Measuring the Environmental Benefits of Wind-Generated Electricity

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Abstract

Production subsidies for renewable energy, such as solar or wind power, are rationalized by their environmental benefits. Subsidizing these projects allows clean, renewable technologies to produce electricity that otherwise would have been produced by dirtier, fossil-fuel power plants. In this paper, I quantify the emissions offset by wind power for a large electricity grid in Texas using the randomness inherent in wind power availability. When accounting for dynamics in the production process, the results indicate that only for high estimates of the social costs of pollution does the value of emissions offset by wind power exceed cost of renewable energy subsidies.

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Wind energy has experienced dramatic growth over the past decade due to declining production costs and generous government subsidies. These politically popular subsidies provide a significant stream of revenue for renewable energy operations, providing about half of the revenues for a wind farm. Subsidies paid to wind farms were on the order of $3 billion in 2010[1]. 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 common to conventional generators, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). Given the lack of national climate legislation, renewable subsidies are likely to be an important policy instrument for carbon mitigation for some time. In this paper, I compare the environmental benefits that stem from wind power production, with the stream of subsidies given to stimulate wind farm power production.

Since electricity produced by wind is emission-free, the development of wind power may reduce aggregate pollution by offsetting production from fossil-fuel generated electricity production. When low marginal cost wind-generated electricity enters the grid, higher marginal cost fossil fuel generators will reduce their output. However, emission rates of fossil fuel generators vary greatly by generator. Thus, the quantity of emissions offset by wind power will depend crucially on which generators reduce their output. This paper introduces an approach to empirically measure the environmental contribution of wind power resulting from these production offsets.

Utilizing information on production decisions in 15-minute intervals on the Texas electricity grid, I estimate the response of each generator to exogenous changes in

1 Subsidies for 2010 were calculated based on Energy Information Administration (EIA) wind power production for 2007 and 2010 in addition to wind subsidy data from 2007 (EIA 2007) (EIA 2011) .

wind power. Realizing that wind power production is not completely random, I control for factors that may drive the incentives for electricity production, which may also be correlated with wind power production. The resulting quasi-experimental residual variation is then used to identify a substitution coefficient for each generator on the grid. Importantly, I show that failing to control for impact that wind has on the dynamic process of electricity production overestimates the production offsets. These production offsets then translate directly into emission offsets using generator emission rates.

Estimated offsets can be valued by appealing to estimates from the literature on the marginal damage costs of emissions. This allows a direct comparison between the value of short run offset emissions with the cost of subsidies which drive investment in wind farms.

Wind Power Subsidies

Over the past decade, installed wind power production capacity has displayed explosive growth. As shown in Figure 1, installed wind capacity more than doubled between 2004 and 2007(AWEA 2008). In 2008 and 2009, net capacity additions of wind power outpaced the net capacity additions of all other generator types combined[2]. 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). [INSERT FIGURE 1]

Two factors have been significant in the growth of wind power. First, technology

2 Annual net capacity additions are defined as the difference in installed electricity generating capacity year-to-year. The net capacity addition for each generator type includes new capacity built, and old capacity which is retired. The net capacity additions for the major fuel types in 2008 are: Wind 8386 MW, Natural Gas 5220 MW, Coal 1259 MW. The net capacity additions for the major fuel types in 2008 are: Wind 9704 MW, Natural Gas 5154 MW, Coal 1426 MW. Data come from the Energy Information Administration annual report (EIA 2010).

advancements in wind turbines have reduced the cost of wind power by 80% over the past 30 years (Wiser and Bolinger 2006). Second, federal and state programs have provided considerable support for wind. The primary subsidies which support wind energy production are state Renewable Portfolio Standards (RPS) and the federal Production Tax Credit (PTC)[3]. Both the federal PTC and state RPSs are output-based subsidies rather than investment subsidies. The financial benefits of state subsidies RPS credits vary greatly by state, but federal subsidies uniformly grant a tax credit of $20 per MWh of production from the wind facility[4]. Since wholesale electricity typically sells for between $30 and $50 per MWh, subsides from the federal component alone represent a 40%-67% increase in revenue for a wind farm operator.The importance of these subsidies to the industry can be seen by looking at the patterns of wind capacity development. The federal PTC was originally enacted as a short term program, but has been continued through a series of short one-to-two-year extensions. The subsidy 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). In 2000, 2002 and 2004, there was a precipitous drop in new wind farm installations coinciding with the expiration of the PTC in each preceding year as shown in

3 Renewable Portfolio Standards are state-level regulations that require a certain proportion of power in the state 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 federal production tax credit (PTC) guarantees an inflation adjusted 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. Even with the downward trend in costs, 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 and Bolinger 2006)

4 Subsidies from renewable portfolio standards range 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 statey (Wiser and Barbose 2008).

figure 2[5]. It is uncontroversial to assert that without federal and state subsidies, investment in new wind farms over the past decade would have been negligible[6]. [INSERT FIGURE 2]

Identifying Offset Emissions

Wind generation has attracted subsidies in large part because it is a "green" energy source. Wind turbines produce none of the environmentally damaging emissions, such as sulfur dioxide (SO_2), carbon dioxide (CO_2), and nitrogen oxides (NO_x), typically associated with electricity production[7]. Carbon dioxide emissions in particular are a source of increasing concern due to the role they play in global climate change.

When wind power is introduced into the electricity grid, every MWh of electricity produced by wind turbines "offsets" pollution that otherwise would have been

5 Since renewal has always included a retroactive extension, there has technically been no gap in the coverage of the PTC. However, investors still risked the possibility of no renewal or a non-retroactive renewal. This uncertainty has led 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 installations or higher installation costs for wind farms (AWEA 2008).

6 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 without the federal production tax credit. Together, though, they have been an effective tool in promoting wind energy

7 Although wind power is "green" in the traditional sense, wind farms do create their own negative externalities. Wind farms are often opposed because of the the aesthetic damage they inflict on the landscape or because of noise "pollution"(Ladenburg and Dubgaard 2007). In addition, turbines may disrupt or kill birds or bats in the area (Baerwald et al. 2008; Smallwood and Karas 2009). This paper will not attempt to create a comprehensive cost-benefit analysis, but rather will measure benefits from the emissions offset by wind farms.

emitted by a conventional, fossil fuel generator[8]. The type and quantity of pollution offsets depend crucially on the specific fossil fuel generator whose production is offset. Emissions per MWh of electricity produced vary greatly between electricity generators due to differing fuel types, generator efficiencies, and installed abatement technologies. For example, an older generation 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). Thus identifying the generating substitutes of wind power is of first order importance in determining the extent of the environmental impact.

The prior literature has approached the measuring offsets in one of two ways. Studies typically use either a static, marginal cost model or a full-information grid engineering model. Static marginal cost models, such as Newcomer, et. al. (2008), order generators in a production stack, from lowest to highest marginal cost. Wind power is then assumed to offset production only from the highest marginal cost generator on the grid at any point in time. Engineering models deploy full-information, dynamic optimization algorithms to minimize electricity production costs under perfect foresight[9]. This approach, while more sophisticated than the marginal cost approach, requires a wealth of proprietary data on generators and transmission lines which would be unlikely to be available to any entity but the grid operator. Neither model uses observed operating behavior to identify offsets.

8 I use the term "offset" to mean the emissions that would have been produced by conventional generators to replace the electricity produced by wind generators. It does not take into account any potential demand response to electricity price changes induced by wind power production.

9 For example, one study conducted by GE Energy for the New York State Energy Research and Development Authority, simulated the introduction of 3,300 MWh wind capacity (10% of total capacity) into the system (GE 2005). Using load and wind profiles from 2000-2001, researchers projected load, wind power, and conventional generation for the year 2008, using GE's 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, but they also were able to calculate emissions changes due to wind power.

In this paper, I introduce an alternative approach for identifying generating substitutes for wind power. Rather than using an engineering or marginal cost stack approach which *calculates* emission offsets given a set of parameters, I use an econometric approach to *estimate* the emissions offset by wind power from observed output decisions. This econometric model exploits random and exogenous changes in the output of wind farms to identify the generating substitutes of wind power from observed, rather than simulated, behavior in such a way that allows for a high degree of heterogeneity among generators. I use a flexible, reduced form model which respects the dynamic constraints of generators, incorporates firms' reactions to uncertainty, and admits market power which may exist in certain states of the market. It does not require proprietary data on generators, but relies only on publicly available generator output and characteristics.

This econometric approach is not without its own drawbacks though. First, since it requires observed behavior, a significant portion of wind power production must exist on a grid in order to estimate its effects. This rules out prospective studies on impact of new wind power capacity on grids where none currently exists, as is common in the engineering literature. Second, since the current approach uses a reduced form model rather than a structural approach, it is not useful for predicting outcomes that are far out of sample. For instance, it might not produce accurate predictions of offset emissions if the amount of installed capacity on the grid were to double from the current observed levels. A full structural model, such as Cullen (2011), or an engineering model would be necessary for simulating outcomes on any grid where installed capacity is significantly different from what is currently observed. Finally, the econometric approach cannot comment on wind-induced reliability, or congestion issues that engineering approaches are geared to address. However, an econometric approach can provide an estimate of the marginal impact of wind power on the production of other generators, based on observed behavior and current market conditions.

This paper is the first of its kind to identify the generating substitutes for wind power using econometric methods. It builds off the author's prior work, Cullen (2008), which also uses an econometric approach to measuring offsets, but in a static, rather than a dynamic, framework. Subsequent works by Kaffine, Mcbee, and Lieskovsky (2011) and Novan (2011), have also employed this approach in examining wind power offsets using other data sources.

This paper is similar in spirit to Holland and Mansur (2008) which investigates how reshaping of the aggregate demand by reducing its variance may affect emissions. Likewise, in this paper, wind farms reshape the residual demand facing individual generators which leads to offset emissions.

After the generating substitutes for wind power are estimated, it is straightforward to calculate emission offsets by wind. The Environmental Protection Agency (EPA) and Energy Information Agency (EIA) collect information on average annual emissions rates for each fossil fuel power plant. For carbon dioxide emissions, more detailed generator level emissions characteristics are available. For a given unit, multiplying the electricity production offset by the emissions rate gives the quantity of emissions offset by wind power[10]. Summing together all the generators on the grid provides an estimate of the total emissions offset by wind power.

10 Real-time hourly emissions are collected by the EPA through Continuous Emissions Monitors Systems (CEMS) on the generator level for many, but not all power generators. An alternative approach would be to analyze the impact of wind power on hourly grid-wide emissions rather than 15 min generator electricity production. This is the approach taken in Kaffine, Mcbee, and Lieskovsky (2011) and Novan (2011). The robustness of the results to using CEMS data, rather than electricity production data, is explored later in the paper.

Wind Production

The exogeneity of wind-generated electricity is an important identifying assumption in this paper and so requires some justification. The output of conventional generators is clearly not exogenous. Most types of generators can adjust their output at will, although the time and cost associated with such adjustments varies. Wind operators, on the other hand, have relatively little control over output since they have no control over their fuel source, the wind. On a calm day, no electricity can be produced. On a windy day, operators can either fully utilize their productive capabilities or curtail their production which is known in the industry as "spilling wind"[11]. Curtailing production, in the absence of transmission constraints, amounts to throwing away free electricity since the marginal cost of fuel is zero and the marginal costs of operation are nearly zero[12].

In fact, nearly all costs associated with wind power production are incurred during the construction and installation phase of a wind farm. A modern 1MWh wind turbine costs roughly $1 million to construct and install. The only marginal costs facing a wind farm are those related to usage induced maintenance. Overall, operating and maintenance costs are very low when compared with fossil fuel or even nuclear plants (Wiser and Barbose 2008). The high fixed-capital costs and the negligible marginal costs of production create incentives for the wind farm

11 Spilling wind is achieved by tilting the blades of the turbine so that some of the wind "spills" over the blades rather than being fully utilized to propel the turbine. Spilling wind also occurs at very high wind speeds. It allows turbines to operate when the total wind energy available is greater than the capacity of the turbine.

12 When curtailment does occur, it is usually in response to transmission congestion. In that case, there is a value to reducing wind power production as it may ease transmission constraints on the system. However, wind curtailment is most likely to occur during peak wind periods when wind power production itself is the source of the congestion. When curtailment occurs due to transmission constraints caused by wind power, the curtailment itself does not introduce endogeneity or bias into the estimates. This can explain why Novan (2011) finds little evidence of endogeneity despite significant curtailment in his sample.

operator to produce as much electricity as possible given the available wind.

Subsidies, which are earned for each MWh of output from the wind farm, further incentivize production. With the addition of federal and state output subsidies, the marginal cost of wind power becomes negative. That is, a wind farm would find it profitable to produce electricity even if wholesale electricity prices were less than zero. For example, with state and federal subsidies at around $30/MWh a wind farm would not voluntarily curtail production unless wholesale electricity prices were less than -$30/MWh. Since such prices are a relatively rare occurrence, wind farms have little incentive to curtail output for economic reasons[13]. Consequently, whenever the wind is blowing, the wind farm will be supplying electricity to the grid[14]. Other generators, which have significant fuel costs, storable fuel, and full control over their output, will reduce output to balance supply and demand on the grid when wind power comes online.

13 Negative wholesale electricity prices occur in 0.19% of periods over the two-year period (2005-2007) of my sample on the grid I am analyzing. Prices below -$30/MWh occur only 0.08% of the time. In addition, there are rare occurrences when wind farms, or conventional generators for that matter, may be required to reduce production, regardless of the price in the market. Generators are sometimes called on to curtail production in emergency situations to ensure the reliability of the grid, or when the generator is causing local transmission congestion patterns that cannot be resolved with price mechanisms. However, like negative prices, these situations do not arise often. It should be noted that as more wind power plants have been built in 2008-2010, ERCOT transmission lines have not been built to accommodate them. Thus negative prices have become a more common in recent years.

14 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).

Although it can be argued that wind power production is exogenous, as output is nearly always determined by the weather, it is not completely random. Wind patterns exhibit systematic seasonal and diurnal fluctuations. For example, on the Texas grid considered in this study, wind power production is high during the winter and spring months and low during the summer and fall. On a daily level, wind power production is higher during the night than during the day. This is illustrated in Figure 3, which plots average hourly demand and average hourly wind power production against each other. Likewise, Figure 4 does the same for average monthly power production. The negative correlation between demand and wind power production is striking and influences the type of generators that will substitute for wind power. In particular, it means that wind power may cut into production from base load generators. On a minute by minute basis, wind power exhibits significant variation around these averages. It is this quasi-experimental variation, driven by weather fluctuations, that can be used for identifying generating substitutes for wind power in the model. [INSERT FIGURE 3 AND 4]

Data

For the econometric analysis, I focus on a grid managed by the Electricity Reliability Council of Texas (ERCOT) which serves the majority of the state of Texas. The period of my analysis starts in April of 2005 and continues through April of 2007.

I chose this electric grid for several 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 grid. The market share of electricity generated by wind, at any point in time, ranges from 0% to 10% of total electricity consumed. Second, this grid is relatively isolated from other grids in the U.S.. The ERCOT grid is also its own interconnection, meaning that it is not synchronously connected to other grids in the U.S.[15]. Less than 1% of daily generation is exchanged with other grids. This means that wind generation in Texas directly displaces other generators on the same grid. This allows me to restrict my analysis to Texas and not model the national grid.

Third, Texas was the largest producer of wind power in the U.S. during this time period. In mid 2007, 27% of all wind power capacity in the U.S. was located in Texas, with 3,352 installed MW of capacity (AWEA 2008). Almost all of Texas' capacity was built after the federal production tax credit was instituted. California had the second largest installed capacity of wind power in 2007, with 2,376 MW, but most of the capacity was installed before the federal PTC was instituted[16]. Thus, wind power in Texas represents 32% percent of new wind power facilities built from 1999-2007 under the PTC[17] (EIA 2010). Measuring offset emissions on the Texas grid represents a significant proportion of total offsets the program may have achieved.

The data were provided by the ERCOT, which oversees the Texas grid. In the data, I observe the electrical output from each generating unit every 15 minutes, over the two year sample. For conventional generators, a generating unit is a single turbine; a power plant typically hosts several turbines. For wind farms, I

15 The fact of ERCOT is also an interconnection is quite unique. The Texas Interconnection is one of only three interconnections in the U.S.. The other interconnections (the East and West Interconnections) are much larger than the Texas Interconnection and are comprised of many different grids, each managed by separate system operators.

16 Texas and California together accounted for 45% of installed wind capacity in the US in 2007.

17 The next highest contributor to net wind capacity levels over this period was Iowa which contributed 8%.

observe the output of an entire wind farm which is the collection of many small turbines. Thus, for a unit that is connected to the grid for the entire sample period, I observe 70,080 output decisions. I also observe the flows of electricity over connection lines to neighboring grids, again in 15-minute intervals.

In addition to output, I know certain characteristics of each unit including fuel type, location, year online, capacity, and owner. In total, there are approximately 540 units, at 220 plants, which supply electricity to the grid managed by ERCOT.

In 2007, there were approximately 80 different firms operating the power plants which supply electricity to the Texas grid[18]. Combined, these generators were capable of producing over 75,000 MW of electricity, at any one time. Generation technology includes coal, nuclear, and natural gas with small amounts of hydro, landfill gas, and various fossil fuel burning generators. Table 1 shows the capacity by year, fuel type, and technology. [INSERT TABLE 1]

Emissions data comes from the EPA's eGRID 2004 program with addition information on generator heat rates coming from the EIA and private sources. The EPA provides annual average emissions rates for SO_2, and NO_x for each plant in terms of mass per MWh of electricity produced[19]. For CO_2 emissions, I use generator level heat rate information which gives the amount of fuel need to generate a MWh of electricity. Together with the CO_2 content of fuels this provides a CO_2 emissions rate for the generator.

I also obtained hourly temperature data from the National Weather Service for the

18 There are additional firms which provide electricity on private networks, but which do not provide electricity to the grid controlled by ERCOT.

19 Although the EPA data only provides emissions rates at the plant level, this will only be a problem if units at the same facility have very different emissions rates of SO_2 and NO_x. Since the turbines at a power plant are typically constructed with the same emissions technology, the plant emissions rate is a reasonable approximation of unit level emissions of SO_2 and NO_x.

time of the data sample. I constructed average temperature data for each hour from weather stations in or near major centers of electricity demand.

The analysis will be conducted at the turbine level with the exception of combined cycle generators. Additionally, a number of generators were excluded because they never produced electricity over the sample period. In all 332 individual unit are included in the analysis. Collectively, they account for more than 99% of both capacity and production in ERCOT[20].

Estimation

The estimation approach used in this paper exploits the randomness and exogeneity of wind patterns to identify the average reduction in output for each generator on the grid due to wind power production. However, as previously highlighted, the diurnal and seasonal patterns of wind are not uncorrelated with other incentives for production by conventional generators. In this model, I will need to control for factors that affect a conventional producer's decision to generate electricity, which may also be correlated with wind power production. In

20 I aggregate the output of combined cycle gas generators to the plant level. Combined cycle gas technology is unique in that it utilizes multi-stage turbines to achieve higher efficiencies. The plants utilize waste heat from first-stage combustion turbines to drive second-stage steam turbines. Due to the complementarities between turbines at the same plant, the relevant output decision is made on the plant level rather than on the generator level. Thus, for combined cycle power plants in my sample, I aggregate the output of the individual turbines to the plant level. After aggregation, the 543 turbines I observe in the data collapse to 387 generating units.
For the analysis, I drop generators that appear infrequently in the data. First, I exclude 39 generators that appear in the sample, but never actually generate electricity. Second, I drop 15 generators that produce for fewer than five hours over the 2 year sample period . These generators don't play an economically significant role, relative to wind power. Finally, I exclude from the analysis one additional generator that appears in the data for fewer than 30 days. Since this generator exits soon after the beginning of my sample it is econometrically difficult to estimate the necessary model parameters with less than 30 days of data. In total, 55 generators are excluded from the sample. The remaining 332 generators are left as potential substitutes for wind power.

particular, one needs to account not only for static, but also for dynamic factors in the generators production decision.

The conventional producer's operation decision is a complicated one. The operating decision is inherently dynamic due to costs associated with startup, shut down, and ramping up and down production (Cullen 2011). The dynamics imply that the estimating equation will need to not only control for contemporaneous variables, but also for elements of the information set which the firm considers when adjusting its optimal bidding function and energy schedule two hours prior to production[21]. Thus the estimating equation will contain lagged information on the state of the market both because of firms' strategies are set two hours prior to production and also to account for firms' expectations in the dynamic framework. The final estimation equation will be akin to estimating the optimal policy function coming from the dynamic programming problem for each of the generators, in reduced form[22].

The estimation procedure will be performed separately with each generator on the grid to allow for complete flexibility across generator characteristics[23]. For each generator, i , I estimate the following production equation and do not place any

21 For details on the institutions of the market see Appendix A.

22 The actual optimal policy function will not be estimated, since the true policy function for a firm maps the information set of the generator into a optimal schedule and bidding function rather than into output. Instead, this paper will estimate a reduced form function that maps the firm's information set onto the realized output of the generator, given its optimal policy. A generator's realized output results from the combination the following factors: (1) its own optimal policies, which it sets at two hours prior to actual production, (2) the policies of other firms, and (3) the realized levels of demand and wind power in the actual production period.

23 The wide variety of generator technologies and vintages imply generators face vastly different cost structures and production incentives. Marginal costs and dynamic constraints, such as startup costs and ramping rates, can vary by orders of magnitude across generators. In addition, two technologically identical generators may respond differently to wind power production because of their geographic location on the grid or because of their ownership structure, which will influence their incentives to respond to price changes induced by exogenous wind power production.

cross equation restrictions on the estimation method. Realized output is modeled as a function of wind power and associated controls:

(1) $$q_{it} = \beta_{i0} + \beta_{i1} Wind_t + \beta_{i2} Wind_t^2 + \boldsymbol{Z}_t \boldsymbol{\gamma}_i + \boldsymbol{V}_t \boldsymbol{\omega}_i + \boldsymbol{D}_t \boldsymbol{\alpha}_i + \epsilon_{it}$$

where q_{it} is the observed quantity of electricity produced by generator i in each 15 min time period t, $Wind_t$ is the amount of wind power produced, $\boldsymbol{Z}_t$ are contemporaneous variables, $\boldsymbol{V}_t$ are lagged control variables, and $\boldsymbol{D}_t$ are date dummies[24].

Contemporaneous controls include aggregate demand, temperature, and a dummy, indicating if key transmission lines are congested. Demand in uncharacteristically included as an explanatory variable since demand in this market is not responsive to wholesale electricity prices, but driven by exogenous variables such as weather, day of week, and time of day[25]. Temperature is included separately, due to its direct effect on generator efficiency; higher outside temperatures reduce the efficiency of the thermodynamic cycle used to drive turbines and lower a generator's effective capacity.

Lagged controls are included to capture the dynamics of generator operation. These include lagged demand, wind power, temperature, and congestion for each 15 min period, starting two hours before production extending back to 25-hours prior to the production period. To capture dynamic constraints, I also include the operating state for the generator, two hours prior to production[26]. To capture

24 Note that the control variables are indexed by t and not by i . That is, I am assuming that firms responding to common market factors in each period. Since the explanatory variables are common across the estimating equations there is no efficiency advantage to using seemingly unrelated regression techniques.

25 See Appendix A for details on demand as an exogenous control.

26 A generator which is not operating will incur startup costs if it called upon to produce electricity during the production period. Because of this, a generator idle two hours before production starts, is less likely to operate during the production period.

potential strategic interactions, the operating state of all the other generators on the grid are included for the same time period[27].

Finally, dummies are included for daily variables which would affect deployment and operation decisions. Some of these variables are potentially observable such as daily spot prices for natural gas, a generator's outage status, or the outage status of competing generators. Others are not observable, such as firms' forward contract positions or changes in the price of consumers contracts for retail power. Including, day by year dummies (i.e. date dummies) controls for both observable and unobservable factors that vary by day. The remaining within-day variation of wind power will be used to identify generating substitutes[28].

The functional form used in estimation is a simple linear function with quadratic expansion of each control variable to allow for non-linearities inherent in the underlying dynamic model.

In all, the estimation equation will include contemporaneous wind power production , 4 contemporaneous controls (7 including quadratic expansion terms), 92 lagged controls (161 including quadratic expansion terms), 332 dummies for the lagged operating state of generators, and 730 date dummies. This set of variables (see Table 2), while not entirely exhaustive, provides a rich set of controls for incentives that a generator may face which may also be correlated with wind power production. [INSERT TABLE 2]

27 The operating state of each rival generator can provide information about the potential profitability for operating in the production period.

28 There is some concern that the date dummies may sweep out important identifying variation in wind power across days which might impact the estimates. As an alternative to including date dummies, I run an alternate specification that controls explicitly for the observable factors of fuel prices and generator outages and also includes month by year dummies to control in part for unobservables. The general results coming from the alternative model are nearly indistinguishable from the current model.

The motivation for including such an extensive set of lagged controls is to control for dynamic constraints and firms' expectations. I assume that firms use the lagged values of demand, wind, and temperature observed over the previous 25-hours, to create their forecasts and future operating plans when submitting their bids to the system operator two hours prior to production. To highlight the importance of dynamics in this setting, I also estimate the static version of the model which excludes the lagged controls $\boldsymbol{V}_t$.

Although we would expect the sum of the marginal impacts to be approximately one, I do not impose constraints which would require 1 MWh of wind power to offset 1 MWh of conventional generation. Since wind power is not produced near demand centers, it could be that the offsets are less than one-to-one due to transmission line losses.

Results

Using the estimated coefficients from each regression, marginal substitution parameters for wind power can be calculated for each generator. Importantly, an increase in wind power in time *t* will not only have a contemporaneous effect, as in the static model, but will also affect production in later periods through the lagged components in the model. To avoid working with an unwieldy number of lagged coefficients when calculating the total marginal effect, I subtract the current wind power production from each of the wind lags. This transformation embeds the total impact of current and lagged wind power into the coefficients on $Wind_t$. The total marginal effect of wind power on the production of generator *i* is then:

(2) $$\frac{\partial q_{it}}{\partial Wind_t} = \beta_{i1} + 2\, Wind_t \beta_{i2}$$

The marginal effect is then evaluated at the average level of wind or equivalently the per period marginal effects are averaged over the sample. Standard errors for each regression are calculated using the Newey-West method with four lags to account for arbitrary heteroskedasticity and serial correlation in the errors (Newey and West 1987). When aggregating the coefficients across generators, contemporaneous cross-equation covariances of the parameter estimates are also taken into account.

The estimated marginal impact of wind power on electricity generation for both the static and dynamic models is shown by fuel type in Table 3[29]. When dynamics are not taken into account, gas accounts for 0.85 MWhs reduction for each MWh of wind, but somewhat surprisingly coal production accounts for 0.18 MWh of production offsets from wind. Other forms of energy production in Texas exhibit economically insignificant reductions. Imports of electricity, whose emissions characteristics cannot be accounted for, experience an increase due to wind. However, when dynamic controls are introduced into the model, the picture changes significantly. Coal offsets drop from 18% to almost zero. The share of offsets attributable to gas increases significantly to 92% of production offsets. Additionally, the offsets within gas technology shifts significantly. Estimated offsets move from relatively clean, cheap combined-cycle generators to more expensive and less efficient steam and gas turbine generators when dynamics are introduced. Imports also decrease, accounting for 7% of marginal offsets. Total

29 Given the large number of generators and estimate parameters, the marginal impacts of wind power are presented here at an aggregated level due to space constraints.

reductions in conventionally generated electricity are very slightly more than one MWh for each MWh of wind, but are not statistically differentiable from a one to one tradeoff. [INSERT TABLE 3]

If extrapolated using total wind power production, marginal offsets in production would represent a significant reduction in production from gas technologies and imports. Although combined cycle gas generators account for the majority of the offsets among gas technologies, their reduction in production would be the smallest as percentage of output (-2.7%) . Wind power would reduce output by a larger percentage in both combustion turbine (-9.1%) and gas steam (-4.7%) technologies. Imports would experience the large decrease on a percentage basis with a 13% decrease in the total quantity imported.

Emissions offset by wind power vary considerably between the static and dynamic models as shown in table 4. Carbon dioxide offsets are estimated to be 947 lbs per MWh of wind in the dynamic model. This is 31% lower than what is implied by the static model and significantly less than the grid's average emissions rate of 1470 lbs/MWh. This is mostly due to the fact that dirty coal generators have negligible estimated offsets once we account for dynamics[30]. Offsets of SO_2 offsets are essentially zero at a statistically insignificant 0.16 lbs per MWh wind, which is one tenth of what the static model would imply. Again this is due to the fact that coal combustion produces most of the SO_2 emissions on the grid. Offsets of NO_x are 0.83 lbs per MWh which is similar to 0.91 lbs estimated in the static model. This grid-wide offset profile will be used in the next section when calculating the value of emissions offset by wind power.

30 Imports also play a role in the difference between the models, but are difficult to quantify. If we assume that imports to have the same emissions offset profile as estimated by each model, then the estimated CO_2 offsets would increase by 70 lbs per MWH in the dynamic case and decrease by 20 lbs in the static case. This would reduce the difference between the models to 18%

[INSERT TABLE 4]

If the point estimates of the marginal offsets are applied to total wind production over the sample period, they imply that approximately 900 tons of SO_2, 5,000 tons of NO_x, and over 5 million tons CO_2 were offset by wind power production from 2005-2007 as shown in Table 5. While wind power accounted for approximately 2% of total electricity production, the emissions offset by wind represent significantly less than 2% of the total emissions over the period.

[INSERT TABLE 5]

A Robustness

There is some concern that applying average emission rates to offset production estimates may not give an accurate estimate of offset emissions. A generator's emission rate, although relatively constant for most technologies, can vary as a function of output level of the plant. Generators generally operate most efficiently when operating steadily near maximum capacity; operating at partial capacity may increase emission rates. Emission rates can also change during ramping. Periods when a generator is ramping up will have higher than average emission rates. Likewise, emission rates drop when a generator is ramping down, though the effect is not necessarily symmetric. This emission "bias" is documented in the engineering literature. Katzenstein and Apt (2009) measure the effect of the output level and ramping on emissions for two types of natural gas generators. From an engineering standpoint, they show that actual emission offsets from wind power may be 20%-50% lower than those implied when using average emission rates. This bias is increasing in the level of penetration of wind power as hypothetical gas generators are forced to operate at lower and lower capacity levels and incur more ramping.

In practice, this bias may be mitigated in the market as the reduction in production may be shared across many facilities which may incur smaller changes in emission due to ramping and reduced efficiency. As a robustness check, I estimate the same model with hourly emissions data from the EPA's Continuous Emissions Monitoring System(CEMS) as the dependent variable. Using CEMS data may be able to account for the changes in the emissions rate due to efficiency changes, though it may exacerbate ramping effects[31].

Not all generators on the grid are part of CEMS which limits the number of generators which can be included in the analysis. Generators which are under 25MW in size or emit SO_2 at low rates are not required to participate. In addition, generators which were part of a combined heat and power plants were excluded from the analysis as CEMS does not differentiate between emissions associated with electricity production and emissions associated with providing steam heat. In total 118 generators out of the 332 candidates were included in the CEMS analysis. These 118 generators represent 66% of production and 62% of capacity in ERCOT.

The results show that for the subset of generators with CEMS measurements, the estimated offsets from wind power were 4% lower for CO_2 when using CEMS data. The estimated offsets for SO_2 were negligible using either dataset. In both cases, the difference between the estimated offsets across datasets were statistically insignificant. Offsets of NO_x did differ significantly across datasets with -0.69 lbs/MWh using production data, but only -0.21 lbs/MWh using CEMS data. This exercise demonstrates that the results are relatively robust to different methods of estimating the marginal impacts for CO_2 and SO_2, though the two

31 If generators ramping up to cover for decreasing wind production exhibit significantly increased emission rates, then CEMS data may overstate emission offsets.

data sources do not agree on the marginal offsets of NO_x emissions[32].

B Valuing Offset Emissions

Given the estimates of emissions offsets by wind, we can now value the offsets. Valuing the offsets allows us to compare the environmental benefits of the subsidy program to the costs of subsidizing wind-generated power production.When valuing offsets we need to consider two important factors: 1) the regulated status of the pollutant, and 2) its marginal damage cost.

First, if a pollutant is already subject to optimal regulation, then offsets yield no additional value. In addition, for emissions regulated under a binding cap-and-trade program, offset emissions do not imply a reduction in total emissions regardless of the optimality of the regulation. Emissions offset at one facility result in pollution permits being freed up for use elsewhere. For this reason, pollutants regulated under cap-and-trade systems, such as SO_2 and NO_x, offsets may not have environmental benefits[33]. Offsets will still imply that the industry reduces costly abatement which may affect the price of permits and thus the

32 Applying the *static* model to CEMS and production data gives estimates that are nearly identical. Offsets of within CO_2, SO_2, and NO_x are respectively within 5%, 1% and 3% of each other and are statistically indistinguishable.
Both methods estimate the average reduction in production from an additional unit of wind. I do not attempt to disentangle how the variability of wind power affects the emissions offset. Rather, I estimate the observed substitution patterns given the observed level of variability in wind power production. Presumably, more variable wind power could mean more substitution to relatively flexible types of gas generators such as gas turbines or combined cycle. Those question are left for further research.

33 If the caps are not binding, then offsets would represent a real reduction in pollutants. Likewise, pollutants regulated under a pollution tax or an emission rate regulation would experience a real reduction in emissions. If the tax or rate regulation were not sufficiently stringent, implying that an externality still existed, then offset emissions would have direct benefits to society.
Additionally even though aggregate emissions may not change, the timing or location of the emissions may shift. The shifting of the distribution of pollutants may be welfare-enhancing or reducing, but is beyond the scope of the paper.

profits of firms, but this secondary effect is beyond the scope of this paper.

Second, marginal damage costs must be estimated in order to value offsets for unregulated pollutants. Although marginal damage costs may vary over time and space, I use a single estimate of the average marginal damage costs to value emissions for each pollutant. Using a uniform value for offset emissions is well-suited for valuing CO_2, though it may not capture the true marginal damage costs of SO_2 or NO_x due to spatial and temporal impacts[34].

A large body of literature exists on the estimated damages of CO_2 emissions. Tol (2005) reviews the literature, which estimates the social costs of CO_2 , 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 , as found in papers published in peer-reviewed journals, was $14 /ton (Tol 2005).

More recently, the U.S. Government has compiled estimates on the social cost of carbon for use in regulatory analyses. The Interagency Working Group On Social Cost Of Carbon compiled the report which estimates the monetized damages associated with an incremental increase in carbon emissions in a given year. The group selected four values which are based on a collection of integrated assessment models, at different discount rates. The values for the social cost of carbon produced by the report were $5, $21, and $35, per ton of CO_2 for the year of 2010, with $21 being the "central" value. The fourth value, of $65/ ton CO_2,

34 Carbon dioxide emissions are an example of a uniformly mixed pollutant. They have no direct effects on human health, but do gradually collect in the atmosphere which may lead to climate change. For this reason, the marginal damage costs of CO_2 emissions are not sensitive to precisely when or where carbon dioxide is emitted in the world. Sulfur dioxide on the other hand has relatively localized and direct impacts(EPA 1998). For this reason, the distribution of emissions, as well as total quantity of emissions, is an important determinant of marginal damage costs of SO_2. This is even more pronounced for NO_x which ,in addition to being localized geographically, has damages that depend crucially on the season in which NO_x is emitted(EPA 1997).

was included to “represent higher-than-expected impacts” from climate change (United States 2010).

For SO_2 and NO_x, selecting the appropriate measure for the value of offset emissions is more nuanced. In most areas in Texas, NO_x emissions are not regulated or the caps on aggregate emissions are not binding. This implies that offsets will result in emissions reductions. One exception to this is that generators inside of the Houston-Galveston-Brazoria (HGB) area are subject to binding cap-and-trade regulation on NO_x emissions. (Texas Commission on Environmental Quality 2011). Since generators in the HGB area will not reduce aggregate NO_x emissions, I exclude those generators from the analysis[35].

Unlike NO_x, emissions of SO_2 are regulated at every power plant. This, and the fact that there are negligible estimated offsets, implies that no benefits will accrue from SO_2 offsets in Texas.

For the value of offset NO_x, we can look at two sources. First the price of NO_x permits in other regions may serve as a proxy for marginal damage costs. However, given that regulations are likely to be implemented in areas of high damage costs, these figures may overstate the value of offset NO_x in Texas. Instead I use estimates from Muller and Mendelsohn (2011), which use a integrated assessment model to calculate spatially differentiated marginal damage costs. In Texas, the estimated costs are in the range of \$100-\$2000/ton of NO_x.
[INSERT TABLE 6]

Using a range of values for marginal damage costs in table 6, it is immediately apparent that the value of offsets are driven by the benefits of CO_2 reductions. As shown in Table 7, the value of emissions offset by wind power ranges from less

35 This has the effect of reducing estimated Nox offsets from -0.83 lbs/MWh to -0.74lbs/MWh.

than $3/MWh in the low value scenario to less than $10/MWh for middle-range estimates to a little more than $17/MWh for the higher end of marginal damage costs. [INSERT TABLE 7]

The value of offset emissions can now be compared per MWh cost of wind subsidies. As previously discussed, wind farms receive federal PTC subsidies of $20 MWh for the first 10 years of operation. In addition to Federal subsidies, wind farms receive a renewable energy credit from the state of Texas, under the Renewable Portfolio Standard, for each MWh of power produced. The market value of these credits varies around $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 benefits expire and continue to receive a state subsidy, the discounted cost of the subsidy is $20/MWh over the life of the wind farm[36], given that the subsidies and value of emissions have the same discount rate[37].

Under the assumption that no wind capacity would be installed without state and

36 The life of the wind farm is assumed to be 20 years. It also is assumed that any change in operating efficiency over the life of the wind farm is negligible.

37 The same discount factor is used for the stream of subsidies and the stream of environmental benefits over the 20 year life of the wind farm. As such, the choice of discount factor is irrelevant for value state subsidies which accrue over the entire life of the wind farm. However, since Federal subsidies are front loaded onto the first 10 years of wind farm operation, the choice of discount factor does affect the average cost of subsidy per MWH of wind output over the life of the wind farm. If the cost of borrowing for the federal subsidy is between 1 and 5 percent, then the average cost/MWH is between $10.50 and $12.51 as opposed to $10 when ignoring the effect of the discount rate. However, if the wind farm lasts for 25 years rather than 20 years, the average cost of the federal subsidy can easily drop below $10. For expositional purposes, I will use $10 as the cost of the federal subsidy.

federal subsidies, the emissions benefits of wind power fail to exceed the $20/MWh subsidy even for higher estimates of marginal damage costs. The social cost of carbon would have to be greater than $42 for the benefits of the subsidy to outweigh its costs based on carbon offsets alone. Note that even then this result does not imply that wind power would be the lowest cost method of reducing CO_2 emissions; it is almost certainly not[38]. However, we can say that the cost subsidizing wind would be justified by the potential benefit of avoided emissions only for significant marginal damage costs of CO_2.

It is worth reiterating at this point that this is not a comprehensive cost/benefit analysis of wind power. The implicit costs of wind power, such as the impact on grid reliability due to wind intermittency or aesthetic damage to the landscape, have not been explored. Likewise, wind power may procure other benefits, such as reduced mercury emissions or particulates, which have not been explored due to data constraints.

While I propose one set of values for assessing emissions, many others could be used to appraise offsets. The primary contribution of this paper is identifying the generating substitutes for wind power. Given the estimated emissions offsets, the value per MWh of wind power can be calculated for any proposed value of offset emissions.

C National Implications

While the numerical results of this paper are specific to the Texas grid, they do provide some guidance on the expected environmental returns to wind power

38 For a detailed discussion of the justifications for wind power subsidies, I refer the reader to the excellent exposition of the topic in Schmalensee (2011).

subsidization elsewhere in the U.S.

First, note that certain types of generators are highly unlikely to have their production crowded out by wind power. Both nuclear and aggregate hydropower production will be largely unaffected by the roll out of wind farms[39]. With these facilities out of the picture, fossil fuel based generators will be the ultimate substitutes for wind power. The resource mix of fossil based generators in Texas provides a way to use the results of this paper as a natural bound to expected emission offsets from wind power in other areas of the US.

Texas has a relatively clean fossil energy portfolio compared to the rest of the US. This can be seen by examining the characteristics of fossil fuel generators in NERC electricity-generating regions across the US as shown in Table 8. Notice that nearly 80% of fossil fuel capacity in Texas (TRE) is gas fired. Texas has a higher share of gas capacity than any other area in the US. Gas generators are relatively clean, producing on average half the CO_2 emission per MWh of coal plants and fifty percent less CO_2 than oil generators. Outside of the Northeast area, Texas also has the highest share of electricity generated by natural gas.
[INSERT TABLE 8]

The environmental offsets estimated in this paper are the result of wind power crowding out production on one of the cleanest fossil fuel portfolios in the nation. Wind power installed in other areas will be competing in a market with a higher

39 Like wind, nuclear and hydropower costs of production are primarily sunk with very low marginal costs of operation. In addition to the economic factors, nuclear power has high technological adjustment costs that make it an unlikely substitute. Hydropower, on the other hand, can be quite flexible in its adjustments of production. Although it may complement wind power production in the very short run, it will not likely reduce overall production in the medium term due to storage constraints and its low costs of production. That is, hydro facilities may accommodate wind shift production within a day, across days or even across months. However, for both economic and environmental reason, hydro facilities are unlikely to spill water over dams without generating electricity.

density of dirtier fossil fuel generators and more limited access to gas capacity. The results from Texas then can be expected to stand for a lower bound on the emissions offsets to be expected in other areas of the US.

D Long-run Implications

The results of this paper are estimated using high frequency data. As such, they reflect the short-run substitution patterns between wind farms and conventional generators. It reflects a scenario where, due to renewable energy subsidization, wind power enters a grid with existing infrastructure and crowds out production from existing generators.

While interesting in its own right, we would also like to learn about the likely emissions offsets of wind power as it grows in its capacity share over a long time horizon. In the long run, not only will existing generators change their production patterns, but an increasing market share of wind farms will also trigger complementary investment in conventional generators. For example, fast reacting gas turbines may be installed to mitigate the intermittent nature of wind power production. Thus some of the emissions offsets in the long run will be due to changes in the operation of installed generators while another component will be due to wind induced changes in investment.

While a full counterfactual analysis of investment trajectories with and without wind power is outside of the scope of this paper, evidence suggests that long run investment changes induced by wind power will have emissions benefits greater than that of short run offsets found in Texas. In a structural model of electricity production, Cullen (2011) finds that meeting new demand with new wind capacity reduces the profitability of coal plants while increasing the profitability of gas fired power plants. On the margin, wind farms combined with gas investment would crowd out investment that otherwise may have been made in coal plants. Given time to adjust, investment dollars are likely to move into gas generation and out of coal generation. Thus, the measurements of short run emissions offsets are likely to underestimate the long run emissions benefits of wind farms[40].

Conclusion

Renewable energy subsidies have been a politically popular program over the past decade. These subsidies have led to explosive growth in wind power installations across the US, especially in the Midwest and Texas. Renewable subsidies are largely motivated by their environmental benefits as they do not emit CO_2, NO_x, SO_2, or other pollutants which are produced by fossil fuel generators. Given the lack of a national climate legislation, renewable energy subsidies are likely to be continued to be used as one of the major policy instruments for mitigating carbon dioxide emissions in the near future. As such, a better understanding of the impact of subsidization on emissions is imperative. This paper introduces an approach to directly measure the impact of wind power on emissions using observed generating behavior.

The quantity of pollutants offset by wind power depends crucially on which generators reduce production when wind power comes online. By exploiting the quasi-experimental variation in wind power production driven by weather fluctuations, it is possible to identify generator specific production offsets due to

40 The long run emission offsets of wind farms depend critically on the counterfactual investment technology without wind. For example, Campbell (2009) uses a simple theoretical model to illustrate that wind farms could increase carbon dioxide emissions if wind and inefficient simple cycle gas generators replace investment in efficient combined cycle generators. Identifying the long run substitutes of wind is an important question and is left for future research.

wind power. Importantly, dynamics play a critical role in the estimation procedure. Failing to account for dynamics in generator operations leads to overly optimistic estimates of emission offsets. Although a static model would indicate that wind has a significant impact on the operation of coal generators, the results from a dynamic model show that wind power only crowds out electricity production fueled by natural gas.

The model was used to estimate wind power offsets for generators on the Texas electricity grid. The results showed that one MWh of wind power production offsets less than half a ton of CO_2, almost one lb of NO_x, and no discernible amount of SO_2. As a benchmark for the economic benefits of renewable subsidies, I compared the value of offset emissions to the cost of subsidizing wind farms for a range of possible emission values. I found that the value of subsidizing wind power is driven primarily by CO_2 offsets, but that the social costs of CO_2, would have to be greater than $42/ton in order for the environmental benefits of wind power to have outweighed the costs of subsidies.

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E Appendix A: Market Institutions

F ERCOT Introduction

The ERCOT grid operates as a quasi-deregulated electricity market which serves most of the state of Texas. It operates almost independently of other power grids with very few connections to outside markets. Electricity generation and retailing are deregulated while the transmission and distribution of energy remains regulated to ensure that competitors in the generation and retailing markets have open access to buy and sell power. Unlike many regulated and even deregulated markets, companies in this market are vertically separated. There are no vertically integrated firms that control generating, transmitting, and retailing resources.

G Power System Basics

An electric system is physically composed of three main parts: 1) facilities which generate electricity, 2) a transmission system to transport the power, and 3) end-users which draw power from the transmission grid. Markets for electricity are a bit unusual in that the production, transmission and consumption of electricity occur at almost the same instant. It is important for the injection of electricity into the grid by generators, and the withdrawal of power by consumers, to be nearly perfectly balanced at every point in time[41]. An imbalance in the production and consumption of electricity leads to changes in voltage on the power grid, with adverse consequences. For example, consuming more energy than is generated leads to dropping electrical voltage, which results in brownouts and in some cases

41 Small amounts of electricity storage capacity exist on some grids, but there are no electricity storage facilities on the ERCOT grid.

leads to blackouts. Excess production, on the other hand, leads to voltage spikes, which can damage electrical equipment. Balancing the supply and demand for electricity is one of the key challenges electricity markets face on a daily basis. Accommodating the exogenous production of wind power requires other generators to adjust their production accordingly.

H Consumer Demand

The sale of electricity to end-users is deregulated in Texas. Multiple retailers compete to sell electricity to the same consumers at a given location. For example, a resident in Houston may have three different electricity providers to choose from, each offering several electricity purchase plans. The plans vary in their price level, price variability, contract length and brand name.

As in most electricity markets, consumers in ERCOT do not respond directly to wholesale price signals. Residential and commercial users purchase electricity at fixed prices which are constant for a period of time, ranging from one month to several years. As such, users have no incentive to reduce consumption when wholesale prices increase during peak daily, or even seasonal, demand periods[42]

For periods where consumers face a constant price for electricity, swings in

42 Some large industrial consumers do curtail electricity use when reserve capacity becomes short but they do not directly respond to fluctuations in the price of electricity in the wholesale market. These 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. 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 . Again, it is important to note that LaaRs respond to events that threaten the reliability of the grid, not to price changes in the wholesale market. Conversations with ERCOT indicated that such circumstances occur infrequently, perhaps several times a year. It is possible that industrial users could respond to price changes in the wholesale market through conditions in bilateral contracts with generators. However, I have not found any evidence to substantiate this.

demand for electricity are driven by exogenous forces, such as temperature variation and diurnal patterns of human activity, which are not influenced by prices in the wholesale markets. For example, energy usage will be higher on a hotter day than a cooler one. Likewise, energy consumption will be higher during the day than during the night, even for the same temperature range.

This means that, conditional on a constant pricing mechanism, demand can be treated as function of exogenous variables.

(A1) $$Demand_t = D(Z_t \mid price)$$

For example, if consumers have contracts for electricity which allow prices they face to vary on a monthly basis, electricity demand variations within a given month will be exogenous. Over a longer period of time, as prices in the wholesale markets change, prices facing consumers will also change and demand will respond accordingly. Over the period of my analysis, I do observed pricing plans in which rates could change on a monthly basis. I do not observe pricing plans that varied on the daily or hourly level, implying that, at least within a month, demand variations for electricity will be exogenous.

I Firm Production

The structure institutions of the wholesale market reveal the incentives underlying production for conventional generators and will motivate the model in the next section. On the ERCOT grid, incentives to generate electricity are driven by wholesale prices for electricity. Firms producing electricity generate revenue in one of two ways. Either they sell power through bilateral contracts or they sell their power and capacity in markets administered by ERCOT. The larger of these two, in terms of electricity sales, is the bilateral market where almost 95% of power generated for the grid is transacted. The primary purpose of the markets administered by ERCOT is to ensure the reliability of the grid. The largest of the ERCOT administered markets is the Balancing Market, a real-time auction that which helps to balance supply and demand. The Balancing Market accounts for almost 5% of electricity sales.

To ensure that there is sufficient supply of electricity to satisfy demand, ERCOT requires generators to submit information about their willingness and intention to supply electricity in the form of scheduled energy production and associated bidding functions. The energy schedules state the firm's intended hourly output from their portfolio of generators for each hour of the day. Bidding functions are also submitted for each hour of the day which gives the portfolio's willingness to deviate from its scheduled production as a function of the wholesale market price.

ERCOT allows firms to submit day-ahead schedules which leave them in long or short positions entering into the production period. For example, a retailer of electricity could schedule electricity deliveries for half of its expected contracted demand with the intention to satisfy the rest of its contracts by purchasing power in the Balancing Market. This allows for considerable flexibility for firms to arbitrage between bilateral markets and the spot market regardless of their contract positions.

After schedules and bids are submitted, they can be updated by the firm up to 90 minutes prior to actual production time. This allows firms to incorporate any new information about the state of the market into their operating plans and bids approximately two hours before production is executed.

ERCOT uses the Balancing Market to match actual generation and actual demand throughout the day. The Balancing Market is cleared every 15 minutes throughout the day and 30 minutes before actual production begins by aggregating the hourly bidding functions submitted by firms and intersecting the supply curve with expected demand. The winning entities are then notified of the increase or decrease in production they will need to make relative to their scheduled production[43]. The Balancing Market not only smooths out deviations between supply and demand, but it also facilitates the least cost provision of electricity by substituting production from firms with low bids for production for firms with high bids, even in the case where aggregate supply does not change[44].

The Balancing Market is also used to manage transmission congestion. The grid is organized into four zones, North, South, West, and Houston, based on transmission bottlenecks. If there is no congestion between zones, then the market clearing prices in the Balancing Market are the same in each zone and the entire grid acts a single market. If transmission lines between zones reach their capacity limit, then ERCOT intersects the bidding functions separately by zone to achieve market clearing prices for each zone which do not exceed the transmission capability between zones. For example if more power is needed in the South zone, but the transmission lines transmitting power into that zone are at capacity, ERCOT will raise the prices in the the South zone, while lowering or keeping constant the prices in the other zones[45].This will increase power production in the

43 Since Balancing Market is only cleared every 15 minutes and 30 minutes ahead of real-time production, it cannot supply the nearly continuous need to balance supply and demand. Second-by-second balancing of supply and demand comes from generators which provide regulation services. These generators provide ERCOT with direct control to part of their generator's output. ERCOT uses these generators to instantaneously follow fluctuations in grid frequency. ERCOT uses the Balancing Market to ensure sufficient reserves of regulation.

44 For a more detailed exposition of the mechanisms of the Balancing Market, I refer the interested reader to Hortacsu and Puller (2008).

45 Congestion can also arise within zones. This type of congestion cannot be resolved with market prices since there is only one price for each zone. To deal with local congestion, ERCOT deploys generators out of bid order. That is, ERCOT deploys specific generators which are not willing to increase production at current prices by offering them prices higher

South zone while reducing production in other zones to decrease the amount of power flowing over transmission lines into the South zone. In uncongested periods, ERCOT does not differentiate between remote generators, such as wind power, 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.

than the prevailing market price. The costs of deploying these resources to alleviate local congestion is covered by an output tax levied on all generators in the zone.

Table 1:
Generator Composition

	Total Capacity (MW)			Share of Capacity		
	2005	**2006**	**2007**	**2005**	**2006**	**2007**
Natural Gas	47537	48372	49109	67.2%	66.2%	64.8%
Coal	15229	15729	15762	21.5%	21.5%	20.8%
Nuclear	4887	4887	4892	6.9%	6.7%	6.5%
Wind	1545	2509	4150	2.2%	3.4%	5.5%
Unknown	856	856	1106	1.2%	1.2%	1.5%
Water	512	512	501	0.7%	0.7%	0.7%
Petroleum Coke	142	143	143	0.2%	0.2%	0.2%
Diesel	40	40	38	0.1%	0.1%	0.0%
Landfill Gas	40	53	59	0.1%	0.1%	0.1%
Total	70788	73101	75760	100%	100%	100%

Table 2:
Estimation Variables

Independent Variables	Description
Contemporaneous Variables	
$Wind_t$	Wind power production for current period (MWH)
$Wind_t^2$	Square of wind power production for current period
$Demand_t$	System demand for current period (MWH)
$Demand_t^2$	Square of system demand for current period (MWH)
$Temperature_t$	Average system wide temperature for current period
$Temperature_t^2$	Square of average system wide temperature for current period
$Congest_t$	Indicator for inter-zonal congestion
Lagged Variables	
$Operate\ 1_{t-9}$	Operating indicator for generator 1 lagged 2 hrs
...	...
$Operate\ 332_{t-9}$	Operating indicator for generator 332 lagged 2 hrs
$Wind_{t-9}$	Wind power production lagged 2 hrs (9 periods)
$Wind_{t-9}^2$	Square of wind power production lagged 2 hrs (9 periods)
$Demand_{t-9}$	System demand lagged 2 hrs (9 periods)
$Demand_{t-9}^2$	Square of system demand lagged 2 hrs (9 periods)
$Temperature_{t-9}$	Average system wide temperature lagged 2 hrs (9 periods)
$Temperature_{t-9}^2$	Square of average system wide temperature lagged 2 hrs (9 periods)
$Congest_{t-9}$	Indicator for inter-zonal congestion lagged 2 hrs (9 periods)
...	...
...	...
$Wind_{t-100}$	Wind power production lagged 25 hrs (100 periods)
$Wind_{t-100}^2$	Square of wind power production lagged 25 hrs (100 periods)
$Demand_{t-100}$	System demand lagged 25 hrs (100 periods)
$Demand_{t-100}^2$	Square of system demand lagged 25 hrs (100 periods)
$Temperature_{t-100}$	Average system wide temperature lagged 25 hrs (100 periods)
$Temperature_{t-100}^2$	Square of average system wide temperature lagged 25 hrs (100 periods)
$Congest_{t-100}$	Indicator for inter-zonal congestion lagged 25 hrs (100 periods)
Dummies	
$Day/Year$	Dummy for each date in the sample

Table 3:

**Power Offsets by Technology:
Static and Dynamic Models**

	Offset MWH (Mwh/MWh Wind)	
Fuel	Static	Dynamic
Coal	-0.18	-0.01
	(0.01)	(0.02)
All Gas[a]	-0.85	-0.92
	(0.02)	(0.04)
CC	-0.62	-0.53
	(0.02)	(0.04)
Steam	-0.18	-0.32
	(0.01)	(0.02)
Turbine	-0.05	-0.07
	(0.00)	(0.01)
Nuclear	-0.010	-0.013
	(0.002)	(0.005)
Hydro	-0.004	-0.001
	(0.001)	(0.002)
Imports	0.03	-0.07
	(0.01)	(0.01)
Market	-1.004	-1.008
	(0.022)	(0.048)

Standard errors in parentheses
[a]Gas technologies include combined cycle (CC), steam turbine (Steam), and combustion turbine (Turbine)

**Table 4:
Emission Offsets by Technology:
Static and Dynamic Models**

	Offset CO_2 (lbs/MWh Wind)		Offset SO_2 (lbs/MWh Wind)		Offset NO_x (lbs/MWh Wind)	
Fuel	Static	Dynamic	Static	Dynamic	Static	Dynamic
Coal	-406	-14	-1.623	0.023	-0.290	-0.060
	(23.5)	(54.7)	(0.087)	(0.205)	(0.018)	(0.042)
All Gas[a]	-832	-932	-0.087	-0.180	-0.616	-0.771
	(19.9)	(44.3)	(0.015)	(0.032)	(0.028)	(0.059)
CC	-550	-460	-0.006	-0.005	-0.263	-0.199
	(18.2)	(39.4)	(0.000)	(0.001)	(0.009)	(0.019)
Steam	-215	-383	-0.073	-0.167	-0.274	-0.469
	(12.2)	(28.1)	(0.015)	(0.032)	(0.027)	(0.056)
Turbine	-67	-89	-0.008	-0.008	-0.079	-0.103
	(5.2)	(11.4)	(0.001)	(0.002)	(0.005)	(0.012)
Nuclear	0	0	0	0	0	0
Hydro	0	0	0	0	0	0
Imports	--	--	--	--	--	--
Market	-1238	-947	-1.71	-0.16	-0.91	-0.83
	(28.2)	(64.1)	(0.087)	(0.206)	(0.033)	(0.070)

Standard errors in parentheses
[a]*Gas technologies include combined cycle (CC), steam tubine (Steam), and combustion turbine (Turbine)*

Table 5:
Offsets 2005-2007

	Tons Offset	Percent of Total Emissions	Percent Wind Production
CO_2	5,492,862	1.23%	
	(371,967)		
SO_2	910	0.11%	1.94%
	(1,197)		
NO_x	4,821	1.68%	
	(406)		

Standard errors in parentheses

Table 6:
Pollutant Values

	Emission Values ($/ton of emissions) Low	Middle	High
NO_x	$100	$400	$2,000
CO_2	$5	$21	$35

Table 7:
Offset Values

	Offset Values ($/MWH of Wind Power) Low	Middle	High
NO_x	$0.04	$0.17	$0.83
	(0.00)	(0.01)	(0.07)
CO_2	$2.37	$9.94	$16.57
	(0.16)	(0.67)	(1.12)

Standard errors in parentheses

Table 8: NERC Region Electricity Generator Characteristics, 2007

		Texas Regional Entity	Midwest Reliability Organization	Reliability First Corporation	SERC Reliability Corporation
Capacity Shares for Fossil Generators	Coal	21%	63%	64%	53%
	Gas	78%	31%	33%	45%
	Oil	0%	6%	3%	1%
Percent of Fossil Fuel Electricity Generation	Coal	41%	92%	90%	79%
	Gas	59%	7%	9%	20%
	Oil	0%	1%	1%	1%
Average Fossil Fuel Emissions	NO_x (lb/MWh)	0.86	3.75	2.84	2.32
	SO_2 (lb/MWh)	3.00	6.95	10.76	7.37
	CO_2 (lb/MWh)	1471	2226	1875	1879
Share of National Electricity Production		8%	5%	24%	27%

		Southwest Power Pool	Northeast Power Coordinating Council	Florida Reliability Coordinating Council	Western Electricity Coordinating Council
Capacity Shares for Fossil Generators	Coal	44%	15%	23%	30%
	Gas	54%	64%	65%	69%
	Oil	2%	21%	12%	1%
Percent of Fossil Fuel Electricity Generation	Coal	71%	26%	32%	49%
	Gas	29%	65%	57%	51%
	Oil	0%	9%	11%	1%
Average Fossil Fuel Emissions	NO_x (lb/MWh)	2.78	0.86	1.93	2.21
	SO_2 (lb/MWh)	4.60	2.95	2.84	1.60
	CO_2 (lb/MWh)	1898	1300	1287	1587
Share of National Electricity Production		5%	7%	5%	18%

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

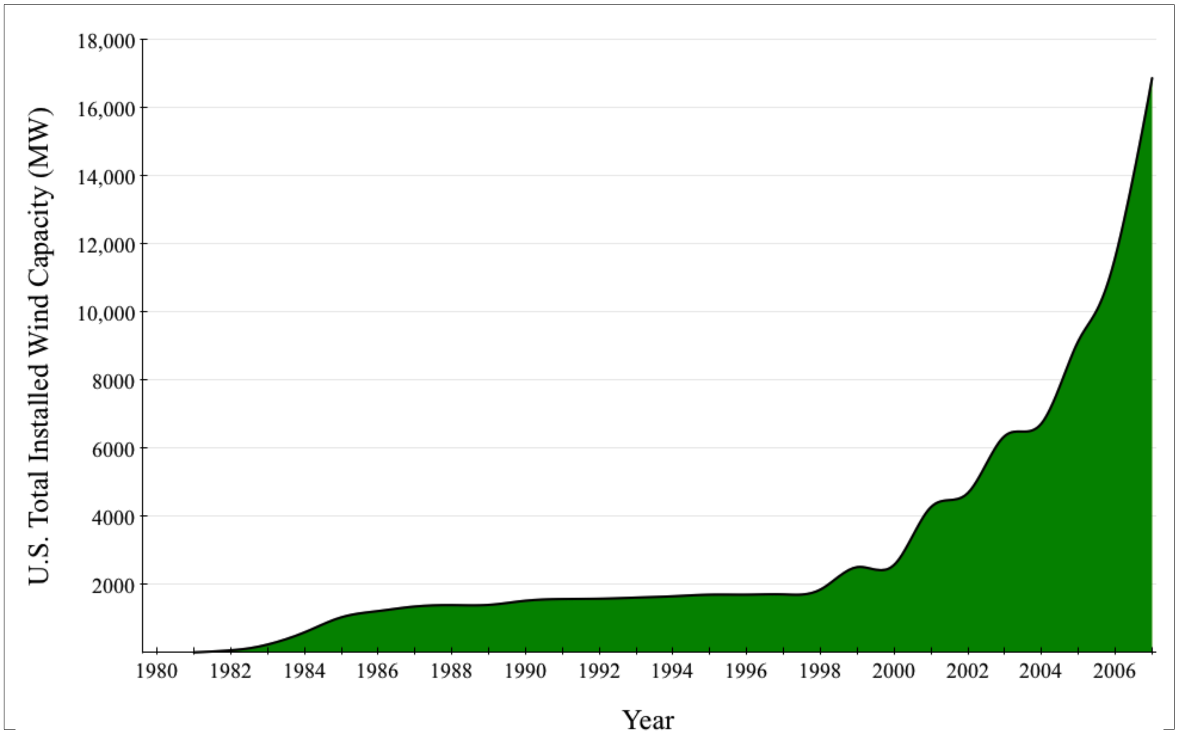
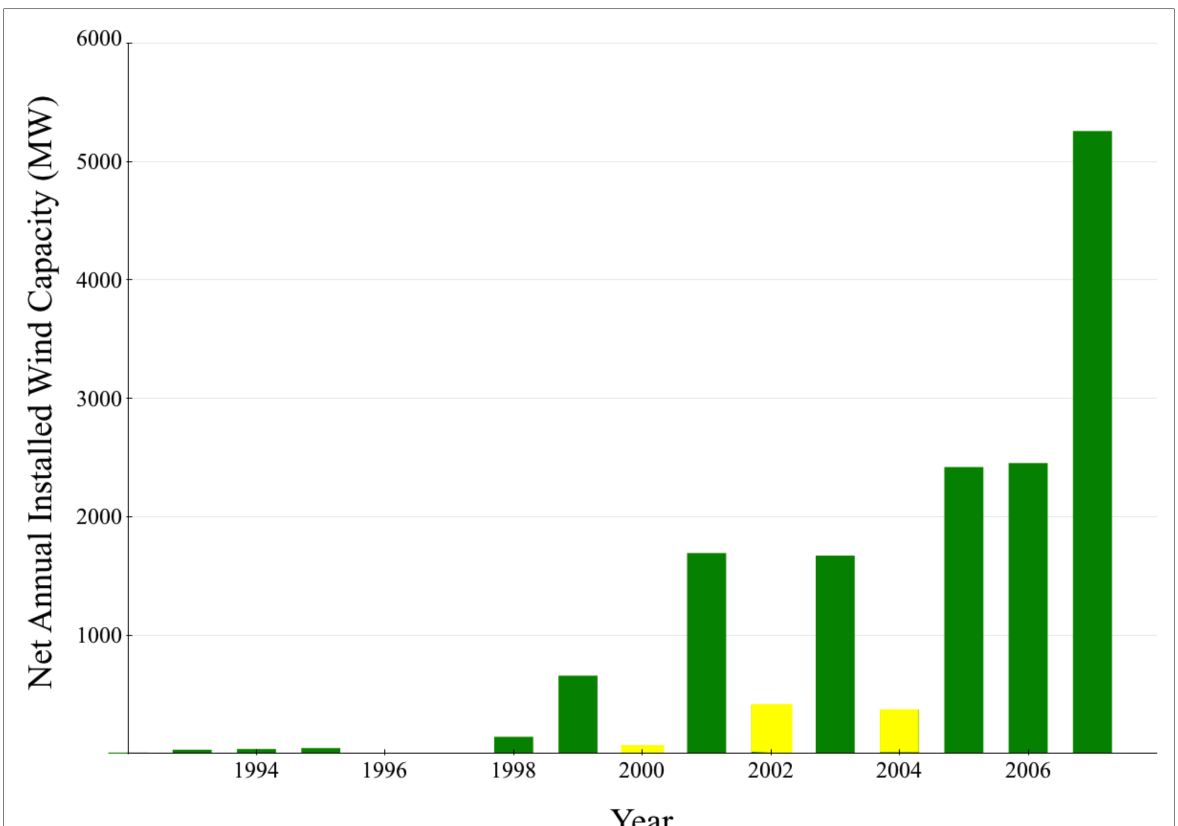


Figure 2: Annual Wind Capacity Addtions in the U.S.



Source: American Wind Energy Association Database

Figure 3: Average hourly wind production and electricity demand

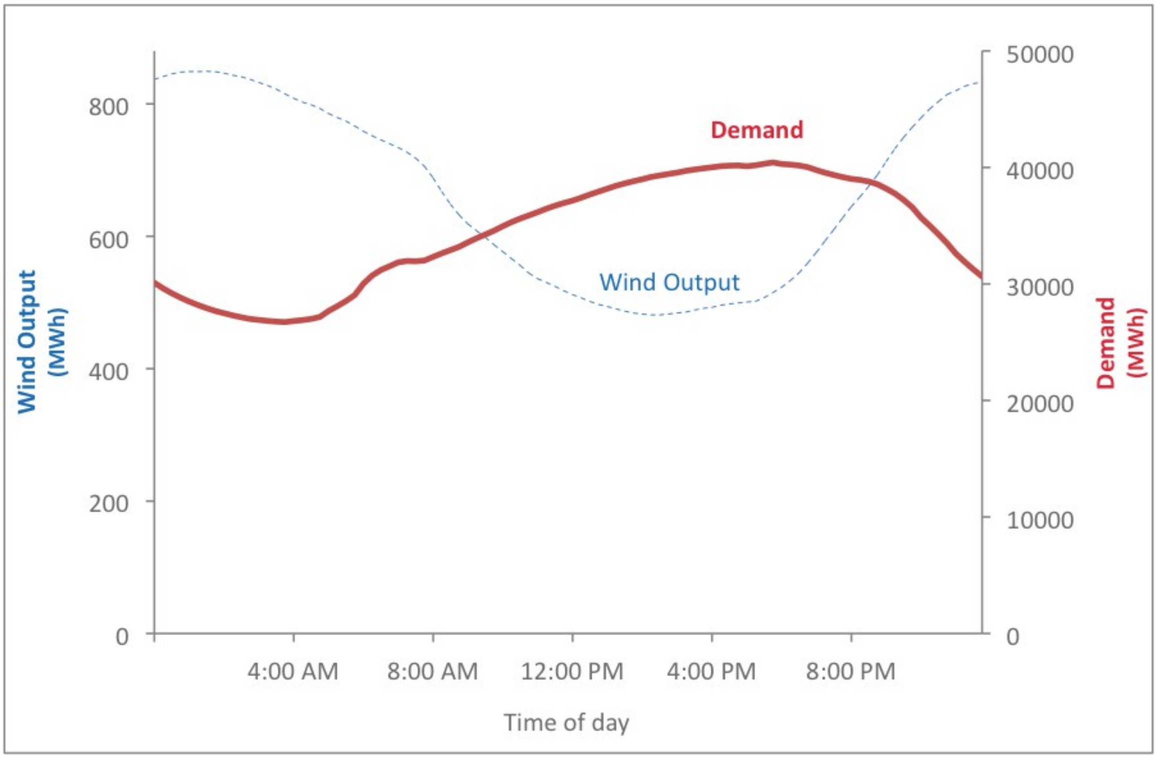


Figure 4: Average monthly wind production and electricity demand