Measuring the Environmental Benefits of Wind Generated Electricity

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Abstract

Production subsidies for renewable energy have been a popular program due to their perceived environmental benefits. However, little empirical research has been conducted which would quantify such benefits. Wind energy in particular has taken advantage of federal subsidies, but what has been the environmental impact? Taking investment in wind capacity as given, I am able to identify the short run substitution patterns between wind power and conventional power for large electricity grid in Texas. I exploit the randomness of wind to identify plant level substitution of wind generated electricity for conventionally generated electricity. I then quantify the avoided emissions and associated costs using plant level emissions information, market clearing prices for pollution permits, and estimates of the social costs of pollution. The end result is the value of avoided emissions due to government subsidies.

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Introduction

Wind energy has experienced dramatic growth over the past decade due to declining production costs and generous government subsidies. These subsidies provide a significant stream of revenue for renewable energy operations, sometimes providing half of the revenues for a wind farm. Subsidies of wind power are said to be justified by the environmental benefits of wind generated electricity because wind power produces none of the pollutants, such as CO_2, NO_x, and SO_2, produced by conventional generators. In this paper, I compare estimates of savings from reduced pollution associated with wind power with the subsidies given to wind farms.

The expressed purpose of output based renewable subsidies is to encourage the development and operation of clean, renewable, energy projects in the U.S. Since electricity production by wind is emission free, the development of wind power may reduce aggregate pollution from electricity production by substituting wind power for power generated by fossil fuel generators. To date, no studies have attempted to empirically measure the environmental contribution of wind power resulting from these substitution patterns.

Wind speed and duration determine the potential output of a wind farm. Once facilities are in place, low marginal costs of production lead wind farm operators to maximize the output given the available wind. When wind-generated electricity enters the grid, high marginal cost fossil fuel generators reduce their output. Since emission rates of fossil fuel generators vary greatly by the type and age of the generator, the quantity of emissions offset by wind power will depend crucially on which types of generators reduce their output, which then determines extent of the reduction in pollution.

Using information on production decisions in 15-minute intervals on the Texas electricity grid, I estimate the response of each generator to exogenous changes in wind power using a reduced form model. Realizing that wind power production is not completely random, I control for weather factors that may drive both the demand for electricity and wind power production. The resulting quasi-experimental residual variation is then used to identify a substitution coefficient for each power plant on the grid. This measures the average reduction in output due to a 1 megawatt (MW) increase in wind energy production.

Using EPA measurements of power plant emission rates, I then convert the reduction in output to a reduction in emissions. Aggregating over all the power plants on the grid gives the total emissions offset due to one additional MW of wind generated electricity. I then construct estimates of the value of reducing emissions using the opportunity cost of reducing emissions for regulated pollutants and estimates from the literature on the marginal damage for unregulated CO_2 emissions. I compare the value of offset emissions to the size of the subsidies assumed to have induced investment in wind farms.

The results show that the value of offset pollutants is largely determined by the value of reducing CO2 emissions. Although the subsidies are not necessarily the lowest cost method of reducing pollution, the value of offset emissions is greater than the cost of federal subsidies for reasonable values of the marginal damage cost of CO2.

The remainder of the paper proceeds as follows. First, I describe the nature of federal and state subsidies received by wind power. Then I discuss the production of wind power and the institutions of the electricity market. This is followed by a literature review and a description of the data. Then I introduce the model and present the results before concluding.

1 Wind Power and Subsidies

Over the past decade, installed wind power production capacity has displayed explosive growth. Installed wind capacity more than doubled between 2004 and 2007 increasing from 6729 MW to 16,847 MW(AWEA 2008). In 2007, wind power was the second most installed power type in the US[1](EIA 2008). Although wind power represents a small fraction of total generating capacity nationwide, it is on track to have capacity shares upwards of 10% in some regional electricity markets(ERCOT 2007).

Two factors have been of significant importance in the growth of wind power. First, technology advancements in wind turbines have reduced the cost of wind power by 80% over the past 30 years (Wiser & Bolinger 2006). Wind power is characterized by large up front equipment costs and relatively low operation costs since the fuel is virtually free. Better tower design and manufacturing processes have reduced the up front costs for the same capacity level which lowers the levelized cost of producing wind power. Second, and perhaps more central to wind power growth, have been federal and state programs which subsidize renewable energy. The primary subsidies which support wind energy are state Renewable Portfolio Standards (RPS) and the federal Production Tax Credit (PTC). It is generally acknowledged that without government subsidies wind farms could not compete with conventional thermal generators which use gas, coal or uranium as fuel(Wiser & Bolinger 2006)

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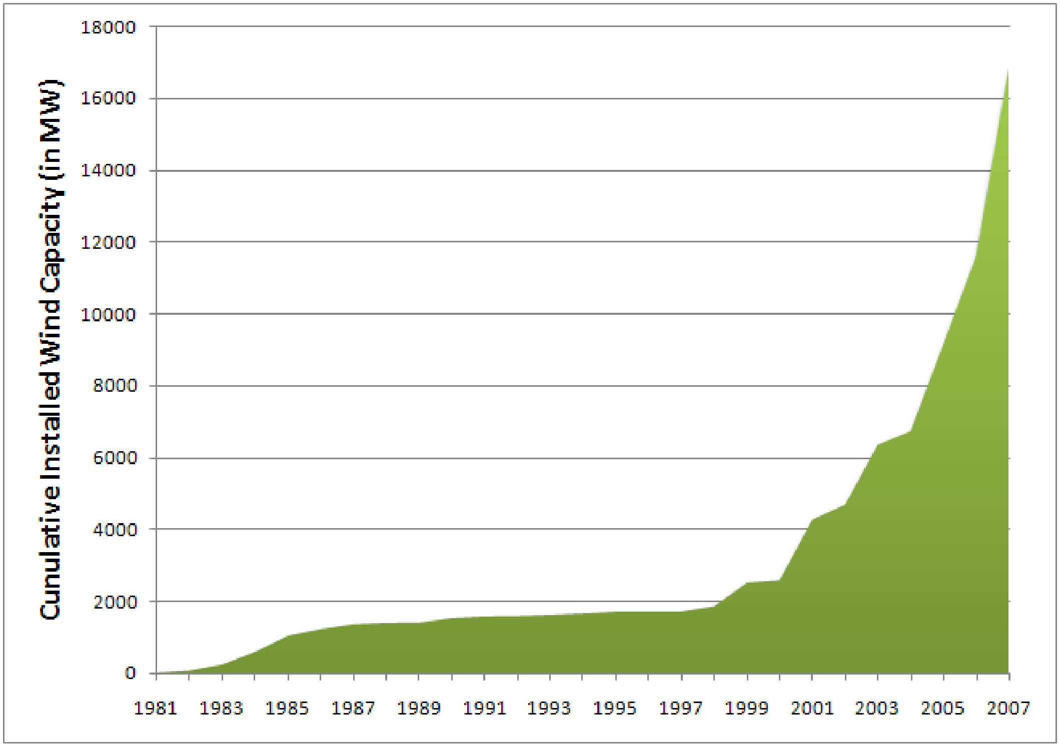
[1] Estimated new capacity installed in 2007 by type: Gas 9800MW, Wind 5244MW, Coal 1600MW, Petroleum 255MW.

Figure 1: Cumulative Installed Wind Capacity in the U.S.



1.1 Subsidies

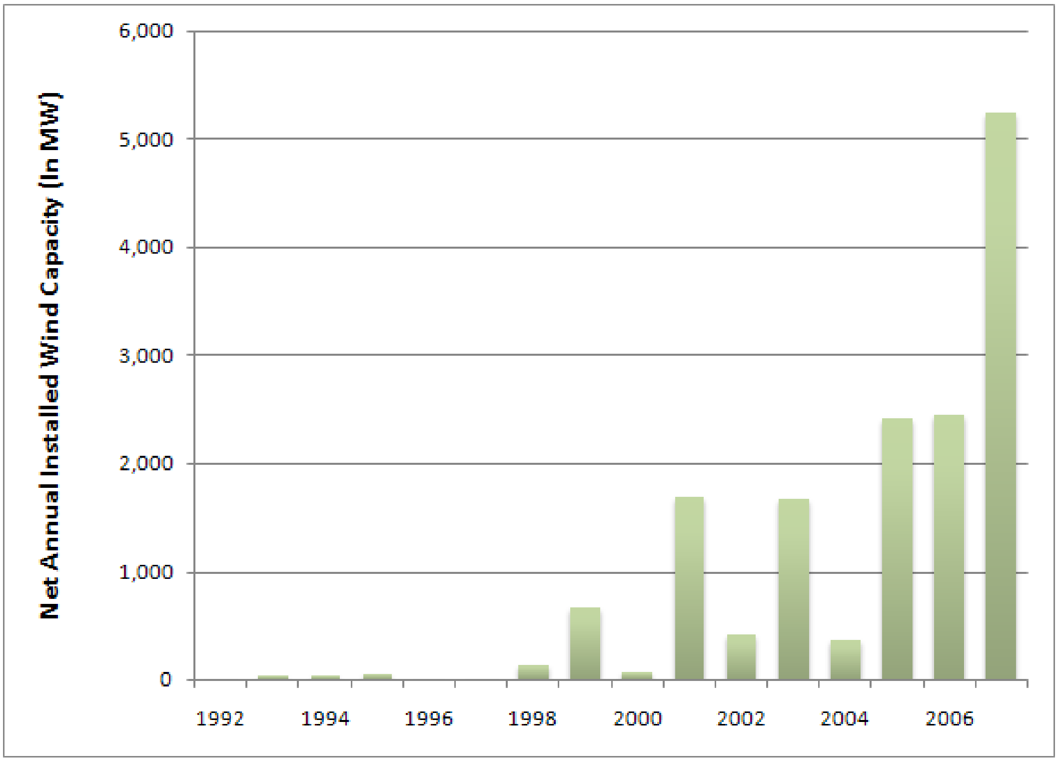
The federal Production Tax Credit and state Renewable Portfolio Standards are similar in that they are both an output based subsidy rather than a lump sum subsidy.

Renewable Portfolio Standards are state level regulations that require a certain proportion of power in the states to be derived from a renewable source. Typically each electricity provider has to produce the required proportion of renewable energy or must buy renewable energy credits from generators that do produce renewable energy. The sale of renewable energy credits is an implicit subsidy to renewable generators such as wind generators. The price of renewable credits varies greatly by state, ranging from $5 MWH to $50 MWH, depending on the specific RPS, the supply of renewable energy credits in the state, and the demand for renewable energy credits outside the state (Wiser & Barbose 2008).

The federal Production Tax Credit (PTC) is the single most important subsidy for wind generators. First instituted in 1992, the PTC guaranteed an inflation adjusted $15 /MWH tax credit for the first ten years of production of the facility. The current value of the subsidy is $20/MWH. Given that the owner of the facility has a sufficiently large tax liability, the tax credit is effectively a payment from the government to the wind farm operator. Since wholesale electricity typically sells for between $30 and $50 per MWH, the PTC represents a 40%-67% increase in revenue for a wind farm operator. Also, there is no uncertainty in the price of the subsidy regardless of how market prices for electricity evolve.

The importance of the PTC to the industry can be seen by looking at the patterns of wind capacity development. The PTC launched in 1992 and was scheduled to expire in 1999, but has been continued through a series of short one to two year extensions. However, more often than not, the subsidy has expired before it has been renewed by congress. It has expired three times, at the end of 1999, 2001, and 2003 and was renewed retroactively after a lapse of anywhere from 3 to 10 months (AWEA 2008). Since renewal has always included a retroactive extension, there has technically been no gap in the coverage of the PTC. However, investors still faced the possibility of no renewal or a non-retroactive renewal. This uncertainty has lead to a boom and bust cycle of wind power development. According to industry advocates, six to eight months before the expiration of the PTC, financing for capital dries up as lenders hesitate to finance wind projects due to the uncertainty surrounding renewal of the subsidy. Also since the subsidy guarantees 10 years of payments only to projects completed before its expiration, developers rush to complete projects before the expiration resulting in smaller than planned

Figure 2: Annual Installations of Wind Capacity in the U.S.



installations or higher installation costs for wind farms (AWEA 2008). Figure 2 shows annual installed wind capacity nationwide between 1992 and 2007. Note the precipitous drop in installed capacity in 2000, 2002, and 2004 after the expiration of the PTC in each preceding year. Since the last expiration, there has been a continued rise in annual installations of wind power. While not conclusive, this does underline the importance of the PTC for the development and operation of wind farms.

It is important to note that Renewable Portfolio Standards (RPS) and the PTC are not independent. Most wind developments have occurred in states with a RPS indicating that the federal PTC alone may not be sufficient to induce the level of investment observed. On the other hand, many state Renewable Portfolio Standards would have been too costly to implement with the federal Production Tax Credit. Together, though, they have been an effective tool in promoting wind energy. Conversely, it is not unreasonable to assume that without the subsidies, investment in wind farms would have been negligible over the past decade. Throughout this paper I maintain this assumption, that federal and state subsidies are responsible for the growth in installed wind capacity over the past ten years[2].

2 Emissions and Wind Power Production

Wind turbines produce none of the emissions typically associated with electricity production such as SO_2, NO_x, and CO_2. Every MWH of electricity produced by wind power "offsets" pollution that otherwise may have been emitted by a conventional generator.

The type and quantity of pollution offset depends crucially on the specific generator whose production was offset. Emissions per MWH of electricity vary greatly across electricity generators due to fuel types, generator efficiency, and installed abatement technology. Thus if wind competes with relatively efficient, clean generators, such as natural gas, the amount of offset SO_2, NO_x, and CO_2 would be much less than if wind power is substituted for power produced by a relatively "dirty" generator, such as an older coal plant. A high polluting coal plant emits 4 times CO_2, 100 times SO_2, 15 times the NO_x as a newer generator burning natural gas (EPA 2006).

If plant level production substitution can be identified then it is straightforward to calculate the offset emissions. The EPA monitors emissions from fossil fuel power plants. They also calculate the average annual emissions rate for each power plant in units of pollution per MWH of electricity produced[3]. For a given power plant, simply multiplying the electricity production offset by wind power by the emissions rate gives the quantity of emissions "offset" by wind power. It is important to note that offset emissions do not necessarily equate to a reduction in total emissions of that type. However, for emissions regulated under a cap and trade framework, emissions offset at one facility results in pollution permits being freed up for use elsewhere. For example, if a fossil fuel plant reduces its output, and therefore SO_2 emissions, due to wind energy production, it now has pollution permits available to use or sell on the open market. As long as the pollution caps are binding, pollution offset by wind power will be emitted elsewhere. Firms will reduce costly abatement as a result of clean energy production and total pollution will not decrease. For unregulated emissions such as CO_2, emissions offset

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[2] The effect of these subsidies on investment in wind farms is a subject of the author's ongoing research.

[3] For cogeneration facilities, facilities that produce steam both to generate electricity and for direct industrial heating purposes, the EPA scales emissions by the proportion of heat used to generate electricity.

by wind power result in a real reduction of total emissions of that type. [4]

Placing a value on offset pollution depends on how the pollutant is regulated. For pollutants under cap and trade regulation the overall level of pollution does not change and there are no social benefits of lower overall pollution. Given the cap, the cost of pollution is internalized by firms thus there is no justification for "offset" pollutants regulated via cap and trade. However, it may be the case that the current cap for a given pollutant is suboptimal. Suppose a pollution cap is too high to be socially optimal. It may well be politically infeasible to simply lower the cap and "take away" pollution permits from the firms. However, the government could simply buy and retire permits on the open market thereby effectively reducing the pollution cap with no impact on the firm's bottom line. An alternative policy to achieve the same objective could be to subsidize wind power while simultaneously reducing the cap by the quantity of pollution offset by wind power. Such a policy might be politically feasible since firms do not incur additional abatement costs and the industry receives subsidies. Thus, under the assumption that both policies are politically feasible, we can compare the cost of wind subsidies with the cost of buying and retiring pollution permits to achieve a similar reduction in pollution. Both policies reduce pollutants by the same amount, but may do so at different costs.

For unregulated pollutants, placing a value on offset emissions requires estimating the social value of reducing the total level of pollution by the amount of emissions offset. The only unregulated pollutant I am able to measure using the EPA monitoring data is CO_2. Given the current concerns regarding global climate change, there have been many studies which estimated the economic value of reducing CO_2 emissions. I use these estimates when calculating the value of CO_2 emissions offset by wind power.

The generating substitutes for wind power depend crucially on the mix of generation in the market, the relative geographic location of generators on the transmission system, the daily wind patterns, and the institutions for balancing real-time electricity supplied with demand. Although one might have expectations about potential substitution patterns there is no way to know a priori. The answer is essentially an empirical one. Since weather is outside of the control of any firm in the market and weather also determines the amount of electricity produced by wind power, wind power will be an exogenous variable in my model below which facilitates the identification of displaced power.

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[4] Emissions rate regulated pollutants also represent real reductions in pollution.

2.1 Wind Production

Electricity is an unusual commodity in that it is not storable. The electricity generated and consumed on an electric grid must be balanced on a second-by-second basis. Most types of generators can adjust the output of their generators at will, although time and cost associated with such adjustments varies. Wind operators, on the other hand, have relatively little control over output. On a calm day, no electricity can be produced. On a windy day, operators basically face a choice of either fully utilizing their productive capabilities or curtailing their production. Curtailing production amounts to throwing electricity away since the marginal costs of production are almost zero[5].

Wind power is characterized by high fixed capital costs and nearly zero marginal costs of production. A modern 1MW wind turbine costs roughly $1 million to install, but its fuel, wind, is free. Other operating and maintenance costs are also very low compared with fossil fuel or nuclear plants (Wiser & Barbose 2008). The high fixed costs and zero marginal costs of production create incentives for the operator to produce electricity to its fullest capacity whenever possible. This is reinforced by the fact that a wind operator cannot store its fuel, wind, or its output, electricity, for use at a later date. The subsidies, which are tied to the output of the wind farm, are an additional incentive to produce whenever possible[6].

Due to its cost characteristics, whenever the wind is blowing, wind power will be supplying its electricity to the grid. Other generators on the grid face higher marginal costs of production, due to fuel costs, and have storable fuel. Since they have full control over their output, they will reduce production to balance supply and demand on the grid when wind power comes on line.

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[5] Curtailing production does happen in emergency situations. It could also happen if wind generated enough power to overload transmission lines by itself.

[6] These incentives are reflected in power contracts. Wind operators usually sell their output through long term 20 year purchase power agreements (PPAs). Over the length of the contract, the buyer agrees to purchase all power that can be generated by the wind farm. Usually the buyer is specifically interested in the environmental attributes of wind power to fulfill some "green" objective such as meeting state renewable portfolio standards. These environmental attributes of production are jointly purchased with the electricity in most contracts. Wind operators, on the other hand, keep the federal PTC accruing from electricity production. If the need arises to curtail production to maintain the reliability of the grid or because the buyer requests a lower production, many PPAs still require that the buyer pay the seller for the electricity that could have been produced, but was not. In addition, the buyer may have to compensate the wind operator for forgone federal tax credits due to the lower output (Windustry 2008)

3 Literature Review

No existing studies have tried to identify the patterns of substitution between wind generators and conventional generators econometrically, though some planning and engineering studies have touched on the subject. One study conducted by GE Energy for the New York State Energy Research and Development Authority, simulated the introduction of 3,300 MW wind capacity, or 10% of total capacity, into the system. Using load and wind profiles from 2000-2001, researchers projected load, wind power, and conventional generation for the year 2008 using specialized GE electrical system simulation software. The impetus for this study was the concern that the increased level wind power would adversely affect the reliability of the grid and impose excessive costs on the transmission system. Although, the objective was to simulate the operation of the grid with a large proportion of intermittent capacity, they also were able to calculate the economic and environmental outcomes. In their simulation they found that 65% of displace would come from natural gas generators, 15% from coal, 10% from oil, and 10% from electricity imports. This results in annual avoided emissions of 6,400 tons of NOx and 12,000 tons of SO2. Their statistics are sensitive to accuracy of day-ahead predictions of wind power and to the way the market schedules day-ahead generation (GE 2005).

4 Data

I analyze output choices of firms in the Texas electricity market over a two year period to estimate substitution parameters. I use data provided by the Electric Reliability Council of Texas (ERCOT). ERCOT oversees the Texas Interconnection (one of four interconnections delivering electricity in the US) which serves the majority of the state of Texas. I focus on this electric grid for two reasons. First, wind capacity represents a nontrivial share of generating capacity. By the end of the sample in March of 2007, wind farms account for over 5% of installed generating capacity on the gird. The share of wind generated electricity actually supplied to the grid ranges from 0% to 10%. The second reason to focus on the ERCOT is that the grid is relatively isolated from other grids. The ERCOT grid has two tie-ins to one neighboring grid over which less than 1% of daily generation is exchanged. This means that wind generation in the ERCOT region directly displaces other generators on the same grid whose output and characteristics I observe.

I observe unit level output for each unit which supplies electricity to the

ERCOT grid for each 15 min interval of each day from April 2005 to April 2007. A unit means a single generating turbine; a single plant usually has multiple turbines. If a unit is connected to the grid for the entire sample period, I observe 70,080 individual output decisions. In addition to output, I have the characteristics of each unit including fuel type, location (county), year online, capacity, and owner. There are approximately 550 units at 220 plants which supply electricity to the grid. I also observe daily flows of electricity from the tie to the neighboring grid[7].

I also have information on plant level emissions from 2004-2005 from the EPA eGRID program. This data is collected from a variety of sources including the Energy Information Administration's surveys including Form-767, and the EPA's own Continuous Emission Monitoring data. Since the emissions data is on the plant level, I aggregate up unit level output and characteristics to the plant level also[8].

5 Electricity Market

Before detailing the model, I first explain the basic structure of power systems and the institutional details of ERCOT. The institutional details specific to a given electricity market play a key role in the production decisions of firms.

5.1 Power System Basics

An electric system is composed of three main parts: generators, a transmission system, and a distribution system. Electricity produced by generators is transmitted over high voltage lines to areas of demand where it is then routed to individual consumers over the lower voltage distribution system.

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[7] Other available data includes price data in each of four ERCOT submarkets. I do not observe the price units received for most of their power since most energy transactions in the ERCOT market are the result of confidential bilateral contracts. I do however observe market clearing prices in the real-time spot energy market. Contractual prices and balancing energy prices should be similar on average or there would be gains from arbitrage.

[8] It would be possible to use unit level emission quantity with output data and fuel consumption data would allow me to quantify the average emissions per KWH for each generating unit without aggregating to the plant level. However, the EPA plant level data is attractive since it has already undergone quality control procedures and corrects emissions for combined heat/electricity generators. In addition, some units share the same boiler or depend on waste heat from first stage units making the relevant output decision a plant level as opposed to a generator level decision.

Electricity is an unusual commodity in that it is not storable[9]. Electricity production and consumption must be balanced on a second-by-second basis. If more power is being consumed than is being produced then the reliability of the grid is threatened. Sufficient imbalances result in brownouts (dropping electrical frequency) or blackouts (complete loss of electrical service). The demand for electricity at any given time is called load. Meeting load reliably is the central function of grid management.

5.2 Institutions of ERCOT

Since 2002, the ERCOT region has been operating as a quasi-deregulated market. Unlike many regulated and even deregulated markets, companies in this market are vertically separated. Generating, transmission/distribution, and electricity retailing firms are separate entities. There are no vertically integrated firms that control generating, transmitting, and retailing resources as was previously the case before deregulation. Generators and electricity retailers negotiate bilateral contracts for the delivery of wholesale electricity or trade it on a real-time spot market called the Balancing Market. Retailers then resell the electricity to end consumers.

5.2.1 Generation

Approximately, 95% of energy supplied on the grid is sold through bilateral contracts with the remaining 5% being provided through the daily Balancing Market. Bilateral contracts result in planned energy transactions across the transmission system.

The Balancing Market is used by ERCOT to reconcile the difference between planned generation/load and actual generation/load. For example, if actual load is lower than predicted load then ERCOT will call on generators to decrease their production based on their bidding functions. Likewise, generators will be called upon to increase production if some other generator goes offline unexpectedly [10]. The Balancing Market is cleared every 15 mins

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[9] Chemical storage of electricity such as in lead-acid batteries are too costly to be used to store any meaningful amount of electricity in a system. Technologies do exist to turn electrical energy into potential mechanical energy which is storable such as compressed air or pumped hydro electrical storage. These technologies do make minor contributions on some grids,but such technologies have not been implemented on the electrical grid in my study.

[10] The Balancing Market is not only used to handle *unexpected* changes in load or generation. Under a relaxed balance energy schedule protocol, ERCOT also allows firms to submit day-ahead schedules which leave them in long or short positions entering into the market. Firms balance their positions through selling or buying electricity in the Balancing

by intersecting the hourly bidding functions submitted by firms. The price required to produce the marginal unit of electricity is the market clearing price in that 15 minute interval[11]. Generators on the grid differ by fuel type, generating technology, and geographic location. For example, coal and nuclear plants have low relative fuel costs and cannot adjust output as quickly as other generating types. These generators tend to produce near maximum capacity and do not participate as heavily in the Balancing Market. Simple cycle gas turbine generators on the other hand can adjust output quickly, but are less efficient and have relatively high fuel costs. Proximity to load can be important for generators especially when key transmission lines are congested as generators located close to load centers face fewer transmission constraints than generators in remote locations.

In 2007 there were approximately 80 different firms operating 180 power plants which supply electricity to the Texas grid managed by ERCOT[12]. Combined, these generators are capable of producing over 75,000 MW of electricity at any one time. Generation technology includes coal, nuclear, natural gas, water, and wind power plants. Table 1 shows the capacity by fuel type and technology.

Table 1: Capacity Shares by Fuel Type

	Total Capacity (MW)			**Share of Capacity**		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Natural Gas	47537	48372	49109	67.20%	66.20%	64.80%
Coal	15229	15729	15762	21.50%	21.50%	20.80%
Nuclear	4887	4887	4892	6.90%	6.70%	6.50%
Wind	1545	2509	4150	2.20%	3.40%	5.50%
Other	856	856	1106	1.20%	1.20%	1.50%
Water	512	512	501	0.70%	0.70%	0.70%
Petroleum Coke	142	143	143	0.20%	0.20%	0.20%
Diesel	40	40	38	0.10%	0.10%	0.00%
Landfill Gas	40	53	59	0.10%	0.10%	0.10%
Total	70788	73101	75760	100.00%	100.00%	100.00%

Market.

[11] For a more detailed exposition of the functionings of the Balancing Market, I refer the interested reader to (Puller & Hortacsu n.d.)

[12] There are additional generators which provide electricity on private networks, but which do not provide electricity to the grid controlled by ERCOT.

5.2.2 Transmission

Most of the time ERCOT operates as a single market and electricity flows freely over the transmission grid. ERCOT does not differentiate between remote generators that make extensive use of transmission lines and those which are located in close proximity to load centers and thus place lower demands on the transmission network. However, firms are charged for creating certain types of congestion on the network.

5.2.3 Demand

As in most electricity markets, demand in ERCOT does not respond directly or immediately to wholesale price signals[13]. That is, users do not respond to price signals in the balancing market. Although emerging technologies may at some point allow consumers to react to real-time energy prices, currently demand is irresponsive to changes in wholesale energy market in the short run.

6 Model

This paper aims to identify the substitution patterns between wind generated power and output by conventional generators using relatively simple and straight-forward model. Each plants output decision is modeled as a linear function of wind output and time-specific characteristics.

Wind generated electricity does not change a firm's output decision directly. Rather, wind generated electricity, as a zero marginal cost producer, shifts the aggregate supply curve down decreasing the price in the balancing market. In uncongested time periods, this results in a lower uniform price for all generators across the grid. In congested time periods, the effect on zonal prices depends on congestion patterns and where wind power enters

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[13] Additionally some large industrial users negotiate lower energy prices by agreeing to have their supply of electricity temporarily interrupted in emergency situations when generating reserves on the grid reach critical levels. However, they do not directly respond to fluctuations in the price of electricity in the wholesale market. Industrial users with interruptible loads are called Loads Acting As Resources (LaaRs). In the event of an unexpected change in load, electricity delivery to the LaaR will be interrupted to maintain the frequency on the grid. Approximately half of responsive reserve services are supplied by LaaRs (MF7). It is important to note that as a general rule LaaRs respond to events that threaten the reliability of the grid, not to price changes in the wholesale market. However, it is possible that industrial users could respond to price changes in the wholesale market through conditions in bilateral contracts with generators. However, such contracts are confidential so are not available to support this hypothesis.

the grid. As the price for energy decreases, conventional generators reduce their output. Given a price level, two other factors can also affect a firm's optimal output decision: the price of fuel and zonal or local transmission congestion.

One possible empirical model would first estimate the effect of wind power on price and then model each firm's response to the change in price controlling for input prices and congestion. However, this approach is overly complex for the research question at hand as it requires estimating each firm's cost function. Instead, I use a reduced form model to directly model the effect of wind output on a conventional generator's output decision without modelling the intermediate price mechanism by which it occurs. With appropriate control variables, the reduced form model allows the estimation of the parameter of interest without modeling the possibly complex cost functions of each firm. The reduced form model exploits the exogeneity and inherent randomness in weather patterns to identify the generator level substitution coefficient.

The reduced form model is constructed for each conventional generator i as follows:

$$Y_{it} = \beta_{i0} + \beta_{i1} Wind_t + \alpha_i Z_{it} + \epsilon_{it} \tag{1}$$

where

t = 15 min interval of a day

Y_{it} = output by generator i in time t

$Wind_t$ = electricity generated by wind farms in time t

Z_{it} = vector of control variables

The parameter of interest in the model is β_{i1}. If $Wind_t$ is uncorrelated with ϵ_{it} then I can interpret β_{i1} as the average reduction in output by generator i due to an 1 MWH increase in wind power.

Although wind power is exogenous, as output cannot be controlled by any firm, it is not completely random. Wind power exhibits systematic seasonal and diurnal fluctuations. Wind production is high during the winter and spring months and low during the summer and fall. On a daily level, wind production is higher during the night than during the day. Because these production patterns are consistently and negatively correlated with peak demand for electricity, this would lead to a simple reduced form model overestimating the substitution between wind power and most generators which increase output during peak periods of demand due to high energy prices. Controlling for seasonal and diurnal variation will be necessary to interpret a reduced form parameter as causal.

Growing wind capacity over my sample period necessitates further controls. Installed wind capacity connected to the grid increased from 1430 MW in April 2005 to 2794 MW in April 2007. This leads to a gradual increase in expected level of wind production in each time period. This trend is likely to be correlated with other trends in the data such as increasing demand for electricity or a change in relative fuel prices. A generator whose fuel price decreases relative to other generators over this period would introduce a positive bias into the substitution coefficient as an increase in average wind output would be correlated with an increase in generator output. Also there is a concern that since demand for electricity is primarily determined by temperature variations, that aggregate demand will be correlated with wind output if wind patterns are also correlated with temperature.

I control for trends and seasonality using a combination of fixed effects and exogenous variables. First to control for diurnal variation, I introduce fixed effects for every 15 minute period within a day[14]. Second, to control for seasonality in wind output I include a fixed effect for every date in my sample over my two year period. This also controls for correlations between wind capacity and fuel prices or wind capacity or average daily demand which trend over the course of my sample. Finally, I control for within day demand fluctuations that may be correlated with wind output by introducing hourly temperatures into my model. I calculate the average hourly temperature in each zone in ERCOT by averaging the hourly temperature readings from two National Weather Service weather stations from the urban centers in each zone[15]. I use hourly temperature to calculate hourly cooling/heating degrees. The cooling or heating degrees is the difference between the outside temperature and 65°. It has been shown that 65° is the temperature when no heating or cooling is need for an average building. I introduce heating/cooling degrees and its square since it has been shown that electricity demand depends on heating/cooling degrees in a non-linear way (Valor, Meneu & Caselles 2001).

The final reduced form model is constructed for each conventional generator i as follows:

$$Y_{ijd} = \beta_{i0} + \beta_{i1} Wind_{jd} + \alpha_{i1} Degrees_{ijd} + \alpha_{i2} Degrees^2_{ijd} + D_{id} + I_{ij} + \epsilon_{ijd} \quad (2)$$

where

jd = interval j on date d

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[14] There are 24*4 = 96 intervals in a day.

[15] Part of the reason for averaging over two stations in the urban center is that sometimes a station will not record a temperature reading for a given hour. Using two stations fills in some of the missing temperature observations and also gives smoother temperature trend that may better reflect average demand. In the very few cases where both stations were missing temperature observations I used a linear interpolation to fill in missing hours.

Y_{ijd} = output by generater i in interval j on date d

$Wind_{jd}$ = electricity generated by wind farms

$Degrees_{ijd}$ = cooling or heating degrees for hour containing interval j on date d

$Degrees^2_{ijd}$ = cooling or heating degrees squared

D_{id} = vector of date fixed effects

J_{ij} = vector of interval fixed effects

7 Results

7.1 Expectations

Given the institutional framework and the underlying model, we might expect certain types of generators to be better substitutes for wind power than others. For example, natural gas generators can easily adjust their output quickly and have high fuel costs. As such they tend to be the marginal producers on most generating grids. Other generators like nuclear or coal have low marginal costs of production and may have high adjustment costs of changing levels of production quickly. Since natural gas plants have high marginal costs and low adjustment costs, we would expect wind power to exclusively displace natural gas generation in most markets, all else equal. This is likely to be true in Texas given that natural gas generators comprise almost 70% of generating capacity. From an environmental perspective this may be less than ideal since gas generators are also the least polluting of fossil fuel plants. However, there are several reasons to question whether this simple intuition will hold. First, the ability to predict wind generation a day-ahead will allow generators with high real-time adjustment costs of production to plan their schedules around wind power. Second, the relative geographic location of generators and load on the transmission grid affects how electricity will flow on the grid. Once injected into the grid, system operators have little ability to determine how electricity will flow through the transmission lines. Thus generators that are closer to each other on the grid will tend to be better substitutes. Third, the time of day that wind power is produced will influence the substitution patterns. Wind energy produced at off peak times may substitute more for baseload coal and nuclear generators.

7.2 Market Level Results

I first show market level results by fuel type to demonstrate that, at least on the aggregate level, that substitution patterns are reasonable. I do not use these results to calculate avoided emissions. For the market level results output was aggregated in each 15 min period over all the grid by fuel type. The regression specification is that specified in equation 2. As expected, most of the substitution induced by wind power comes from gas generators as shown in Table 2. The interpretation of the coefficient is that one addition MWH of wind generated electricity displaces 0.81 MWH of gas generated electricity. However, a significant proportion of substitution still comes from coal plants despite the prevalence of gas capacity in the market. The rest of the displacement comes primarily from coal plants. Nuclear plants are impervious to changes in wind generated electricity. Other smaller generator types also do not seem to react significantly to wind power. The sum of the coefficients over fuel types sum to one implying that over all one MWH of wind power displaces one MWH of conventional generation.

Table 2: Market Level Regression Results

	Gas	**Coal**	**Nuclear**	**Landfill**	**Hydro**	**Methanol**	**Methane**	**Petroleum**	**Other**	**Imports**
Wind Gen	-0.8116	-0.1896	0.0026	-0.0004	0.0001	0.0000	0.0000	0.0000	0.0002	-0.0010
	(30.89)**	(29.93)**	(2.47)*	(3.92)**	-0.1	-1.22	-1.2	-0.23	(7.40)**	-0.39
Degrees	-10.94	1.24	0.04	-0.02	-0.41	0	0.01	-0.02	0	0.13
	(12.80)**	(6.30)**	-1.38	(5.91)**	(23.50)**	-1.1	(8.78)**	(3.51)**	(6.01)**	-1.8
Degrees^2	3.35	0.25	0	0	0.04	0	0	0	0	0.05
	(127.52)**	(43.07)**	-0.03	(5.21)**	(70.95)**	(3.83)**	(8.05)**	(4.84)**	(10.16)**	(21.29)**
Constant	1791	3112	606.7	2.09	47.44	3.91	3.81	34.7	1.28	149.5
	(35.34)**	(255.06)**	(297.94)**	(10.60)**	(43.95)**	(148.21)**	(83.70)**	(126.37)**	(32.27)**	(31.82)**
Date FE	X	X	X	X	X	X	X	X	X	X
Interval FE	X	X	X	X	X	X	X	X	X	X
N	70080	70080	70080	70080	70080	70080	70080	70080	70080	70080
R^2	0.94	0.91	0.99	0.95	0.67	0.95	0.62	0.96	0.88	0.72

Absolute value of t statistics in parentheses

** significant at 5% , ** significant at 1%*

7.3 Plant Level Results

For the plant level results, plant specific coefficients were obtained by regressing plant output on wind output and the control variables as specified in equation 2. In all, 162 regressions, one for each plant, were performed.[16] Parsimonious results for all 162 regressions can be found in the appendix. Table 3 shows the results for the top ten substituting plants. Of the top ten substituting plants, four are coal plants. It is somewhat surprising that the first and third ranked substituting plants are coal, but this may be due to the fact that there are relatively few coal plants in ERCOT which tend to be large. Gas plants on the other hand tend to be smaller and more numerous. The sign of the coefficients are what would be expected with the exception of a few plants which have positive and significant substitution coefficients even though the coefficients tend to be small. Many of these plants are in the same geographic area as the majority of the wind farms. This positive substitution may have to do with increased voltage regulation demands that occur when wind farms are producing power.

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[16] Some plants with very few observations were excluded from the analysis.

Table 3: Plant level Substitution and Avoided Emissions

EPA	**Substitution**				**Emissions Rate lb/MWH**			**Avoided Emissions lb/MWH Wind**		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**SO2**	**NOx**	**CO2**	**SO2**	**NOx**	**CO2**
3470	-0.0870	2.53E-03	Coal	1	5.781	0.447	2150	-5.03E-01	-3.89E-02	-187.11
3460	-0.0758	2.58E-03	Gas	1	0.008	0.655	1381	-5.76E-04	-4.96E-02	-104.60
6179	-0.0628	1.88E-03	Coal	4	5.236	1.945	2126	-3.29E-01	-1.22E-01	-133.38
55132	-0.0462	1.91E-03	Gas	2	0.004	0.195	799	-1.94E-04	-9.03E-03	-36.93
3469	-0.0436	2.14E-03	Gas	1	0.032	0.560	1112	-1.41E-03	-2.44E-02	-48.50
3497	-0.0431	1.46E-03	Coal	2	19.760	1.617	2405	-8.51E-01	-6.97E-02	-103.64
55501	-0.0378	2.55E-03	Gas	2	0.005	0.270	917	-1.74E-04	-1.02E-02	-34.66
6147	-0.0362	1.47E-03	Coal	2	10.770	1.829	2361	-3.90E-01	-6.62E-02	-85.47
55226	-0.0327	2.09E-03	Gas	2	0.005	0.216	933	-1.54E-04	-7.06E-03	-30.55
55357	-0.0315	1.42E-03	Gas	1	0.004	0.114	861	-1.35E-04	-3.60E-03	-27.13
7900	-0.0306	6.97E-04	Gas	4	0.020	1.355	1530	-6.17E-04	-4.14E-02	-46.75
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
Total	-1.2337	1.01E-01						-2.28	-1.16	-1830.53

7.4 Offset Emissions

Given the plant level substitution coefficients, we can now calculate the emissions reductions for each plant by multiplying the emissions rate times the substitution coefficient. This is done for each plant on the grid. Summing over all plants in the system gives the total emissions reduction for an additional MWH of wind power. This is shown in the last line of table 3. Each MWH of wind power offsets 2.28 lbs of SO_2, 1.16 lbs of NO_x, and nearly one ton of CO_2. In 2006, wind farms in Texas produced 6,529,434 MWH of electricity implying annual emissions offsets of 7,457 tons of SO_2, 3,784 tons of NO_x and 5,976,160 tons of CO_2.

Given the estimated emissions offset, their value per MWH of wind power can be calculated using any defined value. I have already argued that an appropriate value to use for cap and trade regulated emissions (SO_2 and NO_x) are the market values for these pollution permits. Table 4 gives low, medium, and high values for the price of pollution permits for SO_2 and NO_x taken from historical transactions in EPA pollution permit markets in the U.S. Evaluating the offset pollution from wind power at these prices gives the cost for reducing pollution by this amount through buying and retiring permits from permit trading markets.

Although CO_2 is not a regulated pollutant in the U.S., there is a literature which estimates the marginal costs imposed by CO_2. Tol (2005) reviews estimates of CO_2 costs and concludes that the costs imposed by CO_2 are less than \$50/ton and probably significantly lower than that. The median marginal damage costs of CO_2 for papers published in peer reviewed journals was \$14 /ton. I choose \$5, \$25, and \$50 per ton as a range of possible social values for reducing CO_2 emissions.

Under the assumption that no wind capacity would be installed without state and federal subsidies, we can compare the market price of offset emissions to the subsidy received to induce the production of wind power. Wind power receives federal PTC subsidies of \$20 MWH. Renewable energy credits in Texas are currently sold under the state's Renewable Portfolio Standard for about \$10 MWH. In total, Texas wind energy receives \$30 MWH in subsidies. However, this overstates the cost of the subsidy per MWH of wind power because it implicitly assumes that firms end production when the PTC expires 10 years after completion of the project. Given that the marginal cost of operating a wind farm is quite low, we would expect established wind farms to continue their operations after the expiration of the PTC for that farm. Under the assumption that wind farms continue to operate after PTC expiration and continue to receive a state subsidy of \$10/MWH, the discounted cost of the subsidy is approximately \$20/MWH given that both subsidies and permit prices increase at the discount rate.

The results of the final calculations are displayed in table 4. Columns four and five of the table show the cost of reducing the cap on regulated emissions by the amount of emissions offset by wind power through the market mechanism of buying and retiring permits. Column six shows the marginal damage cost of CO_2 that could be avoided by using wind power. Column seven gives the total cost of the three pollutants. The final column gives the subsidy necessary to avoid these costs under the assumptions outlined in this paper.

It is immediately apparent that whether the wind subsidy can be in some sense justified depends heavily on the marginal cost to society of CO_2. If the damage cost of CO_2 is greater than about \$20/ton then the environmental benefits of the subsidy are greater than the cost required to spur the production of wind energy. It is, however, important to note that this does not imply that wind power is the lowest cost way of achieving this level of avoided CO_2 emissions. It simply says that the cost of the subsidy could be justified by the marginal social costs of CO_2 emissions.

It is also important to note that this paper does not account for every pollutant offset by wind power. Mercury and particulate matter are also emitted by fossil fuel plants, but are not included in the present analysis due to data constraints. A reduction in these pollutants would increase the justification for a wind power subsidy.

Table 4: Value of Emissions Offset by Wind Power

	Prices or Costs/ton			Buy and Retire		Social Cost	Offset	Wind
	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2	Value	Subsidy
Low	\$200	\$2,000	\$5	\$0.23	\$1.16	\$4.58	\$5.96	\$20.00
Middle	\$433	\$5,000	\$20	\$0.49	\$2.90	\$18.31	\$21.70	\$20.00
High	\$700	\$10,000	\$50	\$0.80	\$5.80	\$45.76	\$52.36	\$20.00

Prices for pollution are in \$/ton

Conclusion

This paper measures the emissions offset by wind power production on the Texas electricity. Using a reduced form model, I estimated plant specific substitution coefficients which reflect how each generator reduces production to accommodate wind generated electricity. In aggregate, over 80% of the electricity substitution comes from relatively low emitting gas fired power plants. Somewhat surprising is that low cost, high polluting coal plants account for approximately 20% of the substitution.

Using plant specific emission rates which vary greatly across plants, I calculate the emissions offset due to electricity production by wind. It is important to note that aggregate emissions do not change for cap-and-trade regulated pollutants such as SO_2 and NO_x since permits that are freed up by offset emissions can be sold to other generators or held for use in the future. Therefore for regulated emissions I compare two environmental policies that would reduce pollution by equivalent amounts. The first policy would subsidizes wind power while reducing the cap on regulated emissions by the amount of emissions offset by wind power. Under an alternative policy, the government would not subsidize wind power, but would reduce the pollution by buying pollution permits on the open market. Not surprisingly, the cost of subsidizing wind power to reduce pollution is much higher than cost of buying permits for the same reduction in regulated pollutants.

In the case of CO_2, however, offset emissions do represent real reductions in total emissions since these are unregulated. I calculate the value of offset CO_2 emissions by appealing to a large literature which estimates the marginal damage costs of the carbon dioxide emissions.

Using several ranges of prices for pollution permits and marginal damage costs, I find that the justification for wind subsidies depend primarily on the marginal damage costs of CO_2. For marginal damage costs of CO_2 greater than approximately \$20/ton, the benefits to society of wind power are greater than the subsidy necessary to induce its production. Although this does not imply that wind subsidies are the least cost solution to reducing emissions, it does show that for reasonable values of pollution costs the environmental benefits of wind power outweigh the cost of its subsidization.

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A Plant Level Results

Table 5: **Plant Level Substitution Estimates**

EPA	**Wind**				**Emissions Rate lb/MWH**			**Avoided Emissions lb/MWH Wind**		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**SO2**	**NOx**	**CO2**	**SO2**	**NOx**	**CO2**
3470	-0.0870	2.53E-03	Coal	1	5.781	0.447	2150	-5.03E-01	-3.89E-02	-187.11
3460	-0.0758	2.58E-03	Gas	1	0.008	0.655	1381	-5.76E-04	-4.96E-02	-104.60
6179	-0.0628	1.88E-03	Coal	4	5.236	1.945	2126	-3.29E-01	-1.22E-01	-133.38
55132	-0.0462	1.91E-03	Gas	2	0.004	0.195	799	-1.94E-04	-9.03E-03	-36.93
3469	-0.0436	2.14E-03	Gas	1	0.032	0.560	1112	-1.41E-03	-2.44E-02	-48.50
3497	-0.0431	1.46E-03	Coal	2	19.760	1.617	2405	-8.51E-01	-6.97E-02	-103.64
55501	-0.0378	2.55E-03	Gas	2	0.005	0.270	917	-1.74E-04	-1.02E-02	-34.66
6147	-0.0362	1.47E-03	Coal	2	10.770	1.829	2361	-3.90E-01	-6.62E-02	-85.47
55226	-0.0327	2.09E-03	Gas	2	0.005	0.216	933	-1.54E-04	-7.06E-03	-30.55
55357	-0.0315	1.42E-03	Gas	1	0.004	0.114	861	-1.35E-04	-3.60E-03	-27.13
7900	-0.0306	6.97E-04	Gas	4	0.020	1.355	1530	-6.17E-04	-4.14E-02	-46.75
55545	-0.0303	1.96E-03	Gas	4	0.004	0.270	877	-1.33E-04	-8.20E-03	-26.61
3494	-0.0282	1.45E-03	Gas	5	0.502	1.975	1327	-1.41E-02	-5.56E-02	-37.39
55098	-0.0261	1.38E-03	Gas	4	0.031	0.788	1844	-8.14E-04	-2.06E-02	-48.11
55168	-0.0258	1.74E-03	Gas	4	0.027	0.646	1655	-6.93E-04	-1.67E-02	-42.77
109	-0.0257	1.03E-03	Gas	2	0.540	1.468	1683	-1.39E-02	-3.77E-02	-43.25
55047	-0.0253	1.38E-03	Gas	1	0.004	0.173	797	-1.01E-04	-4.39E-03	-20.20
55464	-0.0250	1.06E-03	Gas	1	0.007	0.111	1441	-1.83E-04	-2.78E-03	-36.02
55480	-0.0247	3.32E-03	Gas	2	0.004	0.280	874	-1.09E-04	-6.93E-03	-21.62
55320	-0.0243	1.61E-03	Gas	2	0.007	0.253	1350	-1.65E-04	-6.13E-03	-32.80
55327	-0.0236	1.04E-03	Gas	1	0.004	0.083	839	-9.92E-05	-1.96E-03	-19.81
3548	-0.0218	1.15E-03	Gas	4	0.008	1.315	1328	-1.76E-04	-2.86E-02	-28.91

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Table 5: *continued*

EPA Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	NOx	CO2	Avoided Emissions lb/MWH Wind SO2	NOx	CO2
3504	-0.0216	1.22E-03	Gas	2	0.055	0.941	1454	-1.19E-03	-2.03E-02	-31.41
3468	-0.0198	1.16E-03	Gas	1	0.008	1.732	1534	-1.55E-04	-3.44E-02	-30.44
55139	-0.0157	1.55E-03	Gas	2	0.005	0.244	957	-7.52E-05	-3.82E-03	-15.00
3464	-0.0156	8.16E-04	Gas	1	0.026	0.995	1806	-4.04E-04	-1.55E-02	-28.16
3549	-0.0149	6.41E-04	Gas	4	0.008	1.361	1448	-1.16E-04	-2.03E-02	-21.58
7512	-0.0141	1.31E-03	Gas	4	0.004	0.209	848	-6.05E-05	-2.94E-03	-11.93
3506	-0.0136	1.44E-03	Gas	2	0.007	2.059	1418	-9.78E-05	-2.80E-02	-19.26
6181	-0.0135	1.07E-03	Coal	4	7.576	1.689	2437	-1.03E-01	-2.29E-02	-32.97
55215	-0.0134	1.57E-03	Gas	5	0.027	0.572	1594	-3.63E-04	-7.63E-03	-21.29
55062	-0.0122	1.13E-03	Gas	2	0.029	0.892	1673	-3.52E-04	-1.09E-02	-20.46
3490	-0.0119	1.06E-03	Gas	5	0.018	2.464	1327	-2.14E-04	-2.93E-02	-15.78
54817	-0.0118	3.59E-04	Gas	2	0.005	0.248	960	-5.66E-05	-2.93E-03	-11.32
55137	-0.0115	1.36E-03	Gas	4	0.005	0.312	912	-5.27E-05	-3.58E-03	-10.44
55153	-0.0113	1.38E-03	Gas	4	0.005	0.583	926	-5.30E-05	-6.56E-03	-10.43
50815	-0.0109	6.05E-04	Gas	1	0.007	1.145	1281	-7.10E-05	-1.25E-02	-13.99
3452	-0.0107	1.27E-03	Gas	2	0.010	0.405	1314	-1.02E-04	-4.33E-03	-14.05
7097	-0.0106	9.07E-04	Coal	4	1.699	1.857	2232	-1.80E-02	-1.97E-02	-23.70
127	-0.0105	9.55E-04	Coal	5	1.715	3.452	2122	-1.80E-02	-3.62E-02	-22.28
55154	-0.0099	8.13E-04	Gas	4	0.004	0.124	866	-4.35E-05	-1.22E-03	-8.57
3601	-0.0098	7.94E-04	Gas	4	0.008	1.093	1260	-7.41E-05	-1.07E-02	-12.29
33	-0.0094	6.48E-04	Gas	1	0.540	1.468	1683	-5.06E-03	-1.38E-02	-15.78
55223	-0.0089	9.39E-04	Gas	2	0.004	0.172	763	-3.49E-05	-1.54E-03	-6.82

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Table 5: *continued*

EPA Plant ID	**Wind Coefficient**	**SE**	**Fuel**	**Zone**	**Emissions Rate lb/MWH**			**Avoided Emissions lb/MWH Wind**		
					SO2	**NOx**	**CO2**	**SO2**	**NOx**	**CO2**
55299	-0.0084	4.60E-04	Gas	1	0.004	0.098	938	-3.71E-05	-8.25E-04	-7.91
3628	-0.0083	9.09E-04	Gas	2	0.008	1.346	1475	-6.48E-05	-1.12E-02	-12.25
50109	-0.0077	7.46E-04	Gas	2	0.001	0.004	16	-3.86E-06	-3.08E-05	-0.12
55172	-0.0076	1.11E-03	Gas	2	0.004	0.344	863	-3.34E-05	-2.61E-03	-6.55
3453	-0.0076	1.12E-03	Gas	2	0.019	0.447	1556	-1.44E-04	-3.38E-03	-11.78
3631	-0.0070	4.33E-04	Gas	4	0.046	0.775	2254	-3.25E-04	-5.46E-03	-15.87
3612	-0.0069	1.41E-03	Gas	4	0.006	1.563	1250	-4.33E-05	-1.07E-02	-8.59
-1002	-0.0065	9.07E-04	Imports	5	1.468	0.540	1683	0.00E+00	0.00E+00	0.00
55097	-0.0063	2.35E-03	Gas	2	0.005	0.234	899	-2.84E-05	-1.48E-03	-5.67
52088	-0.0058	5.76E-04	Gas	1	0.036	0.644	1261	-2.10E-04	-3.73E-03	-7.30
55313	-0.0058	4.47E-04	Gas	4	0.027	0.383	811	-1.58E-04	-2.21E-03	-4.68
4939	-0.0058	9.50E-04	Gas	4	0.012	2.869	2377	-6.92E-05	-1.65E-02	-13.70
55086	-0.0057	5.21E-04	Gas	4	0.006	0.344	1242	-3.57E-05	-1.95E-03	-7.05
3508	-0.0055	7.58E-04	Gas	2	0.041	15.699	7926	-2.22E-04	-8.61E-02	-43.46
55206	-0.0051	7.77E-04	Gas	4	0.005	0.306	1054	-2.77E-05	-1.57E-03	-5.41
3492	-0.0043	6.91E-04	Gas	5	0.156	2.159	1743	-6.77E-04	-9.38E-03	-7.57
55015	-0.0042	3.24E-04	Gas	1	0.048	1.638	2630	-2.02E-04	-6.96E-03	-11.17
3491	-0.0040	1.43E-03	Gas	2	0.008	0.416	1622	-3.35E-05	-1.68E-03	-6.55
298	-0.0039	1.12E-03	Coal	2	3.468	1.776	2044	-1.35E-02	-6.93E-03	-7.98
6145	-0.0039	6.21E-04	Nuclear	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
55365	-0.0036	3.33E-04	Gas	1	0.871	2.179	1714	-3.15E-03	-7.87E-03	-6.19
10298	-0.0032	2.39E-04	Gas	1	0.019	0.504	638	-6.06E-05	-1.61E-03	-2.03

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Table 5: *continued*

EPA	Wind				Emissions Rate lb/MWH			Avoided Emissions lb/MWH Wind		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**SO2**	**NOx**	**CO2**	**SO2**	**NOx**	**CO2**
55187	-0.0030	4.37E-04	Gas	1	0.003	0.062	656	-1.00E-05	-1.88E-04	-1.99
3576	-0.0030	3.38E-04	Gas	2	0.010	0.882	1575	-2.90E-05	-2.67E-03	-4.77
7325	-0.0030	1.83E-04	Gas	1	0.049	1.459	2894	-1.48E-04	-4.38E-03	-8.69
55091	-0.0027	1.35E-03	Gas	2	0.030	0.504	1716	-8.27E-05	-1.37E-03	-4.68
3609	-0.0027	5.38E-04	Gas	4	0.008	0.266	1599	-2.19E-05	-7.21E-04	-4.33
10670	-0.0027	3.00E-04	Gas	1	2.642	5.980	2295	-7.01E-03	-1.59E-02	-6.09
3439	-0.0026	2.89E-04	Gas	4	0.007	2.551	1431	-1.87E-05	-6.63E-03	-3.72
8063	-0.0025	1.05E-03	Gas	2	0.041	1.349	1543	-1.03E-04	-3.36E-03	-3.84
3502	-0.0023	4.27E-04	Gas	2	0.009	3.015	1514	-1.96E-05	-6.95E-03	-3.49
55144	-0.0023	8.73E-04	Gas	4	0.046	1.669	2741	-1.05E-04	-3.79E-03	-6.23
10554	-0.0023	2.01E-04	Gas	4	0.044	0.598	1283	-1.00E-04	-1.35E-03	-2.90
6136	-0.0019	4.16E-04	Coal	2	6.645	1.170	1959	-1.27E-02	-2.24E-03	-3.75
6183	-0.0018	4.82E-04	Coal	4	6.436	2.469	2816	-1.13E-02	-4.32E-03	-4.93
6243	-0.0017	2.71E-04	Gas	2	0.007	1.171	1441	-1.21E-05	-1.94E-03	-2.39
6178	-0.0016	4.87E-04	Coal	4	11.209	2.828	3749	-1.74E-02	-4.38E-03	-5.81
55470	-0.0016	2.93E-04	Gas	1	0.018	0.048	683	-2.85E-05	-7.36E-05	-1.06
132	-0.0015	1.24E-04	Gas	1	0.540	1.468	1683	-7.87E-04	-2.14E-03	-2.45
3611	-0.0014	1.45E-03	Gas	4	0.158	1.602	1410	-2.25E-04	-2.28E-03	-2.00
3600	-0.0014	1.96E-04	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
6251	-0.0013	5.06E-04	Nuclear	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3559	-0.0011	2.36E-04	Gas	4	0.006	0.592	1176	-6.99E-06	-6.57E-04	-1.31
4937	-0.0009	8.67E-04	Gas	4	0.007	2.044	1274	-6.02E-06	-1.84E-03	-1.14

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Table 5: *continued*

EPA Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	NOx	CO2	Avoided Emissions lb/MWH Wind SO2	NOx	CO2
55311	-0.0008	3.58E-05	Gas	1	0.023	0.378	800	-1.85E-05	-2.99E-04	-0.63
3630	-0.0007	7.64E-05	Gas	4	0.050	2.707	1977	-3.71E-05	-2.01E-03	-1.47
3594	-0.0005	5.68E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
7030	-0.0005	2.19E-04	Coal	2	4.389	1.910	2370	-2.24E-03	-9.77E-04	-1.21
10692	-0.0005	9.82E-05	Gas	1	0.029	0.782	989	-1.31E-05	-3.53E-04	-0.45
3613	-0.0004	2.02E-04	Gas	4	0.016	4.148	3042	-6.41E-06	-1.69E-03	-1.24
71	-0.0004	8.74E-05	Landfill	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3557	-0.0003	6.39E-05	Hydro	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3561	-0.0003	1.31E-04	Gas	2	0.016	0.962	1735	-4.02E-06	-2.46E-04	-0.44
50150	-0.0003	4.23E-05	Gas	4	0.026	0.471	905	-6.66E-06	-1.21E-04	-0.23
6410	-0.0002	2.18E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
4195	-0.0002	7.71E-05	Gas	2	0.225	4.169	4620	-4.70E-05	-8.70E-04	-0.96
216	-0.0002	1.19E-05	Gas	4	0.540	1.468	1683	-1.11E-04	-3.02E-04	-0.35
3466	-0.0002	2.60E-04	Gas	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3595	-0.0002	9.63E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3598	-0.0002	4.57E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50137	-0.0002	1.30E-04	Gas	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50475	-0.0001	9.89E-06	Gas	4	0.019	0.504	637	-2.79E-06	-7.44E-05	-0.09
7	-0.0001	1.40E-04	Petroleum	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
52120	-0.0001	3.50E-05	Landfill	1	0.028	0.446	944	-2.64E-06	-4.29E-05	-0.09
3574	-0.0001	4.31E-05	Gas	2	0.021	1.799	4237	-1.69E-06	-1.45E-04	-0.34
50153	-0.0001	2.04E-05	Gas	1	0.027	0.441	933	-1.99E-06	-3.23E-05	-0.07

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Table 5: *continued*

EPA	**Wind**				**Emissions Rate lb/MWH**			**Avoided Emissions lb/MWH Wind**		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**SO2**	**NOx**	**CO2**	**SO2**	**NOx**	**CO2**
10243	-0.0001	1.58E-05	Gas	4	0.029	0.782	989	-1.94E-06	-5.18E-05	-0.07
67	-0.0001	9.22E-06	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50404	0.0000	1.34E-05	Methanol	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
65	0.0000	1.58E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
6414	0.0000	8.73E-05	Hydro	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3507	0.0000	3.39E-04	Gas	2	0.038	2.965	1623	-8.54E-07	-6.66E-05	-0.04
88	0.0000	5.33E-06	Other	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
63	0.0000	1.73E-06	Hydro	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
103	0.0000	1.87E-05	Methane	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
209	0.0000	6.96E-06	Methane	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
52065	0.0000	4.81E-06	Other	1	0.000	0.016	10	-1.83E-09	-9.94E-08	0.00
61	0.0000	6.88E-07	Gas	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
128	0.0000	2.77E-06	Methane	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
218	0.0000	3.47E-07	Methane	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3437	0.0000	6.79E-06	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
45	0.0000	1.30E-07	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
125	0.0000	1.75E-07	Other	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
145	0.0000	3.92E-13	Methane	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
167	0.0000	4.24E-07	Other	5	0.000	0.000	0	0.00E+00	0.00E+00	0.00
10	0.0000	1.14E-05	Gas	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
791	0.0000	2.24E-06	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
10203	0.0000	5.61E-06	Gas	4	0.030	0.782	989	5.22E-07	1.37E-05	0.02

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Table 5: *continued*

EPA Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	NOx	CO2	Avoided Emissions lb/MWH Wind SO2	NOx	CO2
4	0.0000	1.15E-05	Methane	1	0.000	0.000	0	0.00E+00	0.00E+00	0.00
228	0.0000	6.78E-06	Other	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50229	0.0000	9.35E-06	Gas	1	0.022	0.891	697	6.60E-07	2.64E-05	0.02
52132	0.0000	5.68E-05	Gas	1	0.044	0.718	1519	1.70E-06	2.77E-05	0.06
69	0.0000	1.17E-05	Landfill	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3599	0.0001	6.02E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50569	0.0001	9.19E-06	Gas	2	0.000	1.017	0	0.00E+00	7.09E-05	0.00
10167	0.0001	9.24E-06	Gas	4	45.275	4.808	1225	3.49E-03	3.71E-04	0.09
3597	0.0001	9.76E-05	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
50304	0.0001	2.15E-05	Gas	1	0.023	0.701	772	2.06E-06	6.29E-05	0.07
44	0.0001	2.41E-05	Other	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
-1000	0.0002	4.26E-05	Imports	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
3489	0.0002	1.35E-04	Gas	2	0.008	2.060	1673	1.85E-06	4.54E-04	0.37
3454	0.0003	2.06E-04	Gas	2	0.008	1.679	1458	2.28E-06	5.04E-04	0.44
3627	0.0003	5.72E-05	Gas	2	2.665	9.922	1987	9.14E-04	3.40E-03	0.68
70	0.0004	8.90E-05	Gas	1	0.540	1.468	1683	1.91E-04	5.18E-04	0.59
4266	0.0004	1.58E-04	Gas	2	0.291	13.623	28246	1.29E-04	6.02E-03	12.47
3438	0.0007	1.21E-04	Gas	4	0.007	3.833	1427	5.36E-06	2.85E-03	1.06
50127	0.0008	1.57E-04	Gas	5	0.029	0.468	989	2.41E-05	3.86E-04	0.82
50615	0.0008	6.57E-04	Gas	5	0.005	0.964	1000	4.18E-06	8.05E-04	0.83
6416	0.0009	2.48E-04	Hydro	2	0.000	0.000	0	0.00E+00	0.00E+00	0.00
6648	0.0011	6.53E-04	Coal	4	11.743	2.232	2329	1.30E-02	2.48E-03	2.58

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Table 5: *continued*

EPA Plant ID	**Wind Coefficient**	**SE**	**Fuel**	**Zone**	**Emissions Rate lb/MWH SO2**	**NOx**	**CO2**	**Avoided Emissions lb/MWH Wind SO2**	**NOx**	**CO2**
52176	0.0013	4.10E-04	Gas	5	0.035	1.710	2001	4.33E-05	2.14E-03	2.50
6128	0.0017	1.50E-04	Hydro	4	0.000	0.000	0	0.00E+00	0.00E+00	0.00
-1001	0.0023	2.12E-03	Imports	2	1.468	0.540	1683	0.00E+00	0.00E+00	0.00
6146	0.0036	2.04E-03	Coal	2	6.552	1.810	2329	2.35E-02	6.50E-03	8.37
3442	0.0040	4.39E-04	Gas	4	0.031	2.953	1942	1.23E-04	1.17E-02	7.70
54979	0.0153	7.09E-05	Gas	5	0.000	0.000	0	0.00E+00	0.00E+00	0.00
Total	-1.2337	1.01E-01						-2.28	-1.16	-1830.53