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The Relationship between Wind Generation and Balancing-Energy Market Prices in ERCOT: 2007–2009

E. Nicholson, J. Rogers, and K. Porter
Exeter Associates, Inc.
Columbia, Maryland

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5500-49415
November 2010

Contract No. DE-AC36-08GO28308

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Exeter Associates, Inc.
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NREL Technical Monitor: Erik Ela
Prepared under Subcontract No. LAM-9-99431-01

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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This publication received minimal editorial review at NREL.

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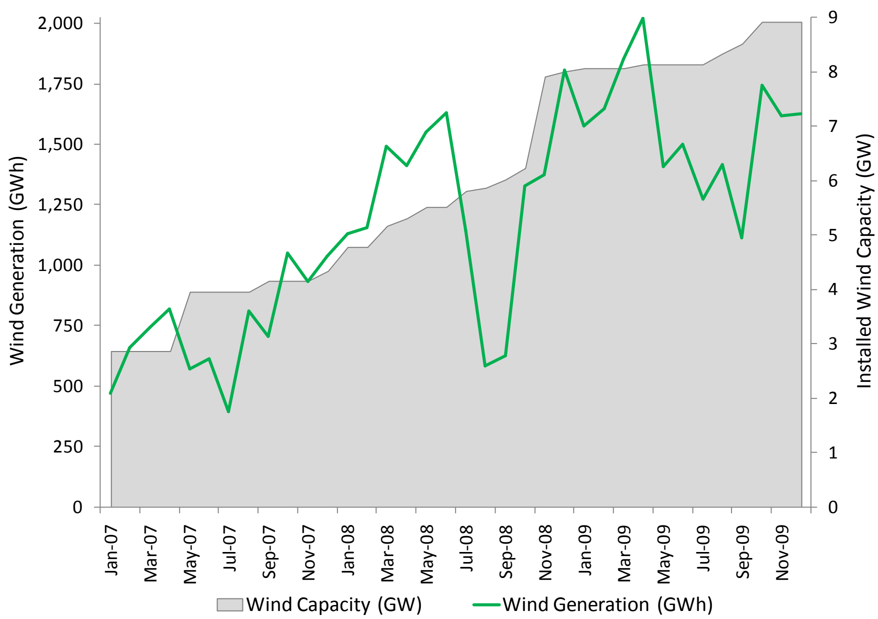
Introduction

Texas has more installed wind capacity than any other state in the United States, with nearly nine gigawatts (GW) of wind. Installed wind capacity in the Electric Reliability Council of Texas (ERCOT) nearly tripled between 2007 and 2009, increasing from approximately 2.8 GW at the beginning of 2007 to over 8.9 GW by the end of 2009.[1] This paper attempts to measure the average marginal effects of wind generation on the balancing-energy market price in ERCOT with the help of econometric analysis. The econometric approach employed in this paper differs from other studies of the effects of wind on electricity markets because those studies, most of which focused on Europe, used production cost modeling. Rather than simulating market outcomes, this paper uses historical data from the ERCOT balancing market and attempts to quantify the average marginal effects of price on wind generation. Figure 1 presents a graph of the installed wind capacity in ERCOT as well as the monthly output. Both increased significantly over the 2007-2009 period.

Figure 1 - ERCOT Wind Capacity and Output; 2007-2009



Sources: ERCOT System Planning Division, "Monthly Status Report to Reliability and Operations Subcommittee" (Jan 2007 – Nov 2008), http://www.ercot.com/committees/board/tac/ros/; Kent Saathoff, "Grid Operations and Planning Report," ERCOT Board of Directors, (Dec 2008 – Dec 2009), http://www.ercot.com/committees/board/.

[1] ERCOT System Planning Division, "Monthly Status Report to Reliability and Operations Subcommittee" (Jan. 2007 – Nov. 2008), http://www.ercot.com/committees/board/tac/ros/; Kent Saathoff, "Grid Operations and Planning Report," ERCOT Board of Directors, (Dec. 2008 – Dec. 2009), http://www.ercot.com/committees/board/.

The ERCOT market is comprised of four congestion zones ("zones") and five key constraints. The zonal balancing-energy prices are equal when there is no congestion between the zones and zonal balancing-energy prices differ in the presence of inter-zonal congestion. A map of the ERCOT system and congestion zones is presented in Figure A1 of Appendix A. ERCOT uses the balancing-energy market to manage inter-zonal congestion. However, ERCOT will convert to a nodal market in late 2010, after which congestion will be managed at the nodal, rather than zonal, level.

Balancing-Energy Market in ERCOT

The balancing-energy market represents a small portion of total transactions in ERCOT, usually less than 5% of the total energy sold in ERCOT.[2] The majority of electricity in ERCOT is sold through bilateral transactions. However, balancing-energy market prices are important because they affect real-time dispatch in ERCOT and influence ERCOT's bilateral market. According to ERCOT's independent market monitor, the balancing energy market serves the following functions: balance supply and demand in real time; manage inter-zonal congestion, and displace higher-cost energy with lower-cost energy given the energy offers of Qualified Scheduling Entities (QSEs).[3] All parties that participate in the balancing market, such as load serving entities and generators, must be represented by a QSE. QSEs submit their load forecasts and resource schedules to ERCOT, who aggregates the schedules for planning purposes. ERCOT permits QSEs to submit unbalanced schedules, which means that QSEs can overstate (or understate) their load schedules with the expectation of selling (or purchasing) the difference in the balancing-energy market.

Balancing-energy market prices are determined by the QSE resource offers and ERCOT's scheduling and dispatch software, which develops zonal balancing energy prices. QSEs submit bids into the balancing-energy market that are essentially stepped supply curves that indicate the output level (in megawatt hours, "MWh") and price (in $/MWh) that the QSE is willing to supply the balancing-energy market. The balancing-energy market has two components – "Inc" or "up balancing" energy and "Dec" or "down balancing" energy. When a QSE submits an Inc bid for up balancing service, it agrees to increase its production up to the quantity indicated in its supply schedule if the balancing-energy market price is greater than or equal to its Inc bid. A QSE can also submit Dec bids, where it agrees to decrease its own level of generation and purchase its requirements from ERCOT instead when the balancing-energy price is less than or equal to its Dec offer.

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[2] Potomac Economics, Ltd, "2008 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2009), 16, http://www.puc.state.tx.us/wmo/documents/annual_reports/2008annualreport.pdf.
[3] Ibid., *ii*.

In real-time, ERCOT uses the balancing-energy market to balance supply and demand. When real-time load differs from forecasted load or when scheduled resources differ from actual resources, which is possible given relaxed balanced schedules, ERCOT makes up the difference by purchasing "up balancing" or "down balancing" energy. If the scheduled energy resources are insufficient to satisfy real-time load, ERCOT will purchase up balancing-energy services from QSEs that submitted Inc bids that cleared the balancing-energy market. When load is below expected levels, ERCOT reduces the level of electricity generated by purchasing down balancing-energy services. In such cases, QSEs with Dec offers that ERCOT accepts will purchase energy from ERCOT at the balancing-energy market clearing price rather than generate electricity themselves.

According to Potomac Economics, ERCOT's independent market monitor, ERCOT's demand for balancing-energy is also affected by load patterns because ERCOT's demand for balancing-energy is positive in the morning when loads ramp up and negative when load ramps down in the evening.[4] This is an artifact of ERCOT scheduling practices because QSEs mostly schedule generation in ERCOT on an hourly basis and bilateral contracts are frequently based on 6 AM – 10 PM blocks. Load typically ramps up and down at a faster pace than the scheduled generation, so ERCOT uses the balancing-energy market to fill in the gaps. Finally, unexpected transmission outages and unplanned generator outages also affect ERCOT's demand for balancing energy.

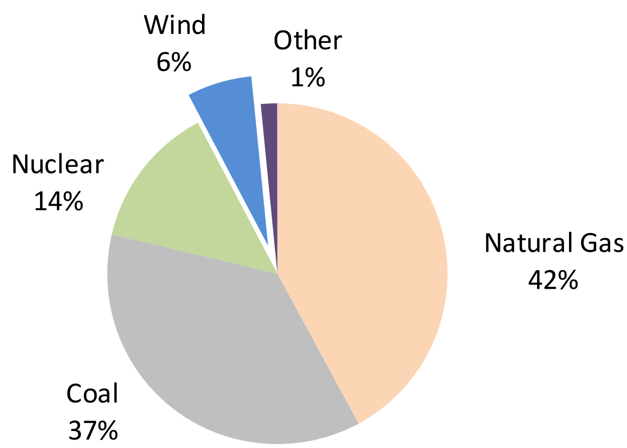
Generation in ERCOT

Generation resources in ERCOT produced 305,432 gigawatt-hours (GWh) of energy in 2009. Electricity generation in ERCOT is dominated by natural gas and coal, with natural gas generally serving as the marginal fuel. Natural gas plants produce the most energy in the summer months (May – September), while coal plants produce the most energy during the rest of the year.[5]

Forty-two percent of the energy generated in ERCOT in 2009 came from natural gas and 37% from coal, as seen in Figure 2. Wind facilities produced 6.2% of energy in ERCOT in 2009.[6] Wind generation constituted between 4% and 5% of total generation between May and September, and between 6% and 9% during the rest of the year.

[4] *Ibid*., 23.
[5] ERCOT, "ERCOT 2009 Demand and Energy Report," (January 2010), http://www.ercot.com/content/news/presentations/2010/ERCOT_2009_Demand_and_Energy.xls.
[6] Ibid.

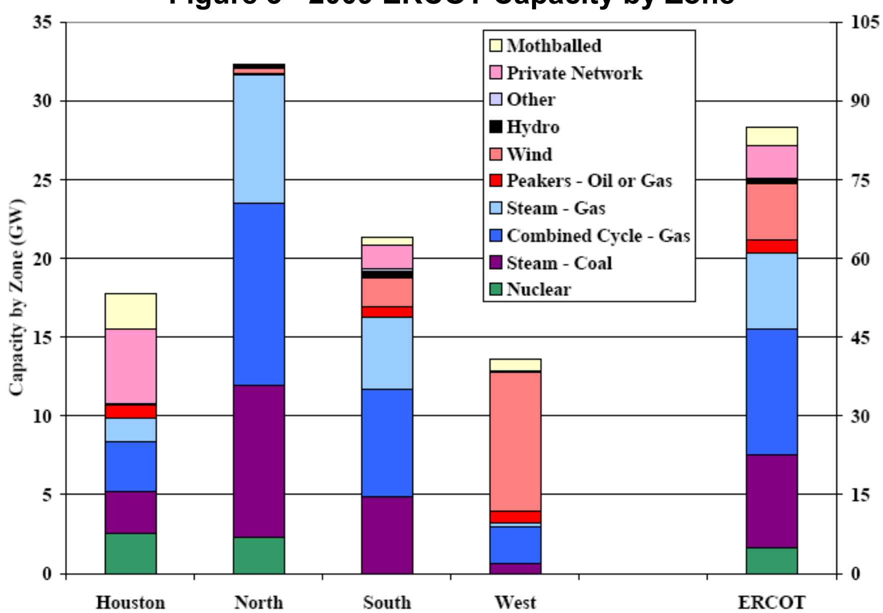
Figure 2 - ERCOT Percent of Energy Generation by Fuel Type; 2009



Source: ERCOT, "ERCOT 2009 Demand and Energy Report," (January 2010), http://www.ercot.com/content/news/presentations/2010/ERCOT_2009_Demand_and_Energy.xls.

The resource mix within ERCOT varies across zones and Figure 3 shows how generation capacity was distributed across the zones in 2009. The vast majority of wind capacity – 90% – is located in the West zone.[7] The North zone contains the most total generation capacity, while the West zone contains the least.

Figure 3 - 2009 ERCOT Capacity by Zone



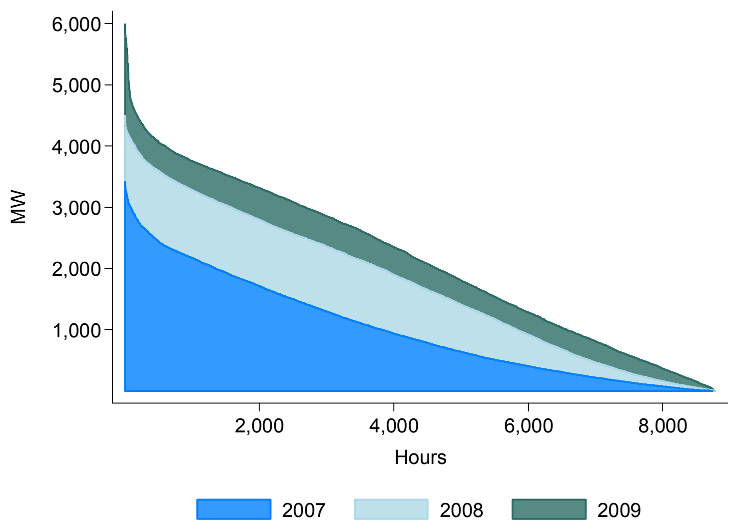
Source: Potomac Economics, Ltd, "2009 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2009), 16, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.

[7] Potomac Economics, Ltd, "2009 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2010), 45, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.

Wind Generation in ERCOT

ERCOT has more than twice the wind capacity of any other organized wholesale electricity market – independent system operator (ISO) or regional transmission organization (RTO) – in North America.[8] The wind capacity expansion from 1,385 megawatts (MW) in 2004 to 8,916 MW in 2009 corresponds to a compound average annual growth rate of 45.1%. The wind generation duration curves for 2007, 2008, and 2009 presented in Figure 4 demonstrate that increased wind capacity over the period resulted in higher levels of wind generation.

Figure 4 - Average Hourly Wind Generation Duration Curves in ERCOT



[8] The RTO/ISOs in North America are: Alberta, CAISO, ERCOT, Ontario IESO, ISO New England, Midwest ISO, New Brunswick SO, New York ISO, PJM Interconnection, and the Southwest Power Pool.

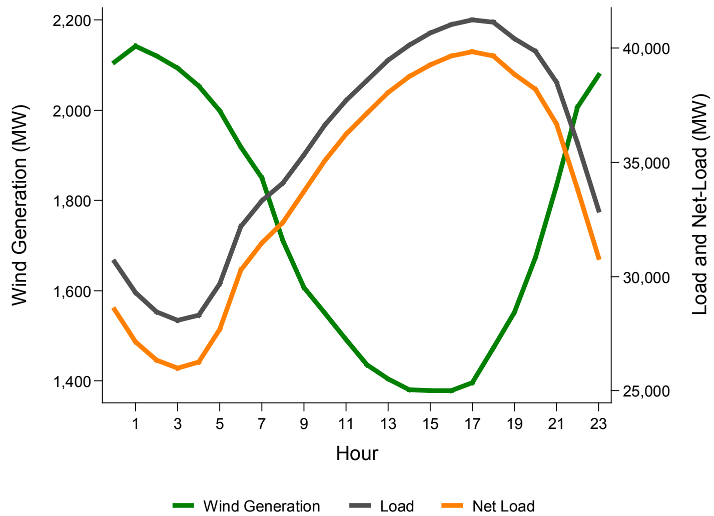
Table 1 summarizes the monthly wind generation dispatched in ERCOT ("wind generation") between 2007 and 2009. Annual wind generation increased almost 73% between 2007 and 2008, from 8.8 GWh to 15.2 GWh. The rate of increase in wind generation slowed to 23% between 2008 and 2009, when 18.8 GWh of wind generation was produced. The maximum hourly wind generation in ERCOT rose by 32% between 2007 and 2008 from 3,407 MW to 4,491 MW, while the maximum hourly wind generation in ERCOT increased an additional 33% between 2008 and 2009 to 5,984 MW.

Table 1 - ERCOT Wind Generation by Month; 2007-2009

	2007			2008			2009		
	Mean (MW)	Max (MW)	Total (MWh)	Mean (MW)	Max (MW)	Total (MWh)	Mean (MW)	Max (MW)	Total (MWh)
Jan	638	2, 82	470,651	1,520	3,449	1,131,144	2,118	4,454	1,575,861
Feb	985	2,339	661,733	1,663	3,474	1,157,666	2,450	4,150	1,646,223
Mar	1,000	2,399	743,974	2,009	3,536	1,492,376	2,499	4,619	1,854,612
Apr	1,156	2,347	821,014	1,959	4,190	1,410,164	2,809	4,722	2,022,367
May	770	2,617	572,858	2,082	3,923	1,548,914	1,892	4,428	1,407,312
Jun	855	2,592	615,690	2,264	4,431	1,629,991	2,084	4,217	1,500,351
Jul	535	2,388	397,113	1,536	3,799	1,142,435	1,713	4,206	1,274,166
Aug	1,090	2,881	810,672	788	3,337	586,040	1,903	4,270	1,415,890
Sep	986	3,064	708,094	869	3,011	624,534	1,549	3,806	1,115,325
Oct	1,411	3,334	1,049,755	1,787	3,785	1,329,219	2,346	5,984	1,745,723
Nov	1,294	3,184	932,007	1,906	4,172	1,372,623	2,248	5,117	1,618,898
Dec	1,395	3,407	1,037,958	2,432	4,491	1,809,107	2,186	5,848	1,626,285
Total	1,009	3,407	8,821,520	1,735	4,491	15,234,213	2,147	5,984	18,803,013
% Change				72.0%	31.8%	72.7%	23.7%	33.2%	23.4%

Figure 5 shows the average hourly load, net load, and wind output in ERCOT in 2008. The average wind generation profile is almost the inverse of the average daily load pattern. While the wind patterns vary from year to year, wind output is lowest during the day and in the summer months, when load is highest.

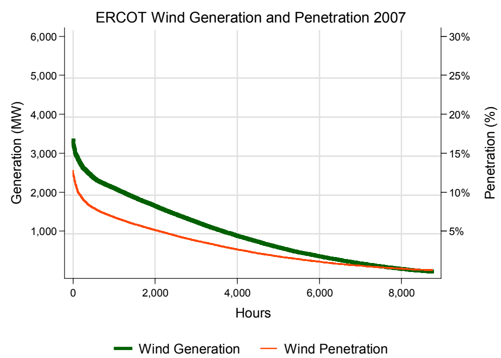
Figure 5 - 2008 Average Hourly ERCOT Load, Net Load, and Wind Generation

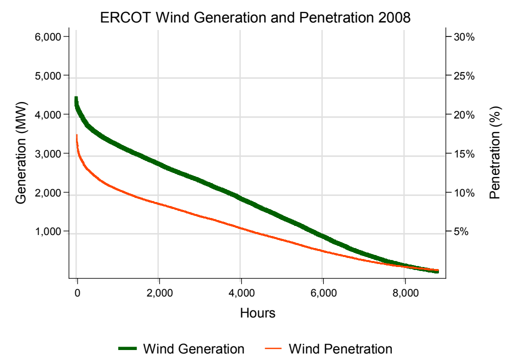


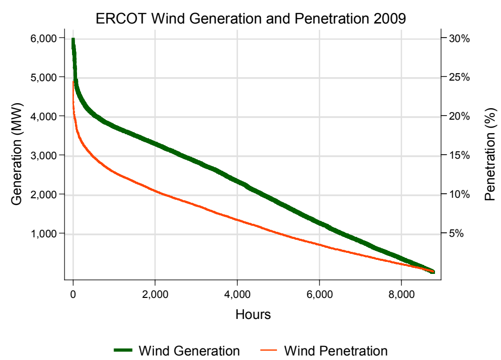
Wind Penetration

Wind penetration, defined as the ratio of wind generation to total generation, depends on several factors including installed wind capacity, wind speeds, and transmission capacity. Figure 6 shows the wind generation duration curves and the wind penetration curves, ranked independently, for 2007, 2008, and 2009. The maximum wind penetration was 12.9% in 2007, increased to 17.6% in 2008, and to 24.4% in 2009.

Figure 6 - ERCOT Wind Generation and Penetration; 2007-2009







Hourly Wind Penetration Rate

	Average (%)	Maximum (%)
2007	3.13	12.93
2008	5.13	17.55
2009	6.17	24.43

Note: wind penetration and generation are ranked independently

Wind penetration in ERCOT was above 5% for 2,200 hours in 2007. In contrast, wind penetration was greater than 5% for over 4,200 hours in 2008. While penetration levels increased between 2007 and 2008, transmission constraints limited the level of wind that ERCOT could dispatch from the West zone to the rest of ERCOT at any given time. ERCOT's market monitor attributed these constraints to increased installed wind capacity in the West.[9]

[9] Potomac Economics, Ltd, "2008 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2009), 87, http://www.puc.state.tx.us/wmo/documents/annual_reports/2008annualreport.pdf.

In 2008, ERCOT could dispatch up to 4 GW of wind from West to the other zones before the interface limit was binding.[10] Additionally, a double-circuit 345-kilovolt (kV) transmission line was out of service for much of February and March 2008, which further reduced the West-to-North transfer capability during those months.[11] The West-to-North transmission constraint limits the wind generation that ERCOT can accommodate and was binding in 60.6% of the 15-minute intervals in 2008 and 35.6% in 2009.[12] ERCOT's independent market monitor found that wind curtailment caused by inter-zonal congestion on the West-to-North interface decreased from 604 GWh in 2008 to 442 GWh in 2009. However, intra-zonal, or "local" congestion in the West zone increased over the same period, and wind curtailment rose from 812 GWh in 2008 to 3,400 GWh in 2009.[13]

Balancing-Energy Market Prices

The three main functions of ERCOT's balancing market are to balance supply and demand, manage inter-zonal congestion, and displace high-cost energy with lower-cost energy when possible.[14] Balancing-energy market-price drivers include natural gas prices, the time of day, and system conditions (e.g., line outages, generator de-ratings, etc). Table 2 displays the average price by month and zone for balancing energy in 2007.

Table 2 - 2007 Average Balancing-Energy Prices in ERCOT ($/MWh)

	Houston	North	South	West
Jan	50.05	50.06	50.09	51.01
Feb	52.49	52.51	52.36	53.29
Mar	54.36	54.27	54.08	54.30
Apr	58.23	54.72	56.22	53.65
May	56.38	52.04	54.21	53.19
Jun	56.35	54.99	55.25	56.13
Jul	48.68	49.14	47.79	49.78
Aug	57.75	56.70	57.26	55.68
Sep	61.18	60.89	61.07	60.40
Oct	49.83	47.23	46.36	46.87
Nov	50.88	46.88	48.53	41.05
Dec	49.69	49.68	49.77	51.44

[10] Ibid., 88.
[11] Ibid., 90.
[12] Potomac Economics, Ltd, "2009 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2010), 85, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.
[13] Ibid., 87.
[14] Potomac Economics, Ltd, "2008 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2009), *ii*, http://www.puc.state.tx.us/WMO/documents/annual_reports/2008annualreport.pdf.

Figure A2 in Appendix A plots the 10th, 25th, 50th, 75th, and 90th percentiles of hourly balancing-energy prices by zone in 2007. The price percentile graphs give an indication of the distribution of balancing-energy prices in each hour. For example, the 75th percentile represents the price level (per hour) that 75% of the balancing-energy prices were below. Note that balancing-energy prices increase in the morning shoulder period when load starts to ramp up, and decrease in the evening shoulder period when load falls.

Table 3 shows the average balancing-energy prices by month and zone in 2008. In contrast to 2007, the 2008 zonal balancing-energy prices are more divergent, particularly in April, May, and June of 2008. The ERCOT market monitor attributed one-quarter of the 2007-2008 price increase in April, May and June to transmission congestion.[15]

Table 3 - 2008 Average Balancing-Energy Prices in ERCOT ($/MWh)

	Houston	North	South	West
Jan	58.70	59.09	58.12	50.98
Feb	58.59	56.46	60.32	56.45
Mar	65.90	65.67	61.41	36.50
Apr	91.59	70.09	76.69	56.41
May	127.44	76.20	142.12	54.80
Jun	119.66	98.61	133.70	79.10
Jul	91.04	90.54	91.30	86.80
Aug	79.98	79.74	80.12	79.21
Sep	42.25	39.94	41.78	40.08
Oct	50.36	43.06	48.04	37.77
Nov	39.16	39.00	39.07	34.28
Dec	40.70	40.52	40.39	27.80

The increase in balancing-energy prices in 2008 relative to 2007 is also attributed to natural gas prices, which increased dramatically in the summer of 2008.[16] ERCOT also increased the offer cap in the balancing market from $1,500/MWh to $2,250/MWh in March 2008.

Unlike the other three zones, balancing-energy prices in the West zone decreased in 2008 relative to 2007. According to ERCOT's independent market monitor, part of the 2007-2008 decrease in West balancing-energy prices can be attributed to the significant increase in installed wind capacity in that zone.[17] As

[15] Ibid., 2.
[16] Ibid.
[17] Ibid., 8.

Figure A3 in Appendix A shows, the 10th percentile of hourly balancing-energy prices in the West zone are below zero in hours zero to nine and 19 to 23 in 2008. Balancing-energy prices in the 90th percentile reached much higher levels in 2008 than experienced in 2007, especially in the South and Houston zones.

The monthly average balancing-energy prices for 2009 are presented in Table 4. Balancing-energy prices fell in 2009 to levels well below 2008, which is attributed to a decrease in natural gas prices. Average natural gas prices fell by 56% between 2008 and 2009.[18]

Table 4 - 2009 Average Balancing-Energy Prices in ERCOT ($/MWh)

	Houston	North	South	West
Jan	31.54	30.78	32.31	23.23
Feb	26.48	26.86	26.28	19.66
Mar	28.28	29.86	25.62	24.04
Apr	23.90	24.10	23.45	12.91
May	30.63	30.61	30.58	23.45
Jun	51.28	31.69	66.89	30.57
Jul	33.07	32.92	32.99	31.90
Aug	30.44	29.90	30.16	28.07
Sep	28.66	25.11	28.32	23.28
Oct	29.55	28.74	29.24	27.06
Nov	26.65	26.59	26.68	26.58
Dec	39.20	39.54	38.97	37.69

In 2009, balancing-energy prices across zones were also closer to each other than they were in 2008 because inter-zonal congestion was less frequent. The hourly balancing-energy price percentiles by zone in 2009 are displayed in Figure A4 of Appendix A.

Negative Balancing-Energy Prices

Under normal circumstances, when ERCOT wants to take generation off the grid (i.e., purchase down-balancing-energy services), QSEs that submit Dec offers that clear the balancing-energy market ramp down their units and purchase energy from ERCOT (at a price below its marginal cost) instead. This price is almost always positive because generators avoid marginal fuel costs when they ramp their units down. However, this is not always true for wind generators. Wind generators receive a production tax credit for each MWh of electricity they generate, and they also sell renewable energy credits (RECs). These revenues are in addition to the revenues they earn in the ERCOT balancing-energy market. With

[18] Potomac Economics, Ltd, “2009 State of the Market Report for the ERCOT Wholesale Electricity Markets,” (August 2010), 2, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.

these additional payments, wind generators have an incentive to produce energy even when the price is negative, i.e., they are willing to pay ERCOT for the right to produce electricity.[19] Wind generators can make a profit with negative balancing-energy prices provided that the value of the production tax credits and the RECs exceed the price (in $/MWh) that they pay ERCOT for the right to produce electricity.[20]

Figure 7 plots the number of hours when the balancing-energy price was negative by year and zone. In 2007, the balancing-energy price was negative in 89 hours in the West zone and was rarely negative in the other three zones. The number of hours in the West with negative balancing-energy prices in 2008 increased almost 13-fold to 1,150 hours. The North, South, and Houston zones also had negative balancing-energy prices in 2008, but only in a few hours in the early morning when wind generation tends to be higher. The number of hours in the West with negative balancing-energy prices decreased by 39% to 704 in 2009 because inter-zonal congestion was less frequent and hence ERCOT used zonal congestion management during fewer hours in 2009 compared to 2008.[21] However, as in prior years, the West had the greatest number hours with negative balancing-energy prices.

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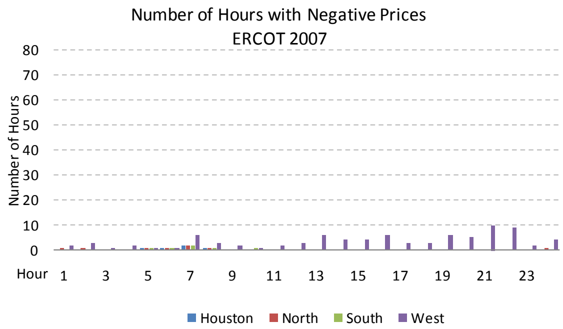
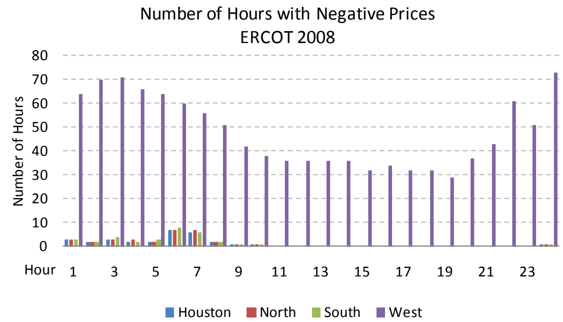
[19] Potomac Economics, Ltd, "2009 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2010), *xxviii*, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.

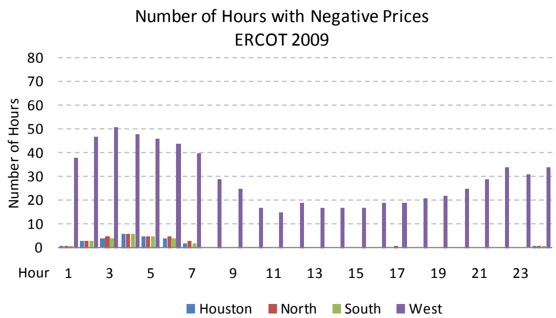
[20] Some wind generators may have a power purchase agreement with load-serving entities that specify a particular power purchase rate per MWh, and are therefore not directly affected by negative prices.

[21] Potomac Economics, Ltd, "2009 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2010), 87, http://www.puc.state.tx.us/WMO/documents/annual_reports/2009annualreport.pdf.

Figure 7 - Count of Negative Balancing-Energy Prices in ERCOT by Hour and Zone







Number of hours with negative balancing-energy prices

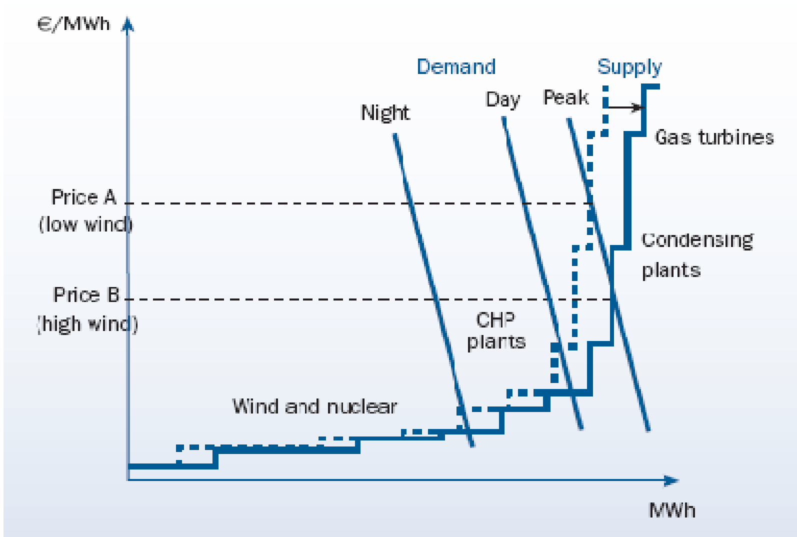
Zone	**2007**	**2008**	**2009**
Houston	5	30	26
North	8	32	30
South	6	33	26
West	89	1,150	704
Total	108	1,245	784

Wind Generation and Balancing-Energy Prices

This section examines the relationship between wind generation and the balancing-energy market price in ERCOT, frequently referred to as the merit order effect of wind energy. European studies of Denmark and Germany found that wind generation decreased the spot price for electricity.[22] Additionally, ERCOT's independent market monitor found that increased wind generation likely lowered the average price in the West zone.[23] We generally expect wind generation will decrease the balancing-energy prices.

Figure 8 presents a European Wind Energy Association (EWEA) graphic that explains the merit order effect. The hatched and solid supply schedule represents the supply slack without and with wind, respectively.

Figure 8 - The Merit Order Effect of Wind Power



Source: EWEA, The Economics of Wind Energy, (March 2009), 18, http://www.ewea.org/fileadmin/ewea_documents/documents/00_POLICY_document/Economics_of_Wind_Energy__March_2009_.pdf.

Wind generation has zero marginal cost so it is located near nuclear generation in the resource stack. An increase in wind generation in a given hour constitutes an increase in the supply of generation, represented by a rightward shift in the supply curve. The merit order effect is the price change resulting from such a supply curve shift.

[22] Pöyry, "Wind Energy and Electricity Prices: Exploring the 'Merit Order Effect'," Literature Review for the European Wind Energy Association, (April 2010), http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/MeritOrder.pdf.

[23] Potomac Economics, Ltd, "2008 State of the Market Report for the ERCOT Wholesale Electricity Markets," (August 2009), 8, http://www.puc.state.tx.us/wmo/documents/annual_reports/2008annualreport.pdf; The market monitor noted that higher levels of wind generation might also increase variability and cause price spikes. While important, the variability of prices is beyond the scope of this paper.

Figure 8 contains three demand curves representing three different levels of electric demand: Night, Day, and Peak. The three demand curves intersect the supply curve at different points. The Night demand curve crosses the relatively flat and low-price portion of the supply curve, while the Peak demand curve crosses the supply curve at the steeper and higher-priced portion. The merit order effect in Figure 8 during the Peak period equals the difference between Price A and Price B. Since the slope of the supply curve is relatively flat during the night and steeper during the day, the merit order effect during the night should be lower than the merit order effect in hours with regular and peak load.

The EWEA commissioned a review of studies that estimated the merit order effect and estimates ranged from 3-23€/MWh.[24] The relationship between wind generation and the balancing-energy market price in ERCOT likely differs from the relationships estimated in Europe because ERCOT did not have a full-fledged real-time electricity market in the 2007-2009 period. A first step in examining the relationship between the level of wind generation and zonal balancing-energy prices is to examine the simple correlation between the two variables. A pair-wise correlation coefficient is a basic statistic that indicates, in a rough way, the sign and strength of the relationship between two variables. Table 5 presents the pair-wise correlations between the zonal balancing-energy prices and generation by fuel type for the three study years. The correlation coefficient ranges between negative one and positive one, where the further the coefficient is from zero, the stronger the co-movement between the two variables. If the correlation coefficient is negative, the two variables tend to move in opposite directions (i.e., variable A is generally above its average when variable B is below its average). If the two variables tend to move in the same direction, the correlation coefficient will be positive.

[24] Pöyry, "Wind Energy and Electricity Prices: Exploring the 'Merit Order Effect'," Literature Review for the European Wind Energy Association, (April 2010), http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/MeritOrder.pdf.

Table 5 – Pair-wise Correlations Between Balancing-Energy Prices and Generation by Fuel Type

	Houston			North		
	2007	2008	2009	2007	2008	2009
Wind	-0.149	-0.045	-0.124	-0.168	-0.113	-0.133
Coal	0.084	0.154	0.144	0.095	0.222	0.158
Natural Gas	0.369	0.373	0.252	0.367	0.400	0.222
Nuclear	-0.023	-0.006†	0.002†	-0.024	0.032	0.007†
Hydro	0.134	0.263	0.168	0.136	0.258	0.154
Other	0.286	0.247	0.130	0.278	0.278	0.115
	South			West		
	2007	2008	2009	2007	2008	2009
Wind	-0.157	-0.028	-0.104	-0.216	-0.300	-0.262
Coal	0.087	0.153	0.115	0.095	0.249	0.216
Natural Gas	0.367	0.351	0.225	0.303	0.356	0.269
Nuclear	-0.027	0.028	0.007†	-0.017†	0.013†	-0.020†
Hydro	0.133	0.235	0.151	0.117	0.221	0.165
Other	0.283	0.230	0.113	0.223	0.241	0.142

†Insignificant from zero at the 5% level

The correlations in Table 5 suggest, but by no means prove, that wind generation is negatively correlated with price. The negative sign means that on average when the level of wind generation is above its average level, the price is below its average level. The balancing-energy prices are correlated with all fuel types, but wind generation levels are negatively correlated with the balancing-energy price in each zone and year. Nuclear generation levels are also negatively correlated with price in some instances; however, nuclear units essentially operate at all hours regardless of the balancing-energy prices, except when they are brought offline for scheduled maintenance. Furthermore, the nuclear correlation coefficients are close to zero and many are statistically insignificant (signified with a † in Table 6), while the wind coefficients are all significant.

The wind correlation coefficients are the strongest (in this case, the most negative) in the West zone, which contains 90% of ERCOT's wind capacity. We expect that higher levels of generation from any fuel type with increasing marginal cost will increase the balancing-energy price because QSEs dispatch their cheap resources before their expensive ones. Hence, it is not surprising to see positive correlations between coal and natural gas and the balancing-energy price. Natural gas has the strongest positive correlation with price, which is consistent with the fact that natural gas is frequently the marginal fuel in ERCOT. The marginal cost of wind is zero, so wind and price are not expected to have a positive correlation coefficient. However, the negative correlation between wind generation and price is partly driven by the average wind generation profile in ERCOT because wind generation is typically greater at night when balancing-energy prices tend to be lower. Hence, wind generation tends to be above its average level when balancing-energy prices are below their average level.

Modeling Electricity Prices

The pair-wise correlation coefficients in Table 5 present an incomplete picture of the relationship between wind generation and hourly prices for balancing energy. Other factors play a role, such as the time of day, weather, and system conditions. Furthermore, hourly electricity prices are characterized by seasonality, price spikes and mean reversion, all of which must be accounted for.[25] 'Seasonality' means that the balancing-energy prices change in a predictable way with the seasons, weeks, or the time of day. ERCOT's balancing-energy market prices are also subject to price spikes – the average hourly price can triple from one hour to the next. Typically, balancing-energy prices return to their previous levels after a price spike within a few hours (usually within one or two hours), which means that the balancing-energy price series exhibits mean reversion.

The goal of this section is to estimate an econometric model of the zonal price of balancing energy and estimate how wind generation affects it. The ordinary least-squares regression model is inappropriate for this task because it assumes that the errors in one time period are independent of the errors in previous periods. Autoregressive Moving Average (ARMA) models permit serial dependence in the errors and are often used to model electricity prices.[26] The ARMAX model is an ARMA model with exogenous variables. Appendix B provides a more detailed description of ARMA and ARMAX models.

Estimation Strategy

We estimated an ARMAX model with the hourly zonal balancing-energy market price as the dependent variable and wind generation, weather, natural gas generation, and previous values of the balancing-energy price and error terms as the dependent variable.[27] The first step in fitting an ARMA or ARMAX model is to make the underlying time series stationary. This is usually accomplished by first differencing,

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[25] Rafał Weron, Modeling and Forecasting Electricity Loads and Prices: A Statistical Approach, (John Wiley & Sons, Ltd, January 2007).

[26] Javier Contreras, Rosario Espínola, Francisco Nogales, and Antonio Conego, "ARIMA Models to Predict Next-Day Electricity Prices," IEEE Transactions on Power Systems, Vol. 18, No. 3, (August 2003), http://www.est.uc3m.es/fjnm/esp/papers/ARIMAprices.pdf; M. Zhou, Z. Yan, Y.X. Ni, G. Li, and Y. Nie, "Electricity Price Forecasting With Confidence-Interval Estimation Through an Extended ARIMA Approach," *IEEE Proceedings – Generation, Transmission and Distribution*, Vol. 153, Issue 2, (Stevenage: IET, March 2006), 187-195, http://ieeexplore.ieee.org/servlet/opac?punumber=2195.

[27] See Appendix B for a detailed description of the ARMAX model.

which means analyzing the period-to-period change in the time-series variable (the balancing-energy price in this case) rather than the level of that variable in each period. However, the price pattern in ERCOT is complex and first differencing (or first and 24^{th} differencing) does not achieve a stationary price series. Since the balancing-energy price data have a persistent daily and weekly pattern, we removed the pattern to separate the daily and weekly trend in the balancing-energy price series from the shocks. This weekly trend was removed by subtracting the median hourly weekly pattern from the hourly balancing-energy prices in each year and zone.[28] What remains is a transformed price series called the "adjusted price" for each zone that represents deviations from the average weekly price pattern.

We posit that the level of wind generation is an exogenous variable. Indeed, ERCOT can curtail wind, but the amount of wind produced at any given time depends on installed wind capacity, wind speeds, and transmission constraints, all of which are exogenous in the short run. Wind is essentially treated as an exogenous shock to the ERCOT system. We attempted to include transmission constraints in the model to help explain the balancing-energy price spikes, but the constraint variables were insignificant.[29] We also included the quantity of natural gas generation in some specifications because natural gas is frequently the marginal fuel in ERCOT.[30] Levels of natural gas generation are expected to have a positive influence on price because the greater the level of natural gas generation, the higher the market clearing price given that ERCOT is moving along the natural gas marginal-cost curve as it dispatches more natural gas generation. Finally, we include hourly temperature to capture the effect of load. Zonal temperatures were calculated broadly because we needed to create a single-temperature variable for each zone. The following city temperatures were used to represent each zone: North: Dallas; Houston: Houston; West: Odessa; South: San Antonio.

Table 6 contains eight of the ARMAX model specifications we estimated separately for each year and zone (i.e., 3 years x 4 zones = 12 estimations for each model specification, and 8 x 12 = 96 estimations were produced in total).[31] Separate models were estimated for each year given the annual differences observed in Table 5. The "adjusted price" is the dependent variable in each ARMAX model. Wind generation varies significantly throughout the day and we allow wind generation to have a different effect

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[28] The first step in calculating the adjusted balancing energy price is to calculate the median price for each of the 168 hours of the week by zone and year. The second step is to subtract this median price from the original price series. The median is preferable to the mean because the median is less responsive to price spikes than the mean.
[29] We used a sample of three months of daily constraint data from ERCOT's Daily Grid Operating Report, which contains information on system alerts and constraints, and tested whether the information in the reports "explained" the price spikes. We found that the coefficients of the grid operating report variables were statistically insignificant.
[30] Ideally, we would use the daily natural gas price at the Houston ship channel, but we do not have access to this price series.
[31] The results of other ARMAX estimations are excluded in the interest of brevity.

at night than it does during the day by including "night-wind" and "day-wind" variables. Night-wind is defined as wind that is generated before 8:00 am and after 7:00 pm. Day-wind is defined as wind that is dispatched after 8:00 am and before 7:00 pm. The number of Autoregressive (AR) and Moving Average (MA) terms in each model are included in the last two columns of Table 6. See Appendix B for definitions of the AR and MA terms.

Table 6 - ARMAX Model Specifications

	Dependent Variable	Independent variables	AR terms	MA terms
Model 1	adjusted price	night-wind, day-wind, temperature, constant	1-2	1-4
Model 2	adjusted price	night-wind, day-wind, temperature, natural-gas, constant	1-2	1-3
Model 3	adjusted price	night-wind, day-wind, temperature, natural-gas, constant	1	1-3
Model 4	adjusted price	night-wind, day-wind, temperature, natural-gas, constant	1	1-3
Model 5	adjusted price	night-wind, day-wind temperature, natural-gas, constant	1-2	1-5
Model 6	adjusted price	wind-generation, temperature, natural-gas, constant	1-2	1-4
Model 7	D.adjusted price	D.night-wind, D.day-wind, D.natural-gas	1	1-3
Model 8	adjusted price	night-wind, day-wind, natural-gas, temperature, constant	1, 24	1-2

Notes: A "-" indicates that all intermediate AR/MA terms were included while a ,"" indicates that no intermediate AR/MA terms were included. The prefix "D." refers to the first difference. Since Model 7 uses first differences, it is referred to as an ARIMAX model.

Estimation Results

The estimation results of the ARMAX models in Table 6 are presented in Table 7.[32] All of the results are statistically significant, the AR terms suggest stationarity, and the ARMAX errors are free of serial dependence.[33] The models were selected by examining the Akaike and Bayesian information criteria, a typical selection process.[34] Five of the 12 zone-year models produce inconclusive results because the ARMAX errors were not stationary.

Table 7 - ARMAX Model Coefficients on Wind Generation

	2007			2008			2009		
	Model	Day ($)	Night ($)	Model	Day ($)	Night ($)	Model	Day ($)	Night ($)
Houston	1	-0.0071*	-.0069*						
North	2	-0.00067*	-.0040*	7	-0.0042*	-0.0029*	1	-0.0035*	-0.0021*
South	2	-0.0057*	-.0034*						
West	2	-0.0118*	-.0094*	3	-0.0164*	-0.0150*			

The coefficients represent an estimate of how the balancing-energy price in ($/MWh) zone changes when wind generation increases by 1 MWh.
*Coefficient is statistically different to zero at the 5% level.

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[32] Contact the authors for the full set of ARMAX estimation results.
[33] We performed Portmanteau and Bartlett tests on the ARMAX errors and Wald tests on the AR terms.
[34] Rafał Weron, Modeling and Forecasting Electricity Loads and Prices: A Statistical Approach, (John Wiley & Sons, Ltd, January 2007).

Focusing on the conclusive results, the ARMAX results show that wind does have a statistically significant impact on the balancing-energy market price in ERCOT. The coefficients on day-wind and night-wind represent how the zonal balancing-energy price changes when an additional MWh of wind is dispatched in a given hour. Consider, the 2007 day-wind coefficient for the Houston Zone, which is -0.0071. This coefficient estimate suggests that if wind generation in ERCOT is increased by 1 MWh between 7:00 pm and 8:00 am, the price in the Houston zone would decrease by $0.0071/MWh, or 0.71¢/MWh. Provided system conditions don't change drastically, a 10 MW increase in wind generation will decrease the price in the Houston zone by 7.1¢/MWh, on average. We caution the reader against extrapolating these results beyond a marginal increase in wind generation, as the model results would be invalid.

A consistent pattern exists between the day-wind and night-wind variables in each zone and year because the coefficients on wind generation during the day (day-wind) are "more negative" than the coefficients of wind generation at night (night-wind). Wind generation has a stronger (i.e., more negative) effect on the balancing-energy price during the day than it does at night. The night-day differential is consistent with EWEA's literature review of the merit order effect in Europe.[35] This result is largely because the slope of the marginal cost curve, which the QSE balancing-energy market offer curve should mimic, is steeper during the day than it is at night. However, the magnitudes of this study are much lower because the studies reviewed by EWEA estimated the entire merit order effect (i.e., the total price effect of all of the wind dispatched in a given hour), while this research only estimates a marginal effect of *one* additional MWh of wind. The majority of the studies that the EWEA report reviewed also were based on production cost simulations, not econometrics, so they estimated the full merit-order effect rather than the marginal effect.

As shown in Table 7, wind generation has the greatest effect on balancing-energy prices in the West zone, where the majority of the wind capacity is located. The coefficients on night-wind and day-wind are also higher in 2008 compared to 2007, which is likely due to increased installed wind capacity. The estimates in Table 7 are incomplete because it is difficult to remove the daily and weekly pattern from balancing-energy prices and make them stationary without significantly transforming the price series. The ARMAX model isn't valid unless the dependent variable is stationary. It is possible to filter and/or transform the balancing-energy prices to make them stationary through methods such as the Fourier or wavelet transforms, but interpreting the wind coefficient becomes more difficult and the results may vary depending upon the transformation used.

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[35] Pöyry, "Wind Energy and Electricity Prices: Exploring the 'Merit Order Effect'," Literature Review for the European Wind Energy Association, (April 2010), http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/MeritOrder.pdf.

Frequently, researchers overcome this problem by analyzing the price of a specific hour each day (e.g., the price in hour 10 for each day in 2007), as this series is often easier to make stationary. Given the missing ARMAX estimations in Table 7, we also employed this hour-by-hour method, analyzing the price data separately for each hour in the day. This second group of estimates can also serve as a check of the reasonableness and magnitude of the estimates in Table 7.

We developed a second set of hour-by-hour ARMAX models that examine the zonal balancing-energy prices in each hour separately (i.e., one estimation examines only hour 10, another only hour 11, etc). The hour-by-hour strategy produces 288 separate estimates of the wind coefficient (24 hours x 4 zones x 3 years = 288 estimates). Multiple ARMAX specifications were estimated on the hour-by-hour balancing-energy price series and the most successful is presented here. The zonal balancing-energy price (unadjusted) was estimated to be a function of wind generation, natural gas generation, and three autoregressive terms (AR1, AR2, and AR3). The hour-by-hour ARMAX estimates for the North and South zones are presented in Table B1 of Appendix B and all of the estimates shown have errors free of serial dependence (i.e., white noise errors). The hour-by-hour coefficients have a similar magnitude to the ARMAX models on the full time series in Table 7.

Very few of the hour-by-hour estimates on wind generation in the North and South zones are statistically significant, particularly in 2008. This does not mean that wind did not have an effect on price. Rather, it means that this particular specification, which only views each hour in isolation and ignores the effect of the price in nearby hours, does not estimate one. The hour-by-hour models also provide a check of the reasonableness of the full time series mode estimates in Table 7.

Table B2 in Appendix B contains the hour-by-hour estimates for the Houston and West zones. Wind generation generally has a statistically significant impact on balancing-energy prices in the West zone. That effect also tends to be stronger during the day than at night. Additionally, the coefficients on wind generation tend to be higher in 2008 compared to 2007 and 2009, which is consistent with the estimates in Table 7. Like the North and South zones, the marginal effect of wind is largely statistically insignificant in the hour-by-hour ARMAX models of the Houston zone balancing-energy price.

Conclusion

Our econometric analysis suggests that wind generation has a small but measurable impact on balancing-energy prices in ERCOT. We also found that the marginal effect of an additional MWh of wind generation is greater during the day because the slope of the supply curve is steeper during the day than it is at night. The results presented in this paper differ from estimates of the merit order effect in Europe because those studies used production cost simulation models to estimate the entire merit-order effect, while this study only estimates the marginal merit-order effect. However, these results contain interesting information about the relationship between wind generation and the balancing-energy market price in ERCOT, and how it varies across the time of day and ERCOT's four zones.

Appendix A – Additional Figures and Graphs

Figure A1 - ERCOT Zones

Source: FERC, "Electric Power Markets: Texas (ERCOT)," Texas (ERCOT) Electric Regions, [http://www.ferc.gov/market-oversight/mkt- electric/texas.asp](http://www.ferc.gov/market-oversight/mkt-electric/texas.asp)

Figure A2 - 2007 ERCOT Balancing-Energy Market Price Percentiles by Zone

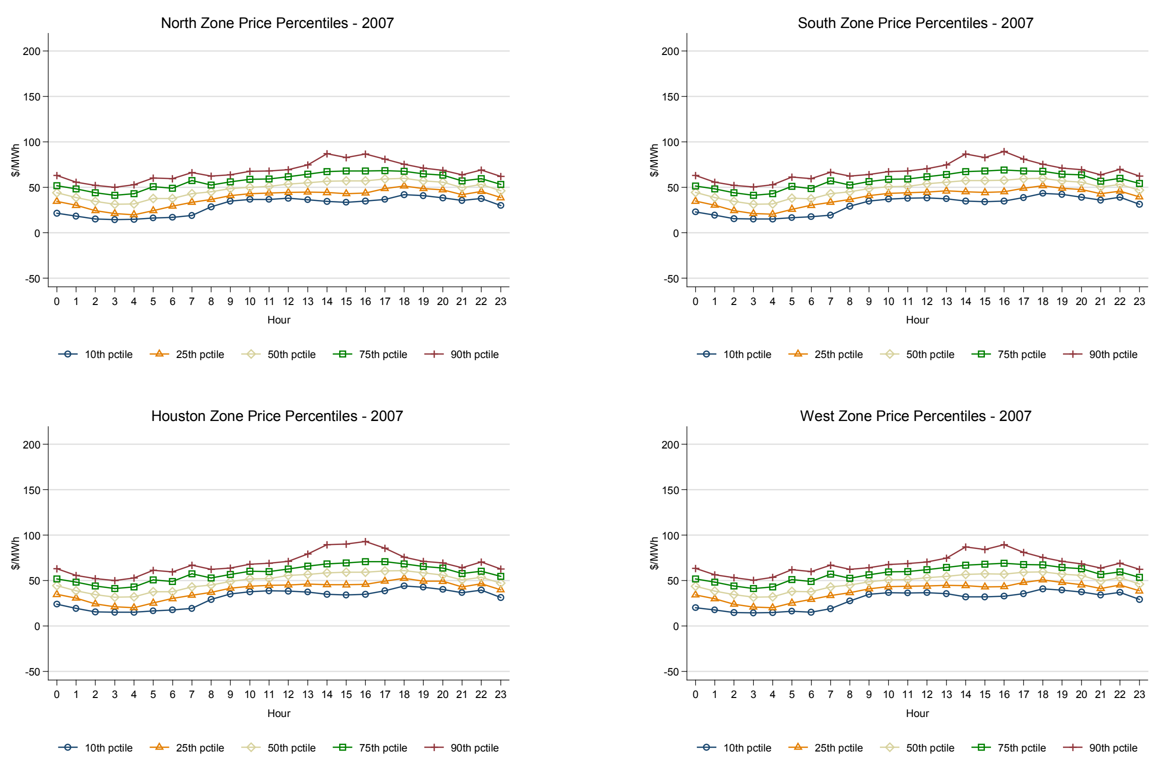
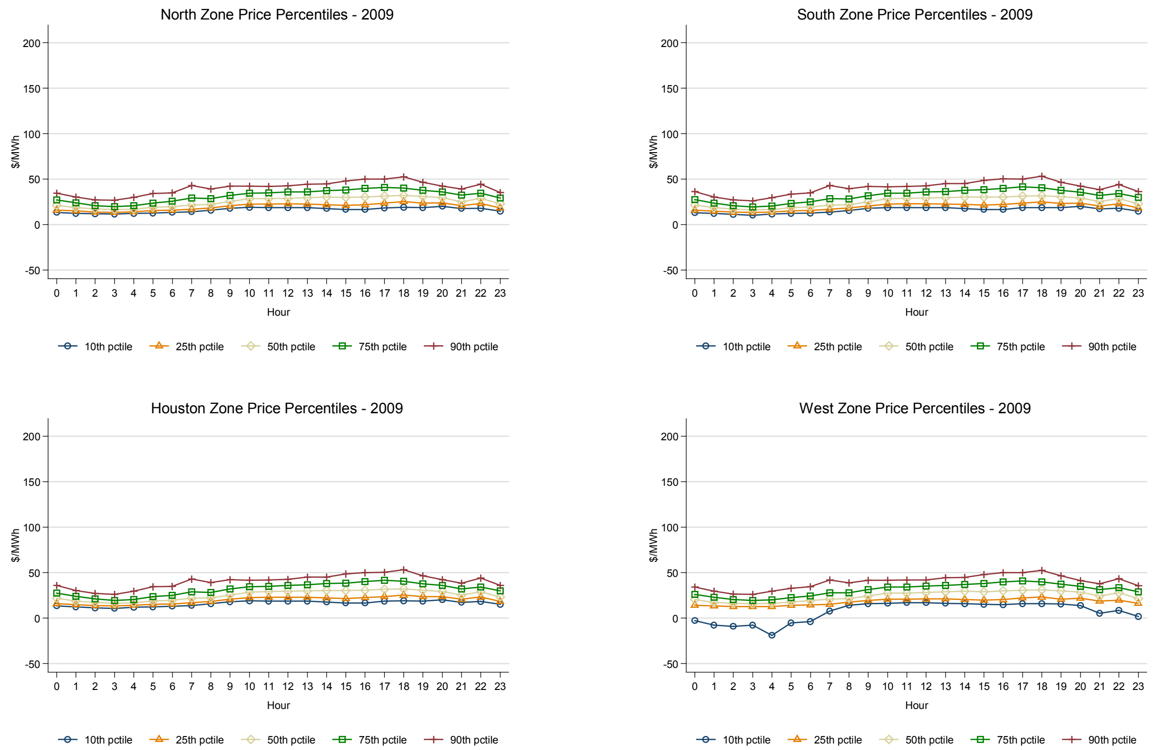


Figure A3 - 2008 ERCOT Balancing-Energy Market Price Percentiles by Zone

Figure A4 - 2009 ERCOT Balancing-Energy Market Price Percentiles by Zone



Appendix B – The ARIMA Model

When examining time-series data, such as the hourly zonal balancing-energy prices in ERCOT, it is reasonable to expect that a given observation at time *t* is related to and/or affected by observations of that variable in previous time periods (e.g., time period *t*-1). Ordinary least-squares regressions are inappropriate in such cases because they assume that the errors are independent over time. Researchers frequently use the ARIMA model to model time-series data with serial dependence in the errors. The ARIMA model is a blend of the moving average and autoregressive models so it allows for a very general form of serial dependence.

Moving average model

The moving average model posits that the dependent variable is a function of lagged values of the error term, known as "MA" terms. With a simple moving average model MA, one term is defined as follows: $y_t = \mu + \epsilon t \quad - \theta_1 \epsilon_{t-1}$ where θ_1 is the first moving average or MA (1) term. Higher order MA terms are the coefficients on the higher order lags of ϵ_t.

Autoregressive model

The autoregressive model assumes that the dependent variable y_t depends on previous, or "lagged," values of y_t itself, and the effect is captured by "AR" terms. A first-order autoregressive model is as follows: $y_t = \mu + \rho_1 y_{t-1} + \epsilon_t$ where ρ_1 is the first order autoregressive, or AR(1), term. Higher order AR terms are the coefficients on the higher order lags of y_t.

ARMA and ARMAX models

The ARMA model incorporates both AR and MA terms. In the ARMA(*p*,*q*) model, the dependent variable y_t is a function of p autoregressive terms and q moving average terms.[36] ARMA(*p*,*q*) models have the following general specification:

$$y_t = \mu + \rho_1 y_{t-1} + \rho_2 y_{t-2} + \cdots + \rho_p y_{t-p} + \epsilon_t - \theta_1 \epsilon_{t-1} - \cdots - \theta_q \epsilon_{t-q}$$

The ARMAX model is an ARMA model that includes exogenous variables. ARMA and ARMAX models that also apply differences to the dependent variable are referred to as Autoregressive Integrated Moving Average ("ARIMA") and ARIMAX models, respectively. After selecting the ARMAX specifications in this study, both the Bartlett and Portmanteau tests were performed on the errors to confirm that the ARMAX errors had the properties of white noise. Once an ARMAX specification with

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[36] William Greene, Econometric Analysis, 4th ed. (Upper Saddle River, NJ: Prentice-Hall, Inc., 2000).

"white noise" errors was found, we performed a Wald test to ensure that the AR coefficients were consistent with those of a stationary time series. The last step was to run sensitivities on the ARMAX specification and select a final model. The Akaike and Bayesian information criteria were used to select between competing ARMAX models that had white noise errors.[37]

Table B1 - Hour-by-Hour ARMAX Models Coefficient on Wind Generation

	North			South		
Hour	2007	2008	2009	2007	2008	2009
0			0.0008			0.0019
1						
2						
3						
4	-0.0064*			-0.0063*		
5	-0.0061*	-0.0012	-0.0006	-0.0064*	0.0001	-0.0009
6	-0.0019	0.0041		-0.0018	0.0052	-0.0001
7		-0.0004			0.0018	
8	-0.0030*	0.0017		-0.0025*	0.0039	
9	-0.0026		-0.0024	-0.0027	0.0015	-0.0026
10	-0.0040*	-0.0046	-0.0035*			-0.0036*
11	-0.0035*	0.0000	-0.0027*	-0.0027	0.0035	-0.0024
12	-0.0045			-0.0027		-0.0033
13	-0.0060		-0.0011	-0.0036	0.0033	
14		-0.0038	-0.0009		0.0050	-0.0025
15	0.0016	-0.0020		0.0026	0.0181	0.0015
16	-0.0069	0.0041	-0.0017	-0.0065		
17	-0.0105	-0.0013	-0.0035	-0.0079	0.0119	0.0004
18	-0.0101	-0.0031	-0.0039*		0.0048	-0.0053
19			-0.0097			
20	-0.0029†		-0.0034			-0.0004
21		-0.0014	-0.0020*		0.0007	-0.0023*
22	-0.0030	-0.0006	-0.0002	-0.0013		-0.0006
23	-0.0020				-0.0031*	-0.0020

* Statistically significant at 5%

† Statistically significant at 10%

Blank – inclusive estimate

[37] Rafał Weron, Modeling and Forecasting Electricity Loads and Prices: A Statistical Approach, (John Wiley & Sons, Ltd, January 2007).

Table B2 - ARMAX Model by Hour – Coefficient on Wind Generation

	Houston			West		
Hour	2007	2008	2009	2007	2008	2009
0		0.0110	0.0010	-0.0089*	-0.0171*	-0.0107
1				-0.0073*	-0.0174*	-0.0056*
2				-0.0083*		-0.0049*
3				-0.0121*		-0.0052*
4	-0.0062*			-0.0105*	-0.0154*	-0.0056*
5		0.0005	-0.0008	-0.0149	-0.0158*	
6	-0.0018	0.0038		-0.0051	-0.0127*	
7		0.0005		-0.0079*		
8	-0.0022*	0.0035		-0.0039*		
9	-0.0017		-0.0025†			-0.0048*
10			-0.0036*	-0.0054*	-0.0243*	-0.0062*
11			-0.0022	-0.0100*	-0.0171*	-0.0055*
12	-0.0028		-0.0025	-0.0142*	-0.0175*	-0.0049*
13	-0.0023	0.0055		-0.0109		-0.0045*
14		0.0040	-0.0027	-0.0115	-0.0230	-0.0037*
15	0.0027	0.0091		-0.0070	-0.0193*	
16		0.0147	-0.0007	-0.0142	-0.0195	-0.0046
17	-0.0074	0.0095	-0.0023	-0.0135	-0.0183	-0.0069
18	-0.0081		-0.0046*	-0.0199*	-0.0192*	-0.0074*
19			-0.0059	-0.0195*		-0.0132
20			-0.0011			-0.0086
21		0.0003	-0.0021*	-0.0090*	-0.0155*	-0.0062*
22	-0.0005		-0.0004	-0.0066*	-0.0167*	-0.0066*
23	-0.0011	-0.0034*	-0.0017	-0.0060*	-0.0252*	-0.0081*

* Statistically significant at 5%

† Statistically significant at 10%

Blank – inclusive estimate

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. **REPORT DATE** *(DD-MM-YYYY)*	2. **REPORT TYPE**	3. **DATES COVERED** *(From - To)*
November 2010	Subcontract Report	2007 to 2009

4. **TITLE AND SUBTITLE** The Relationship between Wind Generation and Balancing-Energy Market Prices in ERCOT: 2007-2009	5a. **CONTRACT NUMBER** DE-AC36-08-GO28308 5b. **GRANT NUMBER** 5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** E. Nicholson, J. Rogers, and K. Porter	5d. **PROJECT NUMBER** NREL/SR-5500-49415 5e. **TASK NUMBER** WE10.4221 5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Exeter Associates, Inc. 10480 Little Patuxent Parkway, Suite 300 Columbia, MD 21044	8. **PERFORMING ORGANIZATION REPORT NUMBER** LAM-9-99431-01
9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. **SPONSOR/MONITOR'S ACRONYM(S)** NREL 11. **SPONSORING/MONITORING AGENCY REPORT NUMBER** NREL/SR-5500-49415

12. **DISTRIBUTION AVAILABILITY STATEMENT**
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. **SUPPLEMENTARY NOTES**
NREL Technical Monitor: Erik Ela

14. **ABSTRACT** *(Maximum 200 Words)*
This paper attempts to measure the average marginal effects of wind generation on the balancing-energy market price in ERCOT with the help of econometric analysis.

15. **SUBJECT TERMS**
Grid; integration; Texas; generation; capacity; markets; electricity; congestion;

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT**	b. **ABSTRACT**	c. **THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1146-E(10/2008)