What's Powering Wind? Measuring the Environmental Benefits of Wind Generated Electricity *

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Abstract

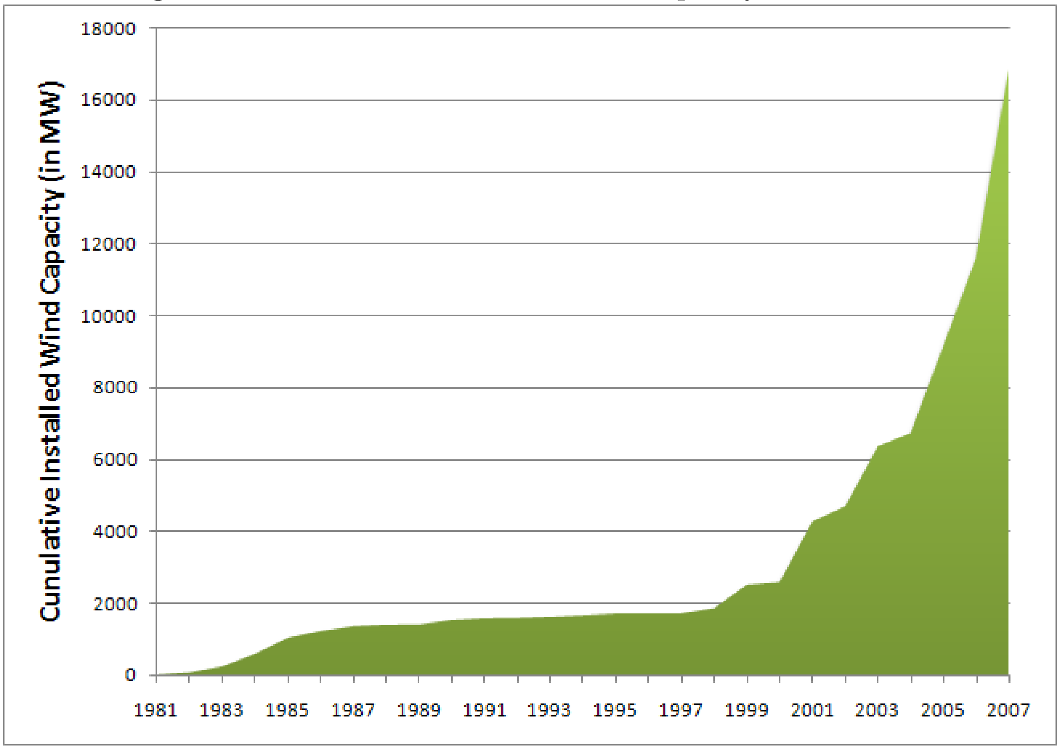
Production subsidies for renewable energy have experienced intermittent support from the federal government. One reason for less than unified support arises from uncertainty over the environmental impact of projects implemented because of such subsidies. Wind energy in particular has taken advantage 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 one geographic area of the US electric grid. I exploit the exogenous nature of wind to identify generator level substitution of wind generated electricity for conventionally generated electricity. I then quantify the avoided emissions and associated costs using generator level emissions information and market clearing prices for pollution permits. The end result is the value of avoided emissions due to government subsidies.

1 Introduction

Wind power has been rapidly growing in the United States. A major contributor to its growth are state and federal subsidies. These subsidies provide a significant stream of revenue for renewable energy operations, sometimes providing half of the revenues for a wind farm. It is uncontroversial to state that without subsidies wind farms would not be competitive with conventional generators. The primary motivation for supporting renewable energy is its lower environmental impact compared with conventional generators. Despite these benefits, federal renewable energy subsidies have been allowed to expire several times. When subsidies have expired, investment in wind farms has plummeted.

One reason for less than unified support for subsidies arises from uncertainty over the environmental impact of projects implemented because of such subsidies. When wind farms produce electricity, other generators, which typically burn fossil fuels, reduce their production. To date, no studies have attempted to empirically measure the environmental contribution of wind power due to these substitution patterns. The emissions offset by wind power depend heavily on the type of generators that substitute with wind power. Using detailed output data from generators on an electricity grid in Texas, I exploit the exogeneity of wind power to identify generator level substitution patterns between renewable wind energy and electricity produced by conventional fossil fuel and nuclear generators. I then use the substitution parameter for each generator to calculate avoided emissions using generator level emission rates from the EPA. Summing over generators

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



in the system gives the total emissions avoided for each megawatt (MW) of electricity produced by wind farms. A lower bound on the value of these avoided emissions can be calculated by appealing to pollution markets for SO_2, CO_2 and NO_x. Under the assumption that wind farms are installed due to subsidies, I can then compare the value of avoided emissions to the cost of subsidies needed to produce wind power. I find that the value of avoided emissions is significantly less than cost of subsidies needed to induce investment in wind power.

2 Wind Power and Subsidies

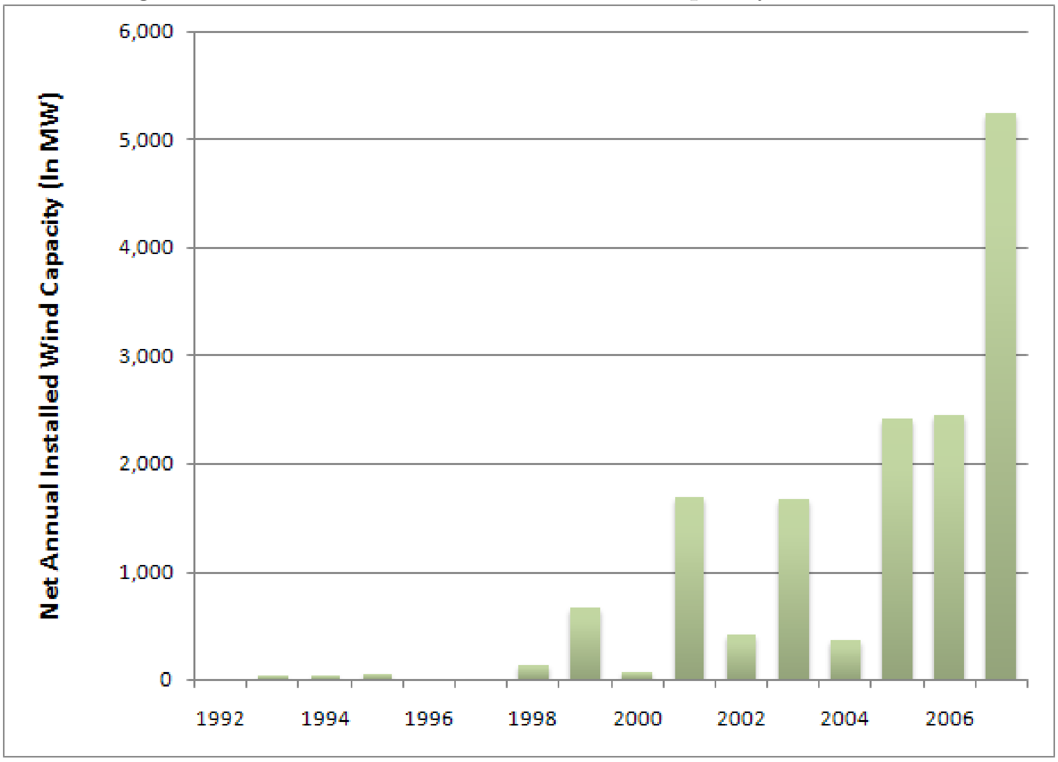
A number of factors have contributed to the growth of wind power. First, technology advancements in wind turbines have reduced the cost of wind power by 80% over the past 30 years(Wiser & Bolinger 2006). These developments include advanced turbine design which can better use wind in a greater range of speeds and also a real reduction in the cost of manufacturing equipment. Second, there is growing demand for pollution free power by firms wishing to promote a "green" image and by environmentally conscious consumers wishing to offset their "carbon footprint". This allows wind generators to receive revenues for the environmental attributes of their power by selling carbon offsets in voluntary markets. However the most important drive of wind energy has been State and Federal programs which subsidize renewable energy. It is generally acknowledged that without government subsidies most wind farms could not compete with conventional thermal generators which use gas, coal or uranium as fuel(Wiser & Bolinger 2006).

There are two main types of subsidies which support wind energy: State Renewable Portfolio Standards and Federal Production Tax Credits. Renewable Portfolio Standards (RPS) 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 guarantees an inflation adjusted \$20 /MWH tax credit for the first ten years of production of the facility. 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. Given that 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 payment of the subsidy regardless of how market conditions evolve.

The importance of this subsidy to the industry can be seen by looking at the patterns of wind capacity development. Since 1999 the subsidy has been continued through short-term 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 the following year at the end of 2000, 2002, 2004(AWEA 2008). The PTC was also set to expire at the end of 2005, but for the first time was renewed before its expiration. 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 installations or higher cost wind farms(AWEA 2008). The 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. After 2005 when the PTC was renewed before it expired, there is an increase in installed capacity rather than a drop. While not conclusive, this does underline the importance of the PTC for the development and operation of wind farms.

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



Without State RPS and the Federal PTC, electricity production via wind farms would be economically unviable. It is not unreasonable to assume that without the subsidies, investment in wind farms since 1997 would have been negligible, as it in fact was over the decade prior. Under this assumption, the Federal and State subsidies are responsible for the annual increases in installed wind capacity over the past ten years.

3 Emissions and Wind Power Production

3.1 Emissions

Advocates of wind power and proponents of its subsidization tout its contribution to the environment as a major motivator for subsidies. 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 generator level production substitution can be identified then it is a straightforward to calculate the offset emissions and the value of those emissions. Multiplying the MWH of production reduced by the emissions rate per MWH for SO_2, NO_x, and CO_2 for a given unit yields the expected offset emissions. The value of the offset emissions can be found by appealing to emissions trading markets. Such markets exist for SO_2, NO_x and to some extent CO_2. The prices in these markets reflect the marginal cost of reducing pollution. It is important to note that emissions regulated via cap and trade, namely SO_2 and NO_x, are not actually reduced by wind power in the aggregate. This is because offset emissions from displaced production free up permits that can be banked for use in future periods or transferred to a different geographic location. What is avoided is the cost of abating the pollution that would have occurred if the wind generated electricity had not been produced. To the extent that the marginal pollution abatement cost curve is increasing, the permit prices represent a lower bound on the value of offset permits since without wind power marginal abatement costs (and thus permit prices) would be higher. For pollutants that are unregulated or not regulated on a cap and trade basis, the offset emissions represent real reductions in the total amount of pollutants emitted.

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.

3.2 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.

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

Production Tax Credit, which is tied to the output of the wind farm, is an additional incentive to produce as whenever possible[1].

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.

4 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 that the increased level wind power

[1]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 the 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)

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 the energy wind power would displace would come from natural gas generators, 15% from coal, 10% from oil, and 10% from electricity imports. This results in avoided emissions of 6,400 tons of NOx and 12,000 tons of SO2. These statistics are sensitive to accuracy of day-ahead predictions of wind power and to the way the market schedules day-ahead generation(GE 2005).

5 Data

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 needs to represent 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 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 which supply electricity to the grid which reside at 200 plants. I also observe daily flows of electricity from the tie to the neighboring grid.

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.

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[2].

[2]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.

6 Electricity Market

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

6.1 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.

Electricity is an unusual commodity in that it is not storable[3]. 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 electicity at any given time is called load. Meeting load reliably is the central function of grid management.

In addition to the requirement that aggregate generation be equal to aggregate load, transmission capabilities must be sufficient to transmit power from the location of generation to the location of load. Transmission congestion occurs when a transmission line is operating at its maximum capacity.

[3]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 no such technologies have been implemented on the electrical grid in my study.

Congestion requires the system to increase output from generators that can transmit power over alternate routes to the load. Alleviating congestion may require higher cost generators to run when lower cost generators are still not operating at maximum capacity.

6.2 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 seperated. 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. This vertical separation was required by the 1999 law that deregulated ERCOT to protect against market power. The generation and retail markets have been competely deregulated, while the transmission infrastructure is privately owned but regulated by ERCOT to ensure the both incumbent and potential generators and retailers have open access to energy and customers. 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.

6.2.1 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. Each generator and retailer must schedule it planned transactions with ERCOT a day ahead of production. ERCOT reviews all submitted schedule to ensure that planned production meets reliability criteria for the grid. Firms are instructed to change their schedules if the grid will not support the proposed production and consumption patterns.

In addition to planned generation, firms also submit hourly bidding function for the delivery of electricity in the Balancing Market. A firms bidding function delineates the change in production the generator is willing to make for a given price for electricity in the Balancing Market. For example, as part of its bidding function a generator may specify that it will increase production by 2MW relative to its planned production if the price in the balancing market is $50 MWH. Firms must specify both increments and decrements in production as a function of the price of energy in the Balancing Market.

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 generator goes offline unexpectedly [4]. The Balancing Market is cleared every 15 mins by intersecting the hourly bidding functions submitted by firms. The price required to produce the marginal unit of electricity is the market clearing price

[4]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 Market.

in that 15 minute interval. ERCOT then sends out generating instructions to all winning bidders in that 15 min interval[5]. 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 an important for generators especially when key transmission lines are congested as generators located close to load centers face fewer transmission constraints that 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[6] 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.

6.2.2 Transmission

Most of the time ERCOT operates as a single market and electricity flows freely over the transmission grid. Since the transmission system is regulated, transmission owners negotiate annual fees with ERCOT to cover the costs

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

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

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%

of maintaining and expanding the transmission grid and to receive a "fair" rate of return on investments. ERCOT distributes these transmission costs across generators according to each firm's share of total production. 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, market rules do charge charge differential prices for certain types of network congestion.

At times of high demand, the transmission network can develop bottlenecks that prevent electricity from flowing from generators to load centers. If left unaddressed, transmission lines can become severely overloaded leading to grid instability or failure. When transmission lines reach capacity, ERCOT re-dispatches generating resources to ease constrained transmission lines. In order to price the costs of re-dispatching generators, ERCOT has identified key transmission routes as Commercially Significant Constraints (CSCs). When transmission constraints begin to bind on one of these routes, the ERCOT market splits into smaller zonal markets. There are currently four of these congestion zones in ERCOT: North, South, West, and Houston. As CSCs begin to bind between congestion zones, ERCOT separately clears the balancing market in each zone to reduce congestion. For example, if the transmission lines providing electricity from the West zone to the Houston zone become overloaded, ERCOT will reduce production in the West zone by lowering the balancing energy price while increasing production in the Houston zone by raising the balancing energy price there. This reduces the flow of electricity from between the two zones, but still meeting the demand for electricity in each zone. Firms responsible for inter-zonal congestion are charged for the cost of producing the higher cost power necessary to alleviate congestion over the congested transmission lines.

Congestion can also occur within zones. For intra-zonal, or local, congestion, ERCOT instructs specific generators, which normally would not produce at the prevailing balancing energy price, to start or increase production in order to maintain the reliability of the grid. The costs of reducing intrazonal congestion are distributed across generators in a zone based upon their share of production within the zone. Thus, larger generators bear a larger proportion of local congestion costs even if they are not responsible for congestion[7].

[7]ERCOT is currently in the process of switching from a zonal pricing system for energy to a nodal pricing system. Under a nodal system each generator faces a potentially different price for electricity which ostensibly incorporates all congestion costs created by the generator.

6.2.3 Ancillary Services

In addition to the market for energy, there are smaller markets for ancillary services which help maintain grid reliability. Outside of balancing energy, ancillary services include regulation, responsive reserves, non-spinning reserves, and replacement reserves. Although important for grid reliability, they represent a very small share of total output. I consequently do not explicitly incorporate them into my model.

6.2.4 Demand

As in most electricity markets, demand in ERCOT does not respond directly or immediately to wholesale price signals. ERCOT does have a deregulated retail electricity market that offers residential, commercial, and industrial users a wide variety of energy plans and contracts. For example, residential users can choose between plans with prices that change biannually or plans with prices that change monthly. However, no users respond to price signals in the balancing market. Additionally some large industrial users negotiate lower energy prices by agreeing to have their supply of electricity temporarily interrupted if generating reserves on the grid reach critical levels, but they are not directly responsive to fluctuations in the price of electricity in the wholesale market[8]. Although emerging technologies may at some point allow

[8]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.

consumers to react to real-time energy prices, currently demand is irresponsive to changes in wholesale energy market in the short run.

7 Model

7.1 Reduced Form Model

This paper aims to identify the substitution patterns between wind generated power and output by conventional generators. 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 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, 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 generater 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 in period within a day[9]. 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 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

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

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[10]. I use hourly temperature to calculate hourly cooling/heating degrees. The cooling or heating degrees in an hour 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

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

[10]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.

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

D_{id} = vector of date fixed effects

J_{ij} = vector of interval fixed effects

8 Results

8.1 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. 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 displace natural gas generation, all else equal. From an environmental perspective this may be less than ideal since gas generators are also less polluting than other 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.

8.2 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. Nuclear plants are impervious to changes in wind generated electricity. Other smaller generator types also do not seem to react significantly to wind power. It is assuring that the sum of the coefficients over fuel types do indeed 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%*

8.3 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. Parsimonious results for all 162 regressions can be found the 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 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. Summing up the coefficients over all of the plant results in a market level substitution coefficient of -1.23. There is not a good explanation why the coefficients do not sum up to one. Also, a few plants have positive and significant substitution coefficients even though the coefficients tend to be small. Many of these plants are in the same zone (zone 5) 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.

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

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 windpower offsets -2.28 lbs of SO_2, -1.16 lbs of NO_x , and nearly one ton of CO_2.

The value of these offsets depends market value of these emissions. Table 4 gives low, medium, and high estimates of the value of reducing these pollutants taken from permit markets[11]. The value of emissions offset by wind power ranges from a mere \$3 MWH to \$31 MWH . Under the assumption that no wind capacity would be installed without these state and federal subsidies, we can compare the market price of offset emissions to the subsidy received to induce the production of windpower. Wind power receives federal PTC subsidies of \$20 MWH. Renewable energy credits in Texas that are sold under the state's Renewable Portfolio Standard are currently selling for \$10 MWH. In total Texas wind energy receives \$30 MWH in subsidies. This subsidy is greater than the price of emissions under both the low and medium scenarios and approximately equal for the highest pollution prices. In making this comparison, I assuming that wind energy does not change the price of pollution permits. If wind power puts significant downward pressure

[11] The pollution prices for SO_2 and NO_x where taken from historical transactions in EPA pollution permit markets in the U.S.. CO_2 is not a regulated pollutant in the U.S.. Low and medium values for CO_2 pollution were taken from transactions voluntary markets in the U.S.. The voluntary carbon markets in the U.S. exhibit vastly different prices for CO_2 offsets in the same time period even though we would expect CO_2 to be a homogeneous bad. The high value CO_2 is based on prices for CO_2 permits in the European CO_2 trading market.

on pollution permit prices then the estimates of the value of offset emissions represent a lower bound. However, given that wind power contributes less than 2% of to electricity production nationwide it seems unlikely that the absence of wind power would significantly increase pollution permit prices.

Table 4: Value of Emissions Offset by Wind Power

	SO_2	**NO_x**	**CO_2**	**Value of Offset Emissions /MWH wind**
Low	$200	$2,000	$2	$3
Average	$433	$5,000	$12	$14
High	$700	$10,000	$27	$31

Prices for pollution are in $/ton

Under the assumption that no wind capacity would have been installed without the current subsidies, it appears that the current prices for pollution do not justify the subsidies wind power receives to operate profitably. In other words, subsidizing wind power as a form of pollution abatement is more costly than other types of abatement.

It should be noted that the total value of offset emissions is primarily driven by prices of CO_2 pollution. Every MWH of wind power offsets nearly one ton of CO_2. As price of reducing CO_2 emissions approach the subsidies received by wind generators for each MWH of production, wind power becomes a cost effective method for avoiding emissions.

It should also be noted that the current prices for pollution permits are largely a function of the cap specified by regulation. As such, the prices may not reflect the true social cost of pollutants. If the true social costs of pollution were high enough, subsidies could be justified.

9 Conclusion

This paper measures the emissions offset by wind power production on one grid in the United States. Using a reduced form model, I estimated generator specific substitution coefficients that reflecting how each generator reduces production to accommodate wind generated electricity. I find that low cost, high polluting coal plants account for approximately 20% of the substitution while gas fired plants account for the remaining 80%. Using generator specific emission rates which vary greatly across plants, I calculate the emissions avoided because of 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 emissions offset due to wind power can be sold in another region of the U.S. or be held for use at a future date. However, offset CO_2 emissions do represent real reductions in total emissions since these are unregulated. For all emissions I can calculate the value of avoided emissions under the assumption that the abatement costs are constant within the range of emissions offset by wind power. Using several ranges of prices for pollution permits I find wind subsidies are not usually justified by the value of avoided abatement. However, they may be justified if the true social cost of unregulated pollutants are high enough.

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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

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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
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	Wind				Emissions Rate lb/MWH			Avoided Emissions lb/MWH Wind		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**SO2**	**NOx**	**CO2**	**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

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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**
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	**Wind**				**Emissions Rate lb/MWH**			**Avoided Emissions lb/MWH Wind**		
Plant ID	**Coefficient**	**SE**	**Fuel**	**Zone**	**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

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Table 5: *continued*

EPA Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	Emissions Rate lb/MWH NOx	Emissions Rate lb/MWH CO2	Avoided Emissions lb/MWH Wind SO2	Avoided Emissions lb/MWH Wind NOx	Avoided Emissions lb/MWH Wind CO2
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 Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	Emissions Rate lb/MWH NOx	Emissions Rate lb/MWH CO2	Avoided Emissions lb/MWH Wind SO2	Avoided Emissions lb/MWH Wind NOx	Avoided Emissions lb/MWH Wind 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

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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**
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	Wind				Emissions Rate lb/MWH			Avoided Emissions lb/MWH Wind		
Plant ID	Coefficient	SE	Fuel	Zone	SO2	NOx	CO2	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

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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**
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 Plant ID	Wind Coefficient	SE	Fuel	Zone	Emissions Rate lb/MWH SO2	NOx	CO2	Avoided Emissions lb/MWH Wind 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

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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
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	Wind				Emissions Rate lb/MWH			Avoided Emissions lb/MWH Wind		
Plant ID	Coefficient	SE	Fuel	Zone	SO2	NOx	CO2	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

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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**
-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