which is also a function of the regulatory institutions in its state and region and the economics of competing technologies. Looking forward, the costs of producing renewable energy are falling, and renewables are low marginal cost generation sources. As more renewables come into the generation portfolio, and as long as natural gas prices remain relatively low, coal-fired power plants will move up the supply curve and out in the dispatch merit order, which may weaken the divergence between rates and levels for more thermally efficient plants.

Based on these findings, do the asserted rebound effects imply that we should eliminate the energy efficiency improvement proposals within the ACE plan (or, any other energy proposal)? Energy efficiency improvements not only reduce GHG emissions, but also benefit the economy as a whole (Mackres, September 6 2012). As noted by Gillingham *et al.* (2013), the rebound effect tends to be overplayed as a criticism against energy efficiency policies. We are not claiming that the ACE rule will necessarily lead to a complete "backfire" of emissions. Instead, we argue that the U.S. EPA should be aware of any potential rebound effects that may occur as a result of the ACE plan's strategic policies. Heat-rate efficiency improvements alone (i.e., without other GHG reduction policies) are no panacea for reducing GHG emissions – and, in fact, heat-rate efficiency policies may lead to an increase in carbon dioxide, methane, and nitrous oxide emissions.

In other words, an emissions-rate-focused policy such as the ACE rule, while likely to improve energy efficiency, is not necessarily sufficient to ensure reductions in GHG emission levels. One method of doing so may be state-level policies targeted at emissions levels, perhaps in conjunction with moving state renewable portfolio standards away from their technology-specific renewables targets and toward emissions reductions and low carbon/zero carbon standards.

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