Economic Efficiency of Utility Plants Under Renewable Energy Policy

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Selected Paper prepared for presentation at the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-28

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Abstracts

Over the last two decades a large number of energy policy changes have occurred specifically with regards to renewable energy. This paper considers how these changes in renewable energy policy affect the production efficiencies of power plants that use renewable and/or nonrenewable energy inputs for electricity production. Using nationwide plant level data from 2003 – 2012 pure technical efficiency is estimated. This study considers the efficiencies of both renewable and nonrenewable energy sources. In addition, this study considers how state level renewable energy policies affect the efficiencies of power plants. In general, this study finds that renewable energy policies do not reduce the efficiencies of electricity generation from a technical aspect.

Keywords: DEA, electricity generation, renewable energy policy

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1.0 Introduction

Since the early 2000s there has been a large increase in the amount of renewable energy that is used to produce electricity in the United States. In 2001, only five states generated 5% or more of their electricity from non-hydroelectric renewable energy. By 2011, 20 states produced 5% or more of their electricity from non-hydroelectricity renewable energy (EIA 2012). The increased generation of renewable energy is in part due to renewable energy policies at the state level that encourage the deployment or purchase of renewable energies. Many of these policies place an emphasis on the use of intermittent renewable energies (i.e. wind and solar). Due to the intermittent nature of renewable energies, non-renewable energies (i.e. natural gas and coal) are used to meet load requirements. This increased magnitude of intermittent production is believed to decrease the efficiencies of power plants. However, there have not been any studies that have determined if traditional power plants are experiencing a decrease in production efficiency.

One of the leading causes for increased use of intermittent sources of energy is renewable energy policy. There are four main state level renewable energy policies used. The state level policies are: renewable portfolio standard (RPS), net metering, public benefit fund, and mandatory green power option. At the state level, the main policy is the RPS. The RPS requires utilities within the state to generate a certain percent or quantity of electricity from renewable energy sources. The percent or quantity that the utility is required to produce, the attainment year, and whether a utility faces a penalty for noncompliance, varies greatly across states. Net metering is another common policy. Net metering allows customers to produce their own electricity from a renewable resource (most commonly solar) and sell it to the utility company while also being able to purchase electricity from the utility when the consumer cannot produce enough electricity to meet their needs. Public benefit funds charge utility consumers a small surcharge on their electricity bill to subsidize the development of renewable energy in the state. The least used policy is the mandatory green power option, where the state requires utility companies to give their customers the option to purchase electricity generated by a renewable energy source.

Two of the four policies – RPS and the mandatory green power option – require power plants to make long term decisions on building new renewable energy facilities to meet their requirements or if they should purchase renewable power from the grid. The public benefit fund is designed to ensure that renewable energy is developed by the power plant. Net metering is less likely to affect the use of renewable energy by the power plants since the power plants cannot offset how much renewable energy they must purchase under net metering by producing electricity from their own renewable energy sources. Numerous studies have shown that renewable energy policies have partially lead to the deployment of renewable energy within the states (Chen, et al. 2009, Shrimali and Kniefel 2011, Shrimali, Lynes and Indvik 2015, Yin and Powers 2010, O. Bespalova 2014, O. G. Bespalova 2011, Carley 2009, Kneifel 2008). In most studies, net metering was not found to affect renewable energy deployment. However, it is likely that increasing the quantity of electricity the power plant receives from net metering will affect overall production decisions.

Due to the increased number of renewable energy policies and their effect on the deployment of renewable energy, the purpose of this study is twofold. The first is to determine if, at the plant level, power plants that use renewable energies are less efficient than power plants that use only traditional sources for electricity production. The second is to determine if renewable energy policies that require utility companies to produce or purchase renewable energy results in less efficient power production. This study considers an average of 4,800 utility plants in the United States from 2003 – 2012. A two-stage data envelopment analysis (DEA) is used to determine the pure technical efficiencies (BCC) of these power plants. In the second stage a truncated regression is used to determine what renewable energy policies and plant specific attributes affect the efficiencies of the utility plants.

2.0 Background

There are numerous studies that estimate production efficiencies of power plants in the U.S. and abroad. DEA studies of electricity production typically fall into one of two categories: generation and distribution. This study focuses on efficiencies from the generation of electricity and is not concerned with the distribution of electricity. Several studies focused on the generation of electricity with most of these studies considering conventional electricity production or compared the efficiencies of power plants in the U.S. to power plants in another country. Only a handful of studies have considered the efficiencies of nuclear plants or renewable energy production.

In the U.S., Cook et al. (1998), Cook and Green (2005), and Cook and Zhu (2007) consider how creating a hierarchy between units and utility plants affect the efficiencies at eight thermal plants in the U.S. Fallahi, Ebrahimi, and Ghaderi (2011) found the overall technical (CCR) and pure technical (BCC) efficiencies of 32 power electric generation management companies in Iran from 2005-2009. Liu, Lin, and Lewis (2010) determined the overall, technical, and scale efficiencies of nine thermal power plants in Taiwan between 2004 and 2006. Sueyoshi and Goto (2001) use a slack-adjusted DEA model, to determine the efficiencies of 10 vertically-integrated and investor-owned Japanese power plants and compares these plants to 15 wholesale generation facilities. Studying power plants in Israel, Golany, Roll, and Rybak (1994) determined the overall technical efficiency (CCR) of 87 power plants operating in a closed market. Whiteman and Bell (1994) consider the overall technical efficiencies (CCR) of 34 utilities from around the world. Park and Lesourd (2000), determine the overall technical (CCR) and pure technical (BCC) efficiencies of 64 conventional power plants in South Korea. The main focus of these studies was on the efficiency scores.

Several studies have used the estimated efficiency scores and determined what is correlated with the efficiency scores using a two-stage analysis. Considering 30 province, autonomous region, and municipality thermal power generation plants in China for the years 1995 and 1996, Lam and Shiu (2001) determined the technical efficiencies of these plants. During the second stage they found that capacity had a positive and statistically significant effect and fuel use per kWh had a negative and statistically significant effect on the efficiency score. Barros and Peypoch (2008) used a two-stage analysis to determine what effects the overall technical efficiency of thermal power plants in Portugal. They find that age of the plant has a negative and statistically significant impact on the overall technical efficiency. In another study, using a two-stage model, Raczka (2001) examined the efficiency of 41 heat plants in Poland. They found that public heat plants, plants that use higher quality coal, and have greater capital utilization have higher technical efficiencies. Using the efficiency scores found by Agrell and Bogetoft (2005), Munksgaard, Pade, and Fristrup (2005) determine the factors that affect the estimated efficiencies of Danish district heat plants. They found that natural gas and straw or biofuels potentially has a negative effect on the efficiency of the utility plant.

Several studies have examined in to how policy affects the efficiencies of power plants. Yaisawarng and Klein (1994) considered how sulfur dioxide controls affect the efficiency of power plants in the U.S. They used overall technical (CCR), pure technical (BCC), and scale efficiencies to analyze the effect of these policies on approximately 60 coal-fired plants from 1985-1989. They found that plants with scrubbers experience lower constant returns to scale and variable returns to scale efficiency levels than plants without scrubbers. In another study, Majumder and Marcus (2001) used a two-stage model to determine if the change in the 1970 Clean Air Act affected the overall technical (CCR) and pure technical (BCC) efficiencies of 150 of the largest investor-owned utilities in the U.S. They found that air pollution had a positive and statistically significant impact on efficiencies while waste pollution had a negative and statistically significant impact using a tobit model.

All of these studies focused on traditional energy sources, namely coal, natural gas, and petroleum. There have been a limited number of studies that have focused on nuclear or renewable energy sources. Pollitt (1996) studied whether ownership affected the productive efficiency of nuclear power plants across the world. Sarica and Or (2007) determined the efficiencies of hydroelectric and wind power plants in Turkey using overall technical (CCR) and pure technical (BCC) efficiencies and assurance region type DEA. Thermal power plants are also considered in this study; however the renewable plants are not analyzed with the nonrenewable plants. Barros (2008) used a two-stage analysis to determine what drives the technical efficiency change and technological change of hydroelectric plants in Portugal. He found that the number of years the plant has been operational had a negative and statistically significant effect on the Malmquist score (TFP) using a tobit model. While these studies examine nuclear and renewable energy they did not consider how the efficiencies of nuclear power or renewable energy compare to conventional energy sources.

3.0 Empirical Framework

A two-stage analysis is used to determine how renewable energy policies affect the efficiencies of power plants. The first stage uses DEA analysis to determine the pure technical efficiency (BCC) scores of power plants from 2003 – 2012. The second stage uses the efficiency scores as dependent variables in a tobit model to determine the affect renewable energy policies have on power plants.

3.1 DEA Model

DEA is a nonparametric approache used to determine the best practice of economic agents. Farrell (1957) first introduced the concept of efficiency analysis as it relates to frontier analysis. Pure technical efficiency (BCC) which measures how far off a producer is from the production variable returns to scale frontier (Banker, Charnes and Cooper 1984). Using pure technical efficiency analysis, researchers are able to determine the minimum inputs to produce a level of output. A linear programming model is used to solve for the pure technical efficiency (BCC):

$$(1) \qquad \min_{\lambda_i, z_i} \lambda_i$$

Subject to:

$$\sum_{k=1}^{K} z_k x_{mk} \leq \lambda_i x_{mi} \quad \text{for } m = 1, \dots, M$$

$$\sum_{k=1}^{K} y_k z_k \geq y_i$$

$$\sum_{k=1}^{K} z_k = 1$$

$$(z_1, \dots, z_K) \geq 0$$

where z is an intensity (or weight) vector, x_i are the inputs, y_i is the output for power plant i where $i = 1, \dots, K$ and λ_i is the measure of pure technical efficiency (BCC). The efficiency scores range from 0 to 1. If λ_i is equal to '1' then the electric plant is efficient or on the fontier. The further away from '1' a plant is, the less efficient it is.

3.1.1 DEA Data

Plant level data was used to determine the pure technical efficiency for conventional and renewable utility plants from 2003 to 2012 in the U.S. The inputs used in the analysis are fuel and capital. There are 31 different types of fuel included in the model (Table 1). The fuel sources are measured by total fuel consumption MMBTU (million British Thermal Units) annually. The broad categories of fuel are coal, petroleum, natural gas and other gases, nuclear, solid renewable fuels, liquid renewable fuels, gaseous renewable fuels, other renewable energy sources, and other energy sources as defined by the Energy Information Administration (EIA) Form 923. Capital is measured by net capacity in megawatts (MW) at a power plant. The output is net generation in megawatt hours (MWh) (Table 1). There are, on average, 4,800 plants per year. The analysis is conducted using cross-sectional data for each of the ten years. The number of power plants each year varies depending on the number of plants in the survey and completeness of the data for each plant during the given year.

It is important to consider three factors: 1) availability of data; 2) the body of literature; and 3) professional opinion of relevant individuals to define DEA variables. A key variable missing from this analysis is labor. It was not included in the analysis due to a lack of availability of a labor variable. Despite not including labor in the analysis, the results are not likely significantly affected. A study conducted by Fallahi, Ebrahimi, and Ghaderi (2011) analyzed the overall technical (CCR) and pure technical (BCC) efficiencies of 32 power electric generation management companies in Iran. They used one output and five inputs in their analysis. The one output was net electricity produced. The inputs were labor – measured as the number of employees per company, capital – installed capacity, fuel, electricity, and average operational time. They found the most important inputs were the installed capacity and fuel that described 91% of the full model. In addition, Welch and Barnum (2009) did not include labor for a number of reasons. Their study was not focused on labor decisions, instead it was focused on fuel choice decisions. Labor makes up a very small portion of the input resources. Lastly, fuel and labor are not substitutes for one another in the electric generation industry. Because they are compliments, only one complimentary variable needs to be included. According to the EIA, expenditures related to labor make up approximately 10% or less of total fuel expenditures for the utility (EIA 2015).

3.2 Econometric Model

Once the pure technical efficiency (BCC) scores are determined, two second stage regression models are used to determine the effect of renewable energy policies on the efficiencies of power plants. Censored tobit models are used rather than OLS models since the dependent variable, the efficiency scores, ranges from 0 to 1. Building on the censored tobit model (Greene 2007), the first model used in the analysis is:

$$\lambda_i^* = \alpha + \beta X_i + \gamma Z_s + \varepsilon_i \qquad \varepsilon_i \sim N[0, \sigma^2]$$

$$\text{(2)} \qquad \lambda_i = \lambda_i^* \qquad \text{if } \lambda_i^* < 1$$

$$\lambda_i = 1 \qquad \text{if } \lambda_i^* \geq 1$$

where λ_i is the observed pure technical efficiency (BCC) score and λ_i^* is the latent variable for plant i; α is the intercept; X_i is a vector of plant specific explanatory variables; and Z_s is a vector of state specific renewable energy policies for state s. The error term, ε_i, is distributed normally with mean 0 and variance σ^2.

The second model used builds on the first model by including interaction terms between renewable and nonrenewable energy inputs as well as interaction terms between energy inputs and renewable energy policies. This tobit model is:

$$\lambda_i^* = \alpha + \beta X_i + \rho F_r F_n + \gamma Z_s + \delta F_j P_s + \varepsilon_i \qquad \varepsilon_i \sim N[0, \sigma^2]$$

$$\text{(3)} \qquad \lambda_i = \lambda_i^* \qquad \text{if } \lambda_i^* < 1$$

$$\lambda_i = 1 \qquad \text{if } \lambda_i^* \geq 1$$

where λ_i, λ_i^*, X_i, Z_s, and ε_i are the same as in the first model. $F_r F_n$ are the interaction terms between the renewable fuel category – F_r and the nonrenewable fuel categories – F_n where r is the renewable fuel category and n is coal, natural gas, and petroleum. $F_j P_s$ is an interaction term between category of inputs j and a subset of renewable energy policies in state s – where j is coal, natural gas, petroleum, nuclear, solid renewable fuel, liquid renewable fuel, gaseous renewable fuel, geothermal, hydroelectric, solar, wind, and other energy sources and P_s is RPS in effect, public benefit fund, and mandatory green power option.

3.2.1 Econometric Data

For the econometric analysis, dummy variables are used for the fuel inputs. This implies that if a power plant used wind power during a given year, the wind variable is equal to ‘1’ and ‘0’ otherwise. Two other plant specific variables are included in the analysis. The first is the plant capital – installed capacity; and the second is the average age of the plant, measured in decades[1]. Since many plants used multiple inputs, the average age across all inputs at a given plant was determined.

To determine the correlation between renewable energy policies and efficiencies of power plants, four renewable energies are included in the tobit model. Since there is a large variation in RPS policies across states, three dummy variables are used in the analysis. The first is equal to ‘1’ if the policy was enacted by the current year and ‘0’ otherwise. The second variable is equal to ‘1’ if there was a voluntary RPS in place during the current year and ‘0’ otherwise. The third variable is equal to ‘1’ if there was a noncompliance penalty associated with the RPS and ‘0’ otherwise. The other three policies – net metering, public benefits funds, and mandatory green power option – are equal to ‘1’ if the policy was in place during a given year and ‘0’ otherwise. Table 2 contains variable means and standard deviations for the variables included in the second stage analysis that are not included in the first stage. This includes means for the policy variables and the mean and standard deviation of the average age of the plant variable.

The second tobit model includes interaction terms between renewable and nonrenewable energy inputs as well as interaction terms between energy inputs and select renewable energy policies. The first interaction term, $F_r F_n$, is a vector of interaction terms comprised of *Renewable Sources*Coal*; *Renewable Sources***Petroleum*; and *Renewable Sources***Natural Gas and Other Gases*. *Renewable*

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[1] Decades is used instead of years for scaling purposes. The average number of years a plant has been operational across all years is approximately 30 years. If the variable was left in year it would be magnitudes larger than the other variables which might affect the results of the analysis.

*Sources**Nuclear* was not included in the analysis since nuclear power is used as a base load and its production level is not likely to change due to intermittent production of other energy sources.

Energy input and policy interaction terms are also considered. The policies that are interacted with the inputs include RPS in effect, public benefit fund, and mandatory green power option. The voluntary RPS, non-compliance penalty, and net metering are not interacted with the inputs. The voluntary RPS policy was not included since it is voluntary so that a utility company will probably not change their input mix if they think they will become less efficient. The non-compliance penalty was not included because the non-compliance penalty sets a cap on the amount the power plant will have to pay to meet the policy requirements. If the power plant believes that it will cost more to be in compliance with the policy, they will pay the penalty and not change their actions. Net metering was not included since it has not been shown to lead to the deployment of renewable energy at the plant level. Categories of energy inputs are used for the interaction terms instead of individual inputs since multiple types of inputs, from the same category, can be used in the same power plant. So if the power plant decides to reduce the use of one non-renewable input to instead use a renewable resource, it may reduce other inputs in the same category. The renewable energy sources are not aggregated to determine if the policies, that exist to encourage renewable energy deployment, affect each renewable energy differently.

The estimated tobit model with interaction terms is:

$$(4)\qquad \lambda = \alpha + \gamma_1 RPS + \gamma_2 Voluntary\ RPS + \gamma_3 Noncompliancy\ Penalty + \gamma_4 PBF + \\ \gamma_5 Net\ Metering + \gamma_6 MGPO + \beta_1 Installed\ Capacity + \beta_2 Average\ Age\ of\ Plant + \\ \beta_3 Bituminous\ Coal + \beta_4 Sub\ Bitinous\ Coal + \beta_5 Lignite\ Coal + \\ \beta_6 Coal\ Based\ Synfuel + \beta_7 Waste\ Coal + \beta_8 Distillate\ Fuel\ Oil + \beta_9 Jet\ Fuel + \\ \beta_{10} Kerosene + \beta_{11} Petroleum\ Coke + \beta_{12} Petroleum\ Coke\ Derived\ Synthesis\ Gas +$$

$$
\begin{aligned}
&\beta_{13}\mathit{Residual\ Fuel\ Oil} + \beta_{14}\mathit{Waste\ Oil} + \beta_{15}\mathit{Natural\ Gas} + \beta_{16}\mathit{Blast\ Furnace} + \\
&\beta_{17}\mathit{Other\ Gas} + \beta_{18}\mathit{Gaseous\ Propane} + \beta_{19}\mathit{Nuclear} + \\
&\beta_{20}\mathit{Agricultural\ Feedstock} + \beta_{21}\mathit{Municpal\ Solid\ Waste} + \\
&\beta_{22}\mathit{Other\ Biomass\ Solids} + \beta_{23}\mathit{Wood\ Waste\ Solids} + \\
&\beta_{24}\mathit{Other\ Biomass\ Liquids} + \beta_{25}\mathit{Black\ Liquor} + \beta_{26}\mathit{Sludge\ Waste} + \\
&\beta_{27}\mathit{Wood\ Waste\ Liquid} + \beta_{28}\mathit{Landfill\ Gas} + \beta_{29}\mathit{Other\ Biomass} + \\
&\beta_{30}\mathit{Geothermal} + \beta_{31}\mathit{Hydroelectric} + \beta_{32}\mathit{Solar} + \beta_{33}\mathit{Wind} + \\
&\beta_{34}\mathit{Other\ Energy\ Sources} + \rho_{1}\mathit{Renewable\ Sources} * \mathit{Coal} + \\
&\rho_{2}\mathit{Renewable\ Sources} * \mathit{Petroleum} + \rho_{3}\mathit{Renewable\ Sources} * \mathit{NG\&OG} + \delta_{1}\mathit{RPS} * \\
&\mathit{Coal} + \delta_{2}\mathit{PBF} * \mathit{Coal} + \delta_{3}\mathit{MGPO} * \mathit{Coal} + \delta_{4}\mathit{RPS} * \mathit{Petroleum} + \delta_{5}\mathit{PBF} * \\
&\mathit{Petroleum} + \delta_{6}\mathit{MGPO} * \mathit{Petroleum} + \delta_{7}\mathit{RPS} * \mathit{NG\&OG} + \delta_{8}\mathit{PBF} * \mathit{NG\&OG} + \\
&\delta_{9}\mathit{MGPO} * \mathit{NG\&OG} + \delta_{10}\mathit{RPS} * \mathit{Nuclear} + \delta_{11}\ \mathit{Nuclear} + \delta_{12}\mathit{MGPO} * \mathit{Nuclear} + \\
&\delta_{13}\mathit{RPS} * \mathit{Solid\ Renewable\ Fuels} + \delta_{14}\mathit{PBF} * \mathit{Solid\ Renewable\ Fuels} + \delta_{15}\mathit{MGPO} * \\
&\mathit{Solid\ Renewable\ Fuels} + \delta_{16}\mathit{RPS} * \mathit{Liquid\ Renewable\ Fuels} + \delta_{17}\mathit{PBF} * \\
&\mathit{Liquid\ Renewable\ Fuels} + \delta_{18}\mathit{MGPO} * \mathit{Liquid\ Renewable\ Fuels} + \delta_{19}\mathit{RPS} * \\
&\mathit{Gaseous\ Renewable\ Fuels} + \delta_{20}\mathit{PBF} * \mathit{Gaseous\ Renewable\ Fuels} + \delta_{21}\mathit{MGPO} * \\
&\mathit{Gaseous\ Renewable\ Fuels} + \delta_{22}\mathit{RPS} * \mathit{Geothermal} + \delta_{23}\mathit{PBF} * \mathit{Geothermal} + \\
&\delta_{24}\mathit{MGPO} * \mathit{Geothermal} + \delta_{25}\mathit{RPS} * \mathit{Hydroelectric} + \delta_{26}\mathit{PBF} * \mathit{Hydroelectric} + \\
&\delta_{27}\mathit{MGPO} * \mathit{Hydroelectric} + \delta_{28}\mathit{RPS} * \mathit{Solar} + \delta_{29}\mathit{PBF} * \mathit{Solar} + \delta_{30}\mathit{MGPO} * \\
&\mathit{Solar} + \delta_{31}\mathit{RPS} * \mathit{Wind} + \delta_{32}\mathit{PBF} * \mathit{Wind} + \delta_{33}\mathit{MGPO} * \mathit{Wind} + \delta_{34}\mathit{RPS} * \\
&\mathit{Other\ Energy\ Sources} + \delta_{35}\mathit{PBF} * \mathit{Other\ Energy\ Sources} + \delta_{35}\mathit{MGPO} * \\
&\mathit{Other\ Energy\ Sources}
\end{aligned}
$$

where RPS is RPS in Effect; PBF is Public Benefits Fund; MGPO is Mandatory Green Power Option; and NG&GO is natural gas and other gases.

The interaction terms between renewable energy sources and nonrenewable energy sources are negative if the intermittent production of some renewable energies effects the fuels that compensate for the intermittent production (coal, petroleum, and natural gas and other gases). It is hypothesized that natural gas and biofuels will have a negative and statistically significant effect on the efficiency scores based on Munksgaard, Pade, and Fristrup's (2005) study. In addition, due to the regulations placed on coal production, it is hypothesized that the use of coal by a power plant will have a negative effect on the efficiency scores. The use of nuclear power and hydroelectric power is hypothesized to have a positive effect on the efficiency scores due to their tendency to be used as the base load. Since wind and solar power are produced intermittently, they could have either a positive or negative effect on the efficiency score. Based on the findings of previous studies (Barros and Peypoch 2008, C. P. Barros 2008), it is hypothesized that the age of the power plants will have a negative effect on the efficiency scores. Several studies have considered variations of capacity in their second stage analysis (Lam and Shiu 2001, Raczka 2001) and found them to have a positive and statistically significant effect on the efficiency scores.

Renewable energy policies are geared toward increasing the quantity of electricity produced by renewable energy resources while decreasing the percentage of non-renewable resources used to produce electricity. For this reason, it is likely that the interaction between many of the non-renewable inputs and renewable energy policies will be negative. However, the interaction between the renewable energy policies and the renewable energy inputs is undetermined. If the renewable energy is inefficient and more of the inefficient renewable energy is required for electricity production, then the interaction is likely to be negative. However, if the renewable energy is overall efficient, then adding more may result in a positive impact on the efficiency scores.

4.0 Results

Two different analyses are conducted in this study. The first analysis estimates the pure technical efficiency (BCC) scores of utility plants from 2003 to 2012. The second analysis uses the pure technical efficiency scores as dependent variables to determine how renewable energy policies are correlated with the efficiencies of power plants.

4.1 DEA Results

The mean pure technical efficiency scores are reported in Table 3 by input fuel. Across all years, nuclear power is the most efficient fuel type. The minimum mean pure technical efficiency score for all years is 0.962. Geothermal, wind, and solar were very efficient in 2003 – 2004 with the mean pure technical efficiency scores being 1.000, 0.982, and 0.994 between the two years, respectively. However the mean efficiency scores began to drop off in 2005. From 2005 to 2012 the minimum mean pure technical efficiency scores are 0.678, 0.513, and 0.524 for geothermal, hydroelectric, and wind, respectively. On average, coal inputs exhibit the lowest mean pure technical efficiency scores of all the inputs.

The cumulative distribution function (CDF) shows the results of the efficiency scores, by fuel category, for 2012 (Figure 1). From the graph, Nuclear is the most efficient fuel input less than 10% of nuclear power plants have an efficiency score of less than 0.95. Overall, renewable inputs are relatively efficient. Less than 80% of power plants that use Gaseous Renewable Fuels have an efficiency score of less than 0.90 while less than less than 85% and less than 90% of power plants that use Liquid Renewable Fuels and Other Renewable Sources have an efficiency score of less than 0.90. Coal is the least efficient fuel source. Almost 90% of power plants that use a coal input have an efficiency score of less than 0.50.

4.2 Econometric Results

Two second stage analyses are conducted using the estimated pure technical efficiency scores from the first stage as the dependent variable in a tobit model. The first tobit model does not include any interaction effects (Table 4) while the second model includes interaction terms between the renewable and nonrenewable fuel inputs as well as interaction terms between the renewable energy policies and fuel inputs (Table 5).

None of the renewable energy policies had a statistically significant correlation with the efficiency scores of electric generation plants across all years of the study (Table 4). *RPS in Effect* is negative and statistically significant in seven of the ten years. These results imply that power plants in states with RPS in effect tend to have lower efficiency scores than power plants in states that do not. Because RPS requires states to supply a certain percentage of electricity from renewable energy sources that may be intermittently produced, more power plants in those states may be underutilized when the intermittent power is being produced and have to ramp up quickly when the intermittent power is no longer producing electricity. However, the effect is relatively small. If a non-compliance penalty is in effect in a state the coefficient is positive and statistically significant in four of nine years. Electric generation plants in states with a non-compliance penalty know the maximum cost of complying with the RPS. If they believe it will cost more money to be in compliance, then the power plants may continue operating as they had been and pay the non-compliance penalty instead of changing their production practices. The public benefits fund variable is negative and statistically significant in 2003 – 2005 and positive and statistically significant in 2009 and 2011. This result may exist because the public benefit fund adds a fee to consumers' electricity bills for a number of years then gives the money to power plants for the development of renewable energy. Since the power plants know they will eventually get the money to help cover the cost of building new renewable energy sources they may wait to change their fuel usage until the money is received to build the new, more efficient, renewable energy plants. Net metering was found to be positive and statistically significant in 2003 and negative and statistically significant in 2007 – 2012. The results in 2007 – 2012 seems intuitive as the power plants do not have control over the quantity or timing of the electricity received from net metering. In addition, when power plants ramp up production in the morning and evenings to meet increased demand periods, they are receiving smaller supplies of electricity from net metering. The mandatory green power option variable is positive and statistically significant in nine out of ten years. This result is somewhat surprising since utility companies are required to give customers the option of purchasing a certain percentage of their power from renewable sources, similar results to RPS in effect may be expected. However, since the total quantity of renewable energy the utility is required to provide is much smaller under mandatory green power option than RPS in effect, the utility may not have to change their production portfolio much, if at all, to meet the demand for renewable energy.

Installed capacity and age of the plant are both negative and statistically significant in each year. This implies that larger plants are less efficient than smaller plants. This contradicts the findings of Lam and Shiu (2001) and Raczka (2001). However, their capacity variable was measured as either a capacity factor or utilization instead of capacity in MW. It is likely that capacity is negative because plants that rely on multiple types of inputs are less efficient than firms that use only one input. This is based on the fact that the average efficiency across all years of power plants that use one input is 0.602 with an average capacity of 124 MW while the average efficiency of power plants that use two or more inputs is 0.237 and an average capacity of 409 MW. Age being negative and statistically significant follows the findings of several studies (Barros and Peypoch 2008, C. P. Barros 2008).

Several fuel inputs are negative and statistically significant in every year – bituminous coal, sub-bituminous coal, lignite coal, distillate fuel oil, natural gas, and sludge waste. While a number of fuel inputs are negative and statically significant for at least half the years – waste/other coal, kerosene, other gases, other biomass liquids, wood waste liquids, and landfill gas. These are not surprising based on the results in Table 3 and Figure 1. Several inputs are positive and statistically significant in every year – nuclear, municipal solid waste, geothermal, and hydroelectric. While a few other fuel inputs are positive and statistically significant for at least half the years – wood/wood waste solids, black liquor, and wind.

The fuel plant characteristic results do not change much between the analysis without interactions and the analysis with interactions (Table 5). There are a few changes in the total effect of the policies that are interacted with the fuel inputs. The mean marginal efficiency of RPS in effect is negative in only five years (RPS in effect was negative and statistically significant in seven years in the no interaction model). However, the absolute value of the largest mean marginal efficiency of RPS in effect is 0.049 which is smaller than the largest effect in the no interaction model (0.071). This shows that the RPS policy has not had a large effect on the efficiency of power plants. The public benefits fund variable has a small negative marginal effect in six years and a small positive effect in four years. Like with RPS in effect, all of the mean marginal effects are small. The largest mean marginal effect of public benefits fund in absolute value terms is 0.038. This is consistent with the results from the analysis with no interactions. The mandatory green power option variable has a positive average marginal effect in seven years. However, like with the previous two policies the average marginal effect is small with the largest, in absolute value, equaling 0.040. Since the average marginal effects of all these policies are small as well as the coefficients that are statistically significant for the policies that were not interacted with fuel inputs, this implies that renewable energy policies do not have a large impact on the efficiency of power plants overall.

The renewable input sources interaction terms yield several statistically significant results. *Coal*Renewable Sources* is negative and statistically significant in 2008 and 2009. *Petroleum*Renewable Sources* is negative and statistically significant in 2005, 2007, and 2011. *Natural Gas and Other Gases*Renewable Sources* is negative and statistically significant in 2008 – 2010. The fuel inputs most used in each of these categories (bituminous coal, distillate fuel oil, and natural gas, respectively) are negative and statistically significant in every year. This result implies that the power plants that use a renewable energy source in addition to these sources are less efficient than those that do not. Based on the mean efficiency scores, coal, petroleum, and natural gas and other gases plants that also used intermittent energy inputs (solar or wind) were on average across all 10 years, less efficient than power plants that use coal, petroleum, or natural gas and other gases and a non-intermittent renewable energy input. Since the efficiency scores are lower for plants that use intermittent energy sources, this implies that the efficiency of traditional electric generation plants may be negatively impacted by incorporating renewable energy in to their production.

5.0 Discussion and Conclusion

Power plants that use nuclear or renewable energy sources are more efficient than power plants that rely on traditional fuel sources from a technical efficiency perspective, despite the intermittency of fuel sources like wind. Solar energy is the one exception to renewable energy being more efficient than non-renewable energy. However, the use of solar energy is not statistically significant in most years.

There are a few key findings from this study. First, renewable energy inputs are just as technically efficient as or more efficient than nonrenewable fuel inputs (with the exception of nuclear). Second, power plants that use multiple types of inputs are less technically efficient than power plants that focus on one input source. This is especially true for plants that use coal, petroleum, or natural gas and other gases and an intermittent renewable energy source. Third, renewable energy policies have had little impact on the technical efficiencies of power plants. Based on the coefficient estimates in the tobit regression with no interactions and the average total effects of the tobit regression with interaction terms, renewable energy policies do not have a negatively significant effect on power plants.

When there was statistical significance, the effect was very small, implying that there was no technical significance.

There are a couple limitations of this study. From a technical efficiency perspective since coal and natural gas are inefficient policies that encourage more efficient forms of electricity (nuclear or renewable energy sources) might make power plants more technically efficient, however, from an economic perspective it might be more costly for rate payers if a higher percentage of technically efficient inputs are used. In addition, the renewable energy policies do not appear to have an overwhelming negative effect on the technical efficiency scores, however these policies may have an effect on the economic efficiency of power plants. Further research should be conducted to determine if the economic efficiencies of power plants are effected by renewable energy policies.

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Table 1 – Input and Output Summary Statistics of Electric Generation Plants from 2003 – 2012 for the DEA Model

	2003 N = 4474	2004 N = 3908	2005 N = 4717	2006 N = 4770	2007 N = 4784	2008 N = 4723	2009 N = 5012	2010 N = 5017	2011 N = 5277	2012 N = 5568
					Coal					
Bituminous Coal	2,426,932	2,630,141	2,309,157	1,834,069	2,049,364	2,049,668	1,666,018	1,839,459	1,479,104	1,208,286
	(13,832,544)	(14,305,601)	(13,571,113)	(11,175,531)	(13,038,947)	(13,160,722)	(11,447,406)	(12,399,583)	(10,744,391)	(9,640,692)
Sub-Bituminous Coal	1,713,801	2,082,531	1,770,558	1,672,859	1,752,465	1,784,999	1,669,233	1,642,564	1,369,475	1,269,942
	(11,973,265)	(13,638,190)	(12,639,861)	(12,091,320)	(12,589,936)	(12,627,125)	(12,049,542)	(11,966,045)	(10,909,549)	(10,055,543)
Lignite Coal	230,959	186,733	212,848	198,088	193,786	191,604	164,302	176,744	157,464	164,263
	(4,358,790)	(3,267,535)	(4,158,973)	(3,961,459)	(3,902,295)	(3,782,337)	(3,333,246)	(3,383,086)	(3,236,410)	(3,464,359)
Refined Coal	120,443	184,344	151,911	107,340	118,996	756	--	--	--	--
	(2,647,011)	(3,191,050)	(3,129,559)	(2,617,533)	(3,082,039)	(30,931)				
Waste/Other Coal	26,269	32,165	33,301	34,406	22,125	26,944	23,931	25,077	18,311	15,530
	(434,032)	(478,376)	(632,757)	(691,542)	(642,098)	(694,550)	(629,971)	(667,956)	(559,082)	(394,623)
					Petroleum					
Distillate Fuel Oil	35,453	30,515	29,419	15,646	18,710	15,545	16,281	16,644	10,338	9,129
	(238,080)	(198,958)	(255,948)	(143,569)	(142,615)	(134,573)	(149,917)	(148,980)	(67,572)	(106,583)
Jet Fuel	179	682	760	630	1,189	821	817	800	770	697
	(5,798)	(27,855)	(28,568)	(28,629)	(49,150)	(45,541)	(46,284)	(41,093)	(40,345)	(37,886)
Kerosene	1,115	1,329	1,226	432	878	546	766	431	412	191
	(26,159)	(28,185)	(28,255)	(8,536)	(24,176)	(14,939)	(22,277)	(8,381)	(10,444)	(4,885)
Petroleum Coke	34,797	58,446	53,787	48,152	42,417	37,126	30,194	28,108	17,115	23,427
	(619,660)	(875,437)	(879,429)	(823,754)	(721,128)	(716,681)	(599,210)	(599,060)	(387,334)	(491,969)
Petroleum Coke-Derived Synthesis Gas	--	--	--	--	--	--	--	--	--	1,111
										(82,924)
Residual Fuel Oil	203,716	228,762	199,635	89,191	95,023	55,523	41,811	33,687	16,562	9,284
	(2,298,735)	(2,458,234)	(2,249,682)	(1,132,671)	(1,182,813)	(845,058)	(645,605)	(633,326)	(459,925)	(218,427)
Waste/Other Oil	3,161	2,850	2,220	2,623	2,484	2,434	1,708	1,391	1,223	782
	(82,151)	(73,974)	(63,594)	(66,772)	(64,815)	(60,812)	(46,028)	(39,334)	(34,798)	(22,358)
					Natural Gas and Other Gases					
Natural Gas	1,308,370	1,579,315	1,467,776	1,537,370	1,641,959	1,553,736	1,539,980	1,592,670	1,482,846	1,750,819
	(5,002,641)	(5,832,321)	(5,569,152)	(5,895,948)	(6,165,204)	(6,042,921)	(6,055,335)	(6,321,418)	(6,213,444)	(7,254,310)

Table 1 – Input and Output Summary Statistics of Electric Generation Plants from 2003 – 2012 for the DEA Model

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
	N = 4474	N = 3908	N = 4717	N = 4770	N = 4784	N = 4723	N = 5012	N = 5017	N = 5277	N = 5568
Blast Furnace Gas	10,088	25,058	17,289	16,473	15,397	20,548	11,818	14,154	16,638	15,379
	(257,059)	(517,391)	(484,431)	(424,000)	(399,939)	(483,605)	(322,147)	(362,383)	(416,748)	(414,273)
Other Gas	32,668	47,659	47,095	50,621	49,266	39,265	38,420	35,565	31,982	34,607
	(593,883)	(646,075)	(639,559)	(662,874)	(617,834)	(501,012)	(485,700)	(466,848)	(461,604)	(485,553)
Gaseous Propane	39	318	96	61	70	47	40	67	22	12
	(1,163)	(17,961)	(3,832)	(1,725)	(2,508)	(2,255)	(1,599)	(3,287)	(684)	(461)
Nuclear										
Nuclear	1,742,534	2,001,137	1,695,086	1,675,606	1,651,666	1,721,710	1,546,952	1,481,194	1,409,406	1,408,720
	(15,992,377)	(17,468,463)	(15,960,461)	(15,855,330)	(16,014,099)	(16,369,741)	(15,610,197)	(14,995,215)	(15,005,738)	(14,902,532)
Solid Renewable Fuel										
Agricultural Feedstock	2,849	4,546	5,224	5,423	4,989	6,825	6,406	6,530	5,646	5,611
	(107,339)	(130,025)	(141,308)	(151,470)	(163,608)	(223,268)	(214,708)	(228,766)	(197,402)	(213,911)
Municipal Solid Waste	--	--	--	34,377	33,606	33,783	31,635	30,691	28,112	26,801
				(334,253)	(323,788)	(334,219)	(320,444)	(315,702)	(293,520)	(285,626)
Other Biomass Solids	1,166	2,620	2,341	1,330	2,424	3,980	3,963	4,529	3,624	4,091
	(75,643)	(91,276)	(89,729)	(61,573)	(87,001)	(117,765)	(125,398)	(122,719)	(110,349)	(138,972)
Wood/Wood Waste Solids	77,628	109,854	105,036	113,160	110,773	103,754	95,139	93,781	84,862	87,697
	(599,916)	(675,026)	(648,435)	(721,794)	(692,735)	(677,307)	(623,362)	(642,521)	(576,038)	(620,903)
Liquid Renewable Fuels										
Other Biomass Liquids	18	53	25	51	37	51	53	40	136	102
	(1,102)	(1,952)	(1,097)	(2,044)	(1,576)	(1,948)	(1,754)	(1,406)	(6,424)	(5,539)
Black Liquor	104,712	164,153	153,758	164,074	155,734	146,936	123,009	134,069	125,112	126,526
	(1,017,501)	(1,298,458)	(1,287,407)	(1,320,649)	(1,276,798)	(1,338,389)	(1,095,082)	(1,198,615)	(1,141,731)	(1,177,079)
Sludge Waste	1,881	1,892	1,633	1,257	1,344	1,029	923	996	849	773
	(64,440)	(38,391)	(37,935)	(23,586)	(25,259)	(18,554)	(18,175)	(21,459)	(16,599)	(15,361)
Wood Waste Liquids	1,967	1,639	1,466	4,960	585	532	519	585	1,100	1,421
	(64,787)	(66,882)	(71,183)	(342,575)	(40,476)	(36,528)	(36,745)	(41,422)	(56,482)	(77,404)

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	2003 N = 4474	2004 N = 3908	2005 N = 4717	2006 N = 4770	2007 N = 4784	2008 N = 4723	2009 N = 5012	2010 N = 5017	2011 N = 5277	2012 N = 5568
Gaseous Renewable Fuels										
Landfill Gas	13,484	16,502	14,248	15,940	16,360	19,421	18,988	14,901	19,618	19,485
	(109,705)	(125,705)	(121,969)	(126,736)	(127,616)	(135,694)	(128,363)	(128,573)	(136,120)	(140,286)
Other Biomass Gas	2,285	2,354	2,383	2,442	2,142	1,614	1,716	1,835	1,747	1,856
	(42,181)	(47,170)	(44,112)	(45,962)	(43,241)	(38,776)	(37,468)	(37,300)	(36,526)	(36,302)
Other Renewable Energy Sources										
Geothermal	32,204	20,669	29,697	30,294	30,241	30,482	29,227	29,595	28,164	26,307
	(784,023)	(786,731)	(739,954)	(726,998)	(736,710)	(718,454)	(693,470)	(689,158)	(673,428)	(654,714)
Hydroelectric	582,251	418,766	572,114	599,101	510,248	530,633	522,678	502,041	567,000	462,001
	(4,791,222)	(4,754,137)	(4,917,582)	(5,179,171)	(4,983,798)	(5,033,422)	(4,705,156)	(4,302,186)	(5,434,314)	(5,058,787)
Solar	1,222	1,301	1,167	1,056	1,264	1,791	1,719	2,324	3,264	7,153
	(31,888)	(33,759)	(30,706)	(28,640)	(32,025)	(40,904)	(37,187)	(42,797)	(45,226)	(77,765)
Wind	25,510	32,415	35,814	55,266	71,157	101,337	143,207	181,703	218,269	230,640
	(244,050)	(296,842)	(305,696)	(440,038)	(522,112)	(703,228)	(714,349	(858,984)	(969,046)	(963,054)
Other Energy Sources										
Other Energy Sources	1,375	15,769	14,516	13,420	9,678	5,403	9,200	10,060	5,653	7,846
	(53,361)	(319,485)	(302,788)	(305,898)	(287,508)	(94,328)	(255,466)	(256,651)	(119,320)	(203,708)
Capacity										
Installed Capacity (MW)	216	238	215	206	209	209	206	207	190	189
	(466)	(492)	(467)	(449)	(459)	(461)	(456)	(455)	(437)	(440)
Output										
Net Generation (MWh)	363,118	393,013	374,063	397,833	398,609	407,112	391,833	396,701	385,303	406,296
	(1,654,573)	(1,812,210)	(1,683,655)	(1,711,957)	(1,730,380)	(1,770,852)	(1,701,588)	(1,661,770)	(1,695,465)	(1,736,936)

Standard deviations are in parenthesis

Table 2 – Summary Statistics of State Policies and Plant Variables from 2003 – 2012 Used in the Econometric Model

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]	N = 51[a]
Mandatory Green Power Option	0.059	0.078	0.078	0.098	0.137	0.137	0.157	0.157	0.157	0.157
Net Metering	0.549	0.608	0.627	0.647	0.667	0.745	0.824	0.843	0.863	0.863
Public Benefits Funds	0.275	0.275	0.294	0.314	0.333	0.353	0.353	0.353	0.333	0.353
RPS in Effect	0.020	0.059	0.098	0.235	0.314	0.392	0.431	0.471	0.529	0.588
RPS Penalty	--	0.039	0.059	0.118	0.176	0.235	0.275	0.275	0.294	0.314
Voluntary RPS	--	--	0.020	0.020	0.059	0.098	0.098	0.118	0.137	0.137
	N = 4474	N = 3908	N = 4717	N = 4770	N = 4784	N = 4723	N = 5012	N = 5017	N = 5277	N = 5568
Plant Operating Year	1974	1977	1975	1976	1977	1977	1980	1980	1982	1984
	(24)	(22)	(24)	(24)	(24)	(24)	(25)	(25)	(25)	(26)

[a] Renewable energy policies are at the state level, so means are taken across states instead of across utility plants. Standard errors are in parenthesis.

Table 3 – Mean Pure Technical Efficiency Scores of Electric Generation Plants in the U.S. 2003 – 2012

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
All Fuels										
	N = 4474	N = 3908	N = 4717	N = 4770	N = 4784	N = 4723	N = 5012	N = 5017	N = 5277	N = 5568
All Fuels	0.630	0.561	0.655	0.402	0.393	0.426	0.437	0.451	0.556	0.483
	(0.379)	(0.377)	(0.352)	(0.320)	(0.314)	(0.324)	(0.322)	(0.322)	(0.345)	(0.325)
Coal										
	N = 392	N = 431	N = 437	N = 397	N = 384	N = 364	N = 375	N = 366	N = 354	N = 326
Bituminous Coal	0.155	0.155	0.151	0.146	0.120	0.149	0.138	0.136	0.151	0.165
	(0.287)	(0.286)	(0.279)	(0.281)	(0.237)	(0.279)	(0.262)	(0.258)	(0.274)	(0.288)
	N = 189	N = 204	N = 213	N = 206	N = 208	N = 219	N = 232	N = 223	N = 221	N = 213
Sub-Bituminous Coal	0.067	0.109	0.112	0.085	0.089	0.096	0.098	0.083	0.097	0.091
	(0.192)	(0.267)	(0.266)	(0.220)	(0.225)	(0.249)	(0.251)	(0.215)	(0.248)	(0.232)
	N = 19	N = 18	N = 18	N = 17	N = 18	N = 17	N = 17	N = 19	N = 20	N = 20
Lignite Coal	0.158	0.067	0.072	0.004	0.014	0.005	0.005	0.008	0.081	0.066
	(0.264)	(0.233)	(0.232)	(0.006)	(0.042)	(0.005)	(0.005)	(0.014)	(0.243)	(0.224)
	N = 21	N = 22	N = 21	N = 18	N = 15	N = 7				
Refined Coal	0.277	0.340	0.365	0.184	0.090	0.092	-	-	-	-
	(0.363)	(0.396)	(0.447)	(0.337)	(0.158)	(0.229)				
	N = 21	N = 25	N = 24	N = 20	N = 13	N = 17	N = 16	N = 15	N = 12	N = 13
Waste/Other Coal	0.378	0.132	0.154	0.022	0.126	0.142	0.226	0.238	0.182	0.171
	(0.453)	(0.268)	(0.250)	(0.020)	(0.290)	(0.324)	(0.376)	(0.373)	(0.382)	(0.368)
Petroleum										
	N = 1480	N = 1463	N = 1504	N = 1401	N = 1365	N = 1312	N = 1310	N = 1297	N = 1285	N = 1234
Distillate Fuel Oil	0.299	0.325	0.276	0.195	0.200	0.209	0.209	0.204	0.215	0.219
	(0.283)	(0.292)	(0.281)	(0.252)	(0.250)	(0.262)	(0.264)	(0.254)	(0.268)	(0.268)
	N = 15	N = 15	N = 18	N = 15	N = 15	N = 26	N = 41	N = 41	N = 38	N = 36
Jet Fuel	0.535	0.547	0.417	0.270	0.258	0.491	0.602	0.596	0.666	0.697
	(0.397)	(0.362)	(0.354)	(0.311)	(0.323)	(0.354)	(0.350)	(0.342)	(0.335)	(0.332)
	N = 41	N = 40	N = 46	N = 47	N = 44	N = 45	N = 47	N = 39	N = 43	N = 43
Kerosene	0.601	0.515	0.397	0.179	0.169	0.204	0.170	0.365	0.270	0.249
	(0.322)	(0.333)	(0.310)	(0.263)	(0.249)	(0.278)	(0.260)	(0.337)	(0.278)	(0.253)

Table 3 – Mean Pure Technical Efficiency Scores of Electric Generation Plants in the U.S. 2003 – 2012

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
	N = 46	N = 56	N = 58	N = 49	N = 45	N = 45	N = 45	N = 38	N = 32	N = 29
Petroleum Coke	0.238	0.272	0.301	0.213	0.177	0.212	0.185	0.244	0.231	0.278
	(0.346)	(0.371)	(0.385)	(0.333)	(0.267)	(0.324)	(0.290)	(0.335)	(0.314)	(0.357)
										N = 1
Petroleum Coke-Derived Synthesis Gas	-	-	-	-	-	-	-	-	-	0.034
										-
	N = 194	N = 212	N = 211	N = 202	N = 180	N = 162	N = 159	N = 139	N = 126	N = 117
Residual Fuel Oil	0.327	0.327	0.327	0.270	0.267	0.290	0.272	0.313	0.324	0.325
	(0.304)	(0.311)	(0.303)	(0.288)	(0.287)	(0.311)	(0.292)	(0.309)	(0.302)	(0.304)
	N = 19	N = 26	N = 23	N = 23	N = 27	N = 40	N = 37	N = 33	N = 28	N = 24
Waste/Other Oil	0.455	0.458	0.476	0.409	0.306	0.284	0.236	0.313	0.325	0.285
	(0.396)	(0.424)	(0.419)	(0.376)	(0.341)	(0.324)	(0.253)	(0.314)	(0.338)	(0.301)
Natural Gas and Other Gases										
	N = 1807	N = 1843	N = 1891	N = 1892	N = 1872	N = 1826	N = 1822	N = 1849	N = 1866	N = 1942
Natural Gas	0.371	0.371	0.406	0.288	0.249	0.288	0.280	0.300	0.330	0.317
	(0.305)	(0.302)	(0.307)	(0.317)	(0.283)	(0.319)	(0.312)	(0.309)	(0.337)	(0.317)
	N = 11	N = 15	N = 15	N = 12	N = 12	N = 13	N = 10	N = 11	N = 12	N = 12
Blast Furnace Gas	0.461	0.410	0.314	0.278	0.256	0.235	0.159	0.280	0.313	0.299
	(0.397)	(0.357)	(0.349)	(0.285)	(0.301)	(0.226)	(0.138)	(0.266)	(0.272)	(0.266)
	N = 47	N = 65	N = 68	N = 68	N = 72	N = 73	N = 73	N = 67	N = 68	N = 71
Other Gas	0.398	0.304	0.330	0.255	0.281	0.242	0.221	0.285	0.273	0.234
	(0.371)	(0.373)	(0.391)	(0.294)	(0.357)	(0.315)	(0.277)	(0.334)	(0.321)	(0.304)
	N = 13	N = 12	N = 16	N = 12	N = 11	N = 7	N = 6	N = 10	N = 10	N = 5
Gaseous Propane	0.478	0.361	0.240	0.236	0.228	0.208	0.326	0.340	0.389	0.300
	(0.403)	(0.396)	(0.299)	(0.284)	(0.290)	(0.327)	(0.344)	(0.339)	(0.352)	(0.284)
Nuclear										
	N = 65	N = 66	N = 66	N = 66	N = 66	N = 65	N = 65	N = 65	N = 64	N = 63
Nuclear	0.979	0.979	0.979	0.962	0.962	0.973	0.969	0.964	0.972	0.965
	(0.128)	(0.127)	(0.126)	(0.125)	(0.130)	(0.053)	(0.056)	(0.132)	(0.061)	(0.086)

Table 3 – Mean Pure Technical Efficiency Scores of Electric Generation Plants in the U.S. 2003 – 2012

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Solid Renewable Fuels										
Agricultural Feedstock	N = 10	N = 12	N = 11	N = 13	N = 12	N = 15	N = 14	N = 12	N = 11	N = 10
	0.612	0.692	0.759	0.317	0.451	0.409	0.369	0.518	0.503	0.452
	(0.397)	(0.360)	(0.329)	(0.282)	(0.338)	(0.399)	(0.362)	(0.438)	(0.377)	(0.423)
Municipal Solid Waste				N = 77	N = 79	N = 71	N = 72	N = 70	N = 74	N = 74
	-	-	-	0.598	0.629	0.627	0.624	0.616	0.601	0.613
				(0.272)	(0.273)	(0.233)	(0.247)	(0.256)	(0.268)	(0.279)
Other Biomass Solids	N = 5	N = 10	N = 12	N = 11	N = 13	N = 13	N = 15	N = 16	N = 16	N = 13
	0.036	0.175	0.092	0.084	0.154	0.291	0.264	0.421	0.378	0.359
	(0.041)	(0.311)	(0.110)	(0.092)	(0.190)	(0.343)	(0.325)	(0.404)	(0.349)	(0.402)
Wood/Wood Waste Solids	N = 160	N = 208	N = 210	N = 213	N = 206	N = 207	N = 213	N = 205	N = 207	N = 204
	0.498	0.481	0.459	0.407	0.395	0.440	0.404	0.444	0.446	0.388
	(0.345)	(0.333)	(0.326)	(0.316)	(0.323)	(0.339)	(0.321)	(0.328)	(0.325)	(0.311)
Liquid Renewable Fuels										
Other Biomass Liquids	N = 3	N = 4	N = 4	N = 5	N = 8	N = 7	N = 9	N = 8	N = 7	N = 6
	0.106	0.120	0.052	0.073	0.135	0.121	0.105	0.056	0.068	0.124
	(0.074)	(0.189)	(0.049)	(0.064)	(0.129)	(0.162)	(0.122)	(0.070)	(0.075)	(0.185)
Black Liquor	N = 68	N = 90	N = 88	N = 90	N = 89	N = 85	N = 83	N = 84	N = 81	N = 83
	0.373	0.379	0.345	0.352	0.297	0.367	0.308	0.354	0.383	0.324
	(0.304)	(0.294)	(0.281)	(0.290)	(0.290)	(0.304)	(0.247)	(0.282)	(0.289)	(0.287)
Sludge Waste	N = 13	N = 23	N = 26	N = 27	N = 27	N = 23	N = 26	N = 26	N = 26	N = 24
	0.063	0.048	0.077	0.044	0.036	0.045	0.064	0.073	0.071	0.044
	(0.102)	(0.054)	(0.192)	(0.059)	(0.034)	(0.039)	(0.126)	(0.128)	(0.122)	(0.107)
Wood Waste Liquids	N = 8	N = 6	N = 3	N = 2	N = 1	N = 1	N = 1	N = 1	N = 3	N = 3
	0.312	0.432	0.317	0.386	0.092	0.212	0.117	0.314	0.307	0.308
	(0.253)	(0.377)	(0.383)	(0.286)	-	-	-	-	(0.297)	(0.375)
Gaseous Renewable Fuels										
Landfill Gas	N = 176	N = 178	N = 183	N = 202	N = 223	N = 235	N = 264	N = 273	N = 297	N = 320
	0.679	0.711	0.673	0.600	0.610	0.596	0.675	0.688	0.704	0.687
	(0.255)	(0.239)	(0.254)	(0.239)	(0.256)	(0.222)	(0.229)	(0.237)	(0.234)	(0.210)

Table 3 – Mean Pure Technical Efficiency Scores of Electric Generation Plants in the U.S. 2003 – 2012

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Other Biomass Gas	N = 34	N = 35	N = 41	N = 39	N = 33	N = 29	N = 33	N = 37	N = 46	N = 60
	0.617	0.515	0.526	0.470	0.501	0.578	0.547	0.558	0.602	0.572
	(0.337)	(0.347)	(0.376)	(0.339)	(0.350)	(0.341)	(0.343)	(0.327)	(0.328)	(0.361)
Other Renewable Sources										
Geothermal	N = 47	N = 32	N = 47	N = 49	N = 51	N = 50	N = 55	N = 56	N = 56	N = 59
	1.000	1.000	0.979	0.678	0.718	0.732	0.712	0.738	0.743	0.690
	(0.000)	(0.000)	(0.026)	(0.212)	(0.217)	(0.194)	(0.235)	(0.214)	(0.194)	(0.212)
Hydroelectric	N = 1353	N = 1335	N = 1365	N = 1381	N = 1370	N = 1363	N = 1370	N = 1376	N = 1377	N = 1348
	0.978	0.982	0.885	0.529	0.513	0.561	0.589	0.606	0.624	0.414
	(0.116)	(0.119)	(0.164)	(0.231)	(0.219)	(0.227)	(0.207)	(0.214)	(0.214)	(0.193)
Solar	N = 11	N = 12	N = 13	N = 14	N = 17	N = 22	N = 56	N = 94	N = 215	N = 363
	0.695	0.691	0.679	0.232	0.291	0.377	0.571	0.598	0.566	0.336
	(0.388)	(0.339)	(0.383)	(0.251)	(0.270)	(0.314)	(0.355)	(0.339)	(0.318)	(0.165)
Wind	N = 167	N = 176	N = 218	N = 263	N = 303	N = 308	N = 501	N = 562	N = 655	N = 776
	0.994	0.996	0.885	0.563	0.623	0.634	0.549	0.544	0.594	0.524
	(0.077)	(0.059)	(0.155)	(0.248)	(0.258)	(0.208)	(0.231)	(0.214)	(0.221)	(0.252)
Other Energy Sources										
Other Energy Sources	N = 7	N = 35	N = 38	N = 32	N = 25	N = 33	N = 36	N = 35	N = 34	N = 28
	0.280	0.547	0.564	0.421	0.378	0.398	0.397	0.403	0.379	0.375
	(0.457)	(0.435)	(0.419)	(0.388)	(0.374)	(0.371)	(0.392)	(0.391)	(0.355)	(0.409)

Standard deviations are in parenthesis

Table 4 – Tobit Model Regression Results with No Interaction Terms from 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Intercept	0.868***	0.892***	0.880***	0.598***	0.589***	0.679***	0.695***	0.732***	0.764***	0.726***
	(0.014)	(0.015)	(0.013)	(0.016)	(0.016)	(0.018)	(0.017)	(0.019)	(0.018)	(0.020)
RPS in Effect (RPS)	-0.046**	-0.071**	-0.049**	0.012	-0.021*	-0.008	-0.028**	-0.011	-0.051***	-0.035***
	(0.021)	(0.031)	(0.022)	(0.012)	(0.011)	(0.012)	(0.011)	(0.012)	(0.012)	(0.013)
Voluntary RPS	-	-	-0.018	0.061***	-0.031	-0.014	-0.018	0.014	-0.003	0.007
			(0.032)	(0.037)	(0.021)	(0.018)	(0.017)	(0.015)	(0.014)	(0.017)
Non-compliance Penalty	-	0.149***	0.104***	0.049	0.012	0.011	0.005	0.009	0.027***	0.035***
		(0.035)	(0.025)	(0.014)	(0.012)	(0.012)	(0.011)	(0.010)	(0.009)	(0.010)
Public Benefits Fund (PBF)	-0.018**	-0.039***	-0.024***	0.009	0.009	0.018	0.019***	0.013	0.040***	0.000
	(0.008)	(0.011)	(0.009)	(0.010)	(0.011)	(0.011)	(0.010)	(0.011)	(0.010)	(0.011)
Net Metering (NM)	0.026***	0.003	-0.002	-0.002	-0.019*	-0.030**	-0.058***	-0.036***	-0.038***	-0.036***
	(0.008)	(0.010)	(0.008)	(0.010)	(0.011)	(0.012)	(0.012)	(0.013)	(0.012)	(0.014)
Mandatory Green Power Option (MGPO)	0.018	0.040*	0.032**	0.052***	0.041***	0.039***	0.029***	0.018*	0.018*	0.034***
	(0.017)	(0.023)	(0.016)	(0.015)	(0.013)	(0.013)	(0.011)	(0.011)	(0.011)	(0.012)
Installed Capacity	-0.013***	-0.024***	-0.012***	-0.024***	-0.015***	-0.031***	-0.029***	-0.035***	-0.028***	-0.025***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Age of Plant	-0.011***	-0.014***	-0.012***	-0.013***	-0.015***	-0.017***	-0.012***	-0.012***	-0.013***	-0.017***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Coal										
Bituminous Coal	-0.326***	-0.263***	-0.329***	-0.099***	-0.125***	-0.093***	-0.098***	-0.102***	-0.128***	-0.094***
	(0.014)	(0.014)	(0.013)	(0.016)	(0.015)	(0.016)	(0.016)	(0.016)	(0.016)	(0.018)
Sub-Bituminous Coal	-0.347***	-0.257***	-0.334***	-0.131***	-0.140***	-0.111***	-0.113***	-0.125***	-0.162***	-0.162***
	(0.018)	(0.019)	(0.016)	(0.020)	(0.019)	(0.020)	(0.019)	(0.019)	(0.019)	(0.021)
Lignite Coal	-0.117**	-0.297***	-0.359***	-0.217***	-0.198***	-0.195***	-0.214***	-0.225***	-0.211***	-0.221***
	(0.052)	(0.061)	(0.052)	(0.065)	(0.061)	(0.064)	(0.063)	(0.059)	(0.058)	(0.064)
Coal-Based Synfuel	0.013	0.105**	0.080	0.084	-0.028	0.067	-	-	-	-
	(0.052)	(0.053)	(0.049)	(0.064)	(0.069)	(0.101)				
Waste/Other Coal	-0.114**	-0.296***	-0.124***	-0.263***	-0.230***	-0.164**	-0.061	-0.086	-0.165**	-0.181**
	(0.051)	(0.051)	(0.046)	(0.061)	(0.075)	(0.065)	(0.065)	(0.066)	(0.073)	(0.077)

Table 4 – Tobit Model Regression Results with No Interaction Terms from 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Petroleum										
Distillate Fuel Oil	-0.227***	-0.251***	-0.235***	-0.211***	-0.184***	-0.223***	-0.215***	-0.251***	-0.264***	-0.244***
	(0.010)	(0.010)	(0.009)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.012)
Jet Fuel	0.020	-0.002	-0.074	-0.098	-0.091	0.075	0.080*	0.041	0.146***	0.119**
	(0.059)	(0.066)	(0.052)	(0.069)	(0.066)	(0.052)	(0.042)	(0.041)	(0.043)	(0.049)
Kerosene	0.031	-0.011	-0.021	-0.243***	-0.210***	-0.222***	-0.227***	-0.052	-0.194***	-0.182***
	(0.036)	(0.039)	(0.033)	(0.040)	(0.040)	(0.041)	(0.039)	(0.042)	(0.039)	(0.043)
Petroleum Coke	-0.011	0.033	0.041	-0.017	-0.027	-0.001	-0.018	0.036	-0.014	0.081
	(0.035)	(0.035)	(0.030)	(0.039)	(0.039)	(0.040)	(0.040)	(0.043)	(0.048)	(0.055)
Petroleum Coke-Derived Synthesis Gas	-	-	-	-	-	-	-	-	-	-0.415
										(0.279)
Residual Fuel Oil	-0.013	-0.015	-0.039**	0.023	0.067**	0.059***	0.072***	0.106***	0.073***	0.110***
	(0.018)	(0.020)	(0.017)	(0.022)	(0.021)	(0.023)	(0.023)	(0.025)	(0.026)	(0.029)
Waste/Other Oil	0.006	0.054	0.138***	0.113*	0.003	-0.051	-0.120***	-0.033	0.003	-0.033
	(0.056)	(0.052)	(0.049)	(0.059)	(0.051)	(0.043)	(0.044)	(0.046)	(0.050)	(0.059)
Natural Gas and Other Gases										
Natural Gas	-0.283***	-0.248***	-0.197***	-0.107***	-0.153***	-0.113***	-0.116***	-0.129***	-0.108***	-0.095***
	(0.010)	(0.011)	(0.010)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.013)
Blast Furnace	0.029	-0.016	-0.062	-0.060	-0.064	-0.068	-0.146*	-0.085	0.021	-0.062
	(0.071)	(0.069)	(0.071)	(0.077)	(0.074)	(0.074)	(0.081)	(0.077)	(0.073)	(0.084)
Other Gas	-0.134***	-0.177***	-0.259***	-0.118***	-0.030	-0.112***	-0.139***	-0.091***	-0.155***	-0.182***
	(0.036)	(0.033)	(0.028)	(0.033)	(0.031)	(0.033)	(0.031)	(0.034)	(0.033)	(0.035)
Gaseous Propane	0.002	-0.044	-0.087	-0.160**	-0.142*	-0.167*	-0.084	-0.043	-0.110	-0.181
	(0.065)	(0.070)	(0.055)	(0.077)	(0.077)	(0.099)	(0.105)	(0.081)	(0.080)	(0.126)
Nuclear										
Nuclear	0.510***	0.549***	0.401***	0.604***	0.569***	0.620***	0.613***	0.597***	0.542***	0.562***
	(0.044)	(0.043)	(0.035)	(0.037)	(0.036)	(0.037)	(0.036)	(0.037)	(0.037)	(0.039)
Solid Renewable Fuel										
Agricultural Feedstock	0.058	0.073	0.226***	-0.099	0.059	0.028	-0.001	0.152**	0.131*	-0.017
	(0.077)	(0.074)	(0.073)	(0.073)	(0.074)	(0.068)	(0.068)	(0.074)	(0.077)	(0.092)

Table 4 – Tobit Model Regression Results with No Interaction Terms from 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Municipal Solid Waste	-	-	-	0.157***	0.209***	0.173***	0.184***	0.135***	0.222***	0.141***
				(0.031)	(0.030)	(0.032)	(0.031)	(0.032)	(0.031)	(0.034)
Other Biomass Solids	-0.057	-0.012	-0.064	-0.035	-0.046	-0.008	-0.042	0.028	0.088	0.092
	(0.106)	(0.079)	(0.065)	(0.082)	(0.075)	(0.074)	(0.067)	(0.067)	(0.069)	(0.086)
Wood/Wood Waste Solids	-0.001	-0.033	-0.076***	0.037	0.093***	0.080***	0.061***	0.054**	0.047**	0.059**
	(0.023)	(0.022)	(0.020)	(0.024)	(0.023)	(0.024)	(0.023)	(0.024)	(0.023)	(0.025)
Liquid Renewable Fuel										
Other Biomass Liquids	-0.068	-0.185	-0.315***	-0.172	-0.126	-0.183*	-0.216**	-0.206**	-0.310***	-0.260***
	(0.167)	(0.122)	(0.110)	(0.118)	(0.090)	(0.100)	(0.086)	(0.091)	(0.095)	(0.113)
Black Liquor	0.094**	0.109***	0.090***	0.110***	0.020	0.114***	0.044	0.054	0.111***	0.020
	(0.037)	(0.036)	(0.032)	(0.038)	(0.036)	(0.038)	(0.038)	(0.038)	(0.038)	(0.040)
Sludge Waste	-0.257***	-0.352***	-0.302***	-0.324***	-0.336***	-0.432***	-0.297***	-0.326***	-0.462***	-0.382***
	(0.066)	(0.056)	(0.047)	(0.057)	(0.055)	(0.061)	(0.056)	(0.055)	(0.056)	(0.062)
Wood Waste Liquids[a]	-0.353***	-0.144	-0.242**	0.053	-0.451*	-0.398	-0.491*	-0.255	-0.320**	-0.194
	(0.088)	(0.123)	(0.126)	(0.265)	(0.254)	(0.263)	(0.257)	(0.255)	(0.146)	(0.160)
Gaseous Renewable Fuels										
Landfill Gas	-0.115***	-0.073***	-0.126***	0.044**	0.115***	0.019	0.108***	0.070***	0.057***	0.082***
	(0.020)	(0.022)	(0.019)	(0.022)	(0.021)	(0.021)	(0.020)	(0.022)	(0.019)	(0.021)
Other Biomass Gas	-0.026	-0.030	-0.058	0.034	0.136***	0.108**	0.101**	0.055	0.132***	0.064*
	(0.040)	(0.042)	(0.035)	(0.043)	(0.045)	(0.050)	(0.045)	(0.043)	(0.040)	(0.039)
Other Renewable Energy Sources										
Geothermal	0.321***	0.259***	0.310***	0.147***	0.242***	0.216***	0.214***	0.191***	0.278***	0.161***
	(0.042)	(0.065)	(0.040)	(0.040)	(0.038)	(0.039)	(0.037)	(0.036)	(0.036)	(0.038)
Hydroelectric	0.198***	0.288***	0.287***	0.037**	0.059***	0.065***	0.087***	0.055***	0.190***	0.060***
	(0.014)	(0.016)	(0.013)	(0.016)	(0.015)	(0.016)	(0.016)	(0.016)	(0.016)	(0.017)
Solar	0.190***	0.113	0.095	-0.179**	-0.082	-0.057	0.055	0.006	-0.004	-0.040*
	(0.069)	(0.076)	(0.062)	(0.071)	(0.062)	(0.056)	(0.036)	(0.029)	(0.021)	(0.020)
Wind	0.313***	0.328***	0.374***	0.007	0.101***	0.071***	0.006	-0.028*	0.113***	-0.007
	(0.024)	(0.026)	(0.024)	(0.021)	(0.019)	(0.020)	(0.017)	(0.017)	(0.016)	(0.017)

Table 4 – Tobit Model Regression Results with No Interaction Terms from 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Other Energy Sources										
Other Energy Sources	-0.114	-0.020	-0.046	0.053	0.064	0.022***	0.034	0.049	-0.033	0.061
	(0.087)	(0.044)	(0.036)	(0.048)	(0.051)	(0.047)	(0.045)	(0.046)	(0.048)	(0.055)
Sigma	0.223***	0.239***	0.215***	0.263***	0.252***	0.260***	0.254***	0.253***	0.249***	0.273***
	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	4474	3908	4717	4770	4784	4723	5012	5017	5277	5568
Censored	358	557	957	143	152	167	162	213	233	205
Log Likelihood	51.93	-371.44	-159.68	-586.24	-398.85	-554.22	-456.50	-484.14	-420.42	-907.80

Standard errors are in parenthesis. ^{a} Excludes black liquor. *** implies significance at the 1% level, ** implies significance at the 5% level, and * implies significance at the 10% level.

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Intercept	0.841***	0.879***	0.860***	0.588***	0.578***	0.647***	0.647***	0.713***	0.752***	0.712***
	(0.022)	(0.022)	(0.020)	(0.022)	(0.024)	(0.026)	(0.025)	(0.027)	(0.030)	(0.032)
RPS in Effect (RPS)	-0.072	0.163**	0.140***	0.088***	0.002	0.006	0.012	0.020	-0.025	0.019
	(0.074)	(0.069)	(0.053)	(0.032)	(0.035)	(0.036)	(0.036)	(0.042)	(0.037)	(0.038)
Voluntary RPS	-	-	-0.021	0.033	-0.030	-0.013	-0.011	0.032*	-0.004	0.011
			(0.029)	(0.033)	(0.023)	(0.017)	(0.016)	(0.017)	(0.016)	(0.019)
Non-compliance Penalty	-	0.052	0.043	0.016	-0.007	-0.006	-0.008	-0.007	0.016*	0.013
		(0.048)	(0.034)	(0.015)	(0.013)	(0.012)	(0.011)	(0.010)	(0.010)	(0.010)
Public Benefits Fund (PBF)	0.062**	-0.038	-0.006	-0.056*	-0.050	0.009	0.017	0.005	-0.008	-0.016
	(0.031)	(0.033)	(0.030)	(0.030)	(0.035)	(0.036)	(0.037)	(0.043)	(0.040)	(0.036)
Net Metering (NM)	0.024***	0.001	-0.005	0.002	-0.008	-0.014	-0.051***	-0.031*	-0.039***	-0.045***
	(0.009)	(0.010)	(0.009)	(0.010)	(0.012)	(0.012)	(0.013)	(0.014)	(0.014)	(0.016)
Mandatory Green Power Option (MGPO)	-0.038	-0.055	-0.121*	-0.054	0.048	0.039	0.078*	-0.023	0.024	-0.012
	(0.108)	(0.074)	(0.065)	(0.058)	(0.053)	(0.052)	(0.046)	(0.043)	(0.042)	(0.046)
Installed Capacity	-0.012***	-0.022***	-0.011***	-0.026***	-0.016***	-0.033***	-0.030***	-0.037***	-0.030***	-0.027***
	(0.002)	(0.003)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.003)
Age of Plant	-0.011***	-0.014***	-0.012***	-0.012***	-0.015***	-0.016***	-0.012***	-0.012***	-0.012***	-0.017***
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Coal										
RPS * Coal	0.105	-0.123**	-0.145***	-0.117***	-0.069***	-0.084***	-0.127***	-0.064	-0.051*	-0.012
	(0.069)	(0.053)	(0.043)	(0.026)	(0.024)	(0.029)	(0.035)	(0.040)	(0.029)	(0.034)
PBF * Coal	-0.067***	-0.035	-0.028	-0.006	0.008	0.008	0.089**	0.025	-0.018	0.001
	(0.025)	(0.026)	(0.026)	(0.026)	(0.024)	(0.032)	(0.036)	(0.042)	(0.034)	(0.034)
MGPO * Coal	0.005	0.101*	0.122**	-0.013	0.006	-0.010	0.011	-0.003	0.007	-0.014
	(0.102)	(0.058)	(0.055)	(0.038)	(0.037)	(0.040)	(0.039)	(0.038)	(0.039)	(0.044)
Bituminous Coal	-0.314***	-0.259***	-0.329***	-0.068***	-0.110***	-0.061***	-0.076***	-0.079***	-0.114***	-0.092***
	(0.020)	(0.019)	(0.018)	(0.019)	(0.017)	(0.020)	(0.020)	(0.018)	(0.020)	(0.024)
Sub-Bituminous Coal	-0.340***	-0.259***	-0.333***	-0.090***	-0.121***	-0.074***	-0.086***	-0.098***	-0.129***	-0.144***
	(0.021)	(0.021)	(0.020)	(0.017)	(0.018)	(0.023)	(0.022)	(0.020)	(0.025)	(0.027)
Lignite Coal	-0.117**	-0.303***	-0.363***	-0.178***	-0.186***	-0.172***	-0.170***	-0.201***	-0.191***	-0.215***
	(0.058)	(0.061)	(0.056)	(0.026)	(0.025)	(0.029)	(0.030)	(0.027)	(0.051)	(0.054)

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Coal-Based Synfuel	0.001	0.084	0.068	0.089	-0.011	0.099	-	-	-	-
	(0.046)	(0.061)	(0.059)	(0.078)	(0.033)	(0.111)				
Waste/Other Coal	-0.059	-0.275***	-0.078*	-0.227***	-0.166***	-0.079	-0.004	-0.026	-0.066	-0.151*
	(0.079)	(0.053)	(0.041)	(0.035)	(0.060)	(0.080)	(0.083)	(0.080)	(0.092)	(0.091)
Coal * Renewable Sources	-0.012	0.010	0.079*	-0.029	0.001	-0.072*	-0.066*	-0.055	0.006	0.013
	(0.051)	(0.045)	(0.046)	(0.039)	(0.039)	(0.041)	(0.036)	(0.039)	(0.041)	(0.045)
Petroleum										
RPS * Petroleum	0.052	-0.164***	-0.061*	-0.074***	-0.023	-0.044	-0.043	0.014	-0.039	-0.090***
	(0.071)	(0.041)	(0.032)	(0.026)	(0.027)	(0.029)	(0.029)	(0.034)	(0.030)	(0.031)
PBF * Petroleum	-0.110***	-0.015	-0.042*	-0.007	0.001	-0.039**	-0.036	-0.052	0.003	0.008
	(0.025)	(0.027)	(0.025)	(0.024)	(0.028)	(0.029)	(0.030)	(0.036)	(0.033)	(0.030)
MGPO * Petroleum	0.059	-0.031	-0.013	0.008	-0.065	-0.080*	-0.116***	-0.056	-0.074**	-0.023
	(0.086)	(0.062)	(0.055)	(0.050)	(0.045)	(0.046)	(0.039)	(0.038)	(0.037)	(0.039)
Distillate Fuel Oil	-0.190***	-0.225***	-0.202***	-0.173***	-0.150***	-0.169***	-0.153***	-0.224***	-0.220***	-0.179***
	(0.016)	(0.015)	(0.014)	(0.017)	(0.017)	(0.018)	(0.019)	(0.019)	(0.022)	(0.023)
Jet Fuel	0.080	0.027	-0.028	-0.050	-0.055	0.116**	0.127***	0.060	0.165***	0.147***
	(0.073)	(0.068)	(0.064)	(0.084)	(0.074)	(0.052)	(0.043)	(0.041)	(0.049)	(0.051)
Kerosene	0.080*	0.007	0.016	-0.183***	-0.177***	-0.150***	-0.160***	-0.013	-0.138***	-0.110**
	(0.043)	(0.037)	(0.038)	(0.044)	(0.040)	(0.046)	(0.042)	(0.055)	(0.050)	(0.043)
Petroleum Coke	0.016	0.089*	0.086**	0.029	0.004	0.023	0.009	0.055	0.033	0.123
	(0.043)	(0.051)	(0.039)	(0.050)	(0.041)	(0.053)	(0.048)	(0.050)	(0.058)	(0.076)
Petroleum Coke-Derived Synthesis Gas	-	-	-	-	-	-	-	-	-	-0.500***
										(0.104)
Residual Fuel Oil	0.014	0.009	-0.010	0.046**	0.088***	0.094***	0.104***	0.128***	0.104***	0.128***
	(0.022)	(0.025)	(0.023)	(0.024)	(0.025)	(0.029)	(0.028)	(0.032)	(0.033)	(0.032)
Waste/Other Oil	0.043	0.109	0.194	0.138*	0.032	-0.027	-0.071	0.006	0.040	-0.005
	(0.083)	(0.075)	(0.081)	(0.083)	(0.068)	(0.056)	(0.050)	(0.059)	(0.074)	(0.064)
Petroleum * Renewable Sources	-0.053	-0.043	-0.097**	-0.034	-0.074**	0.003	-0.015	-0.011	-0.072**	-0.012
	(0.043)	(0.037)	(0.039)	(0.031)	(0.033)	(0.034)	(0.032)	(0.031)	(0.036)	(0.033)

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Natural Gas and Other Gases										
RPS * N&O G	-0.150***	-0.064	-0.100**	0.064**	0.078***	0.130***	0.062**	0.000	-0.004	-0.039
	(0.041)	(0.044)	(0.039)	(0.027)	(0.027)	(0.028)	(0.030)	(0.035)	(0.030)	(0.032)
PBF * N&O G	0.001	0.024	0.016	0.035	0.006	-0.054*	-0.039	-0.004	0.043	0.021
	(0.025)	(0.026)	(0.026)	(0.025)	(0.029)	(0.030)	(0.031)	(0.037)	(0.033)	(0.030)
MGPO * N&O G	0.028	0.107**	0.106**	0.004	-0.029	-0.028	-0.007	0.018	0.001	-0.022
	(0.096)	(0.054)	(0.051)	(0.043)	(0.039)	(0.036)	(0.035)	(0.035)	(0.035)	(0.037)
Natural Gas	-0.293***	-0.268***	-0.202***	-0.127***	-0.169***	-0.130***	-0.112***	-0.114***	-0.099***	-0.057**
	(0.017)	(0.017)	(0.016)	(0.016)	(0.018)	(0.018)	(0.019)	(0.018)	(0.023)	(0.026)
Blast Furnace	0.019	-0.003	-0.063	-0.038	-0.055	-0.037	-0.130***	-0.090	0.021	-0.067
	(0.105)	(0.091)	(0.110)	(0.078)	(0.085)	(0.054)	(0.042)	(0.078)	(0.089)	(0.079)
Other Gas	-0.128**	-0.180***	-0.261***	-0.139***	-0.044	-0.129***	-0.141***	-0.092**	-0.157***	-0.180****
	(0.054)	(0.046)	(0.051)	(0.041)	(0.044)	(0.039)	(0.033)	(0.041)	(0.044)	(0.038)
Gaseous Propane	-0.002	-0.028	-0.085	-0.158***	-0.154***	-0.164***	-0.094	-0.040	-0.096	-0.145
	(0.066)	(0.070)	(0.060)	(0.057)	(0.050)	(0.048)	(0.077)	(0.067)	(0.068)	(0.095)
NG * Renewable Sources	0.097**	0.079**	0.039	-0.041	-0.036	-0.065**	-0.064**	-0.065**	-0.084**	-0.095***
	(0.041)	(0.040)	(0.040)	(0.033)	(0.036)	(0.033)	(0.032)	(0.033)	(0.036)	(0.032)
Nuclear										
RPS * Nuclear	1.160***	-0.231*	-0.280***	-0.045	0.061	0.045	0.031	0.111	0.033	-0.021
	(0.127)	(0.135)	(0.080)	(0.050)	(0.054)	(0.042)	(0.054)	(0.077)	(0.051)	(0.058)
PBF * Nuclear	-0.040	0.011	0.085	0.067	0.016	-0.035	-0.022	-0.069	0.020	0.016
	(0.109)	(0.103)	(0.089)	(0.049)	(0.049)	(0.044)	(0.056)	(0.079)	(0.054)	(0.053)
MGPO * Nuclear	1.078***	0.918***	0.188	0.009	-0.352	-0.079	-0.122**	-0.046	-0.066	-0.012
	(0.149)	(0.157)	(0.126)	(0.069)	(0.237)	(0.061)	(0.059)	(0.073)	(0.052)	(0.051)
Nuclear	0.498***	0.542***	0.389***	0.621***	0.593***	0.652***	0.640***	0.593***	0.545***	0.584***
	(0.092)	(0.089)	(0.071)	(0.044)	(0.032)	(0.029)	(0.030)	(0.039)	(0.038)	(0.046)
Solid Renewable Fuel										
RPS * Solid Renewable Fuel	0.146	0.092	-0.043	-0.044	-0.002	-0.006	0.116***	0.018	-0.019	0.025
	(0.124)	(0.075)	(0.071)	(0.043)	(0.048)	(0.049)	(0.048)	(0.064)	(0.059)	(0.060)
PBF * Solid Renewable Fuel	-0.048	-0.049	-0.027	0.083*	0.120**	0.123**	0.018	0.063	0.061	0.008
	(0.054)	(0.053)	(0.055)	(0.043)	(0.048)	(0.051)	(0.049)	(0.064)	(0.060)	(0.055)

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
MGPO * Solid Renewable Fuel	0.096	0.103	0.235***	0.107	-0.018	-0.061	-0.040	0.081	-0.043	-0.022
	(0.110)	(0.097)	(0.089)	(0.089)	(0.073)	(0.070)	(0.056)	(0.067)	(0.061)	(0.070)
Agricultural Feedstock	0.020	0.066	0.261**	-0.108	0.046	0.065	0.041	0.173	0.180	0.021
	(0.149)	(0.114)	(0.113)	(0.086)	(0.110)	(0.109)	(0.090)	(0.110)	(0.119)	(0.123)
Municipal Solid Waste	-	-	-	0.167***	0.193***	0.141***	0.145***	0.102**	0.260***	0.155***
				(0.039)	(0.043)	(0.043)	(0.041)	(0.044)	(0.046)	(0.055)
Other Biomass Solids	-0.093*	-0.040	-0.097	0.012	-0.061	0.019	0.009	0.052	0.146**	0.131
	(0.052)	(0.078)	(0.070)	(0.116)	(0.067)	(0.088)	(0.074)	(0.073)	(0.069)	(0.085)
Wood/Wood Waste Solids	-0.011	-0.060	-0.077**	0.046	0.075*	0.083*	0.058	0.048	0.088**	0.080*
	(0.046)	(0.041)	(0.037)	(0.037)	(0.044)	(0.043)	(0.039)	(0.043)	(0.042)	(0.049)
Liquid Renewable Fuel										
RPS * Liquid Renewable Fuel	-	1.305***	0.072	-0.061	0.035	-0.082	0.033	0.025	0.157	0.218**
		(0.115)	(0.134)	(0.095)	(0.105)	(0.083)	(0.104)	(0.124)	(0.111)	(0.094)
PBF * Liquid Renewable Fuel	-0.104	-0.047	-0.100	-0.112	-0.196**	-0.240***	-0.217**	-0.144	-0.271*	-0.198**
	(0.113)	(0.093)	(0.098)	(0.088)	(0.085)	(0.083)	(0.090)	(0.143)	(0.125)	(0.099)
MGPO * Liquid Renewable Fuel	-0.276	-0.408***	-0.303**	-0.295**	-0.046	-0.047	-0.091	-0.195*	-0.046	-0.087
	(0.171)	(0.138)	(0.150)	(0.124)	(0.098)	(0.088)	(0.076)	(0.106)	(0.093)	(0.103)
Other Biomass Liquids	-0.076	-0.151***	-0.241***	-0.114**	-0.039	-0.106	-0.158***	-0.177***	-0.259***	-0.307***
	(0.057)	(0.055)	(0.082)	(0.058)	(0.068)	(0.077)	(0.055)	(0.052)	(0.058)	(0.075)
Black Liquor	0.099*	0.117**	0.095*	0.192***	0.129**	0.238***	0.161***	0.144**	0.183***	0.044
	(0.059)	(0.059)	(0.053)	(0.051)	(0.057)	(0.061)	(0.048)	(0.056)	(0.053)	(0.051)
Sludge Waste	-0.248***	-0.305***	-0.243***	-0.282***	-0.280***	-0.332***	-0.225***	-0.252***	-0.405***	-0.374***
	(0.087)	(0.067)	(0.059)	(0.071)	(0.056)	(0.056)	(0.051)	(0.062)	(0.056)	(0.068)
Wood Waste Liquids[a]	-0.270***	0.051	-0.088	0.345***	-0.351***	-0.156	-0.342***	-0.136	-0.144	-0.177
	(0.094)	(0.175)	(0.187)	(0.128)	(0.110)	(0.097)	(0.093)	(0.099)	(0.139)	(0.183)
Gaseous Renewable Fuels										
RPS * Gaseous Renewable Fuel	0.442***	-0.197***	-0.137**	-0.086**	-0.042	-0.006	-0.060	-0.097	-0.029	0.007
	(0.142)	(0.062)	(0.059)	(0.040)	(0.045)	(0.043)	(0.051)	(0.063)	(0.052)	(0.050)
PBF * Gaseous Renewable Fuel	-0.088**	0.057	0.034	0.092**	0.082*	0.013	0.033	0.076	0.078	0.035
	(0.045)	(0.044)	(0.044)	(0.040)	(0.048)	(0.044)	(0.052)	(0.062)	(0.054)	(0.045)

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
MGPO * Gaseous Renewable Fuel	-0.016	0.334***	0.318***	0.183**	-0.008	-0.013	-0.082	-0.006	0.021	0.074
	(0.131)	(0.110)	(0.113)	(0.082)	(0.070)	(0.058)	(0.065)	(0.068)	(0.058)	(0.054)
Landfill Gas	-0.094***	-0.089***	-0.138***	0.055*	0.125***	0.043	0.157***	0.106***	0.066*	0.061
	(0.034)	(0.030)	(0.030)	(0.031)	(0.037)	(0.033)	(0.035)	(0.037)	(0.036)	(0.041)
Other Biomass Gas	-0.043	-0.077	-0.050	0.067	0.169**	0.147**	0.186***	0.131**	0.170**	0.099*
	(0.063)	(0.058)	(0.062)	(0.058)	(0.066)	(0.068)	(0.072)	(0.063)	(0.067)	(0.057)
Other Renewable Energy Sources										
RPS * Geothermal	-	-	-0.086	-0.264**	-0.058***	-0.124	-0.019	0.125	0.029	-0.093
			(0.127)	(0.107)	(0.053)	(0.085)	(0.109)	(0.161)	(0.085)	(0.099)
PBF * Geothermal	-0.138*	-0.134*	-0.072	0.239***	0.279	0.165**	0.120	0.070	0.060	0.099
	(0.075)	(0.076)	(0.074)	(0.078)	(0.082)	(0.076)	(0.083)	(0.080)	(0.059)	(0.069)
MGPO * Geothermal	-	-	-	-	-	-	-	-	-	-0.636***
										(0.059)
Geothermal	0.389***	0.266***	0.310***	0.240**	0.140***	0.245***	0.169*	0.034	0.243***	0.201**
	(0.066)	(0.043)	(0.104)	(0.104)	(0.046)	(0.081)	(0.101)	(0.148)	(0.072)	(0.085)
RPS * Hydroelectric	0.071	-0.220***	-0.156***	-0.082**	-0.050	-0.045	-0.048	-0.030	-0.017	-0.019
	(0.078)	(0.053)	(0.046)	(0.033)	(0.035)	(0.037)	(0.037)	(0.043)	(0.039)	(0.041)
PBF * Hydroelectric	-0.078**	0.021	-0.002	0.128***	0.108***	0.080**	0.032	0.055	0.118***	0.055
	(0.031)	(0.038)	(0.033)	(0.032)	(0.036)	(0.038)	(0.038)	(0.044)	(0.042)	(0.037)
MGPO * Hydroelectric	0.058	0.079	0.163**	0.189***	0.056	0.072	0.002	0.111**	0.045	0.166***
	(0.109)	(0.077)	(0.066)	(0.063)	(0.056)	(0.055)	(0.047)	(0.046)	(0.044)	(0.048)
Hydroelectric	0.220***	0.309***	0.305***	0.016	0.046*	0.056**	0.113***	0.040	0.157***	0.026
	(0.022)	(0.025)	(0.021)	(0.023)	(0.025)	(0.025)	(0.025)	(0.025)	(0.028)	(0.032)
RPS * Solar	-	-0.052	0.314	-	-	-	-0.229	-0.171	-0.107	-0.032
		(0.237)	(0.221)				(0.150)	(0.111)	(0.084)	(0.072)
PBF * Solar	0.390***	-	-	-0.104	0.214**	0.075	0.137*	0.188**	0.122*	0.033
	(0.116)			(0.105)	(0.102)	(0.102)	(0.077)	(0.076)	(0.066)	(0.047)
MGPO * Solar	-	-	-	-	-0.205**	-0.051	-0.015	-0.035	0.001	-0.017
					(0.100)	(0.090)	(0.080)	(0.096)	(0.077)	(0.062)
Solar	-0.292***	0.032	-0.205	-0.111	-0.185**	-0.079	0.189	0.060	0.048	-0.022
	(0.061)	(0.217)	(0.208)	(0.095)	(0.091)	(0.080)	(0.159)	(0.090)	(0.071)	(0.066)

Table 5 – Tobit Model Regression Results with Interaction Terms 2003 – 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
RPS * Wind	0.147	-0.177***	-0.134**	-0.205***	-0.117***	-0.133***	-0.075*	0.074	0.021	-0.011
	(0.110)	(0.061)	(0.058)	(0.042)	(0.043)	(0.039)	(0.040)	(0.046)	(0.043)	(0.048)
PBF * Wind	-0.053	-0.008	-0.001	-0.029	-0.011	-0.110**	-0.029	-0.110**	-0.062	-0.053
	(0.044)	(0.053)	(0.054)	(0.045)	(0.048)	(0.044)	(0.042)	(0.046)	(0.043)	(0.041)
MGPO * Wind	0.177	0.145	0.301***	0.070	-0.112	-0.005	-0.075	0.027	-0.013	0.034
	(0.152)	(0.096)	(0.116)	(0.079)	(0.073)	(0.061)	(0.053)	(0.048)	(0.045)	(0.051)
Wind	0.310***	0.349***	0.373***	0.159***	0.226***	0.247***	0.097**	-0.014	0.157***	0.034
	(0.034)	(0.038)	(0.040)	(0.039)	(0.040)	(0.035)	(0.032)	(0.031)	(0.033)	(0.037)
Other Energy Sources										
RPS * Other Energy Sources	-	0.003	0.420***	-0.275**	-0.448***	-0.447***	-0.354	-0.314	-0.400***	-0.197
		(0.213)	(0.148)	(0.119)	(0.118)	(0.092)	(0.156)	(0.203)	(0.099)	(0.230)
PBF * Other Energy Sources	0.053	-0.315*	-0.711***	-0.150	0.039	0.195*	-0.010	0.103	0.292**	0.099
	(0.150)	(0.175)	(0.129)	(0.129)	(0.095)	(0.104)	(0.153)	(0.187)	(0.140)	(0.241)
MGPO * Other Energy Sources	-	-	-	-	0.005	0.070	-0.021	-0.061	0.038	0.023
					(0.153)	(0.120)	(0.178)	(0.180)	(0.229)	(0.353)
Other Energy Sources	-0.129	0.047	0.036	0.209***	0.258***	0.172***	0.195**	0.168*	0.074	0.132
	(0.149)	(0.072)	(0.065)	(0.076)	(0.087)	(0.066)	(0.091)	(0.096)	(0.084)	(0.103)
Sigma	0.219***	0.235***	0.212***	0.257***	0.248***	0.254***	0.250***	0.249***	0.245***	0.270***
	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	4474	3908	4717	4770	4784	4723	5012	5017	5277	5568
Censored	358	557	957	143	152	167	162	213	233	205
Log Likelihood	113.44	-307.78	-94.22	-485.94	-321.05	-445.65	-386.64	-422.65	-353.99	-869.29

Standard errors are in parenthesis. [a] Excludes black liquor. *** implies significance at the 1% level, ** implies significance at the 5% level, and * implies significance at the 10% level.

Figure 1 – Cumulative Distribution Function of the Pure Technical Efficiency Scores by Fuel Category 2012