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A regression analysis of the prices of ancillary services operating reserves in the Texas Market

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A regression analysis of the prices of ancillary services operating reserves in the Texas Market

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

May,2018

Abstract

A regression analysis of the prices of ancillary services operating reserves in the Texas Market

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The University of Texas at Austin, 2018

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Ancillary services are an important part of the electricity market to keep the system in balance. This work studies ancillary services in the ERCOT electricity market. Having a better understanding of the relationship of ancillary services to other elements including the generation levels of the various resources, the Day-Ahead Market Price, quantities of ancillary services, and changes in market rules as specified in Nodal Protocol Revision Requests (NPRRs) is meaningful to the market. This paper uses a general linear regression model, a Panel Data Model and Seemingly Unrelated Repressors and finds that Regulation Down is different from other three ancillary services in general. The results shows that coal's generation levels and NPRR352 have a significant negative influence. The Day Ahead Market Price has a significant positive influence on all the ancillary services. Effects of other elements are different.

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Chapter 1: Background

INTRODUCTION

Power system operators are responsible for providing energy to end-consumers and ensuring system reliability. They maintain an array of ancillary services to ensure it is always possible to balance the supply and demand for energy in real-time. Ancillary services are an integral part of any well-functioning interconnected power system.

Ancillary services are an important part of the whole service and deserve focus. In the last decade, there has been increasing interest in how ancillary services are organized and procured, spurred by the Federal Energy Regulatory Commission (FERC)'s attempts to promote more competition in wholesale electricity markets. There are many studies related to the market and policy design. For ancillary services themselves, there has been analysis of quantity, however, there is little research related to the prices of the ancillary services. This is important as customers pay for the ancillary services and they can also be ancillary service resources themselves. Actually, in Order 888[1], FERC defined six generic types of ancillary services and indicated that customer loads should have opportunities to participate in these markets as part of its overall goal to facilitate more competitive. FERC has indicated that "demand must have the opportunity to supply operating reserves if it meets the necessary operational requirements, which should be designed to enable demand response participation" (Heffner 2007). So all the participants, customer, load-serving entities and generators are all interested in anticipating the prices of AS in ERCOT's formal

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1 *Standardized Transmission Service and Wholesale Electric Market Design*, FERC Working Paper FERC, March 2002.

market. This work is trying to fill the gap in our understanding the types and relative influence of different variables on ancillary services.

There are seven distinct power markets in the United States, each power market offers its own set of ancillary services, and precise definitions, requirements, and market mechanisms differ between markets. Although not regulated by the FREC, ERCOT is one of nine ISOs in North America, managing the flow of electricity on the Texas Interconnection that supplies power to 24 million Texas customers. By studying the ancillary services in such a large and open market we can better understand how different variables affect them.

ERCOT

The Electric Reliability Council of Texas (ERCOT) is the Independent System Operator (ISO) for the State of Texas. It was established in its current form as a power market operator in 2001. ERCOT[2] manages the scheduling of power on an electric grid consisting of 82,000 megawatts of generation capacity and more than 46,500 miles of transmission lines in order to keep electric power flowing to approximately 24 million Texas customers – representing about 90 percent of the state's electric load as illustrated *Figure.1*. Its stakeholders include consumers, cooperatives, generators, power marketers, retail electric providers, investor-owned electric utilities, transmission and distribution providers and municipally owned electric utilities.

PURPOSE OF THE THESIS

This work studies the relationship between ancillary services price and related variables to help all participating individuals and groups to anticipate the prices of AS in

[2] The data comes from ERCOT official website in 2018

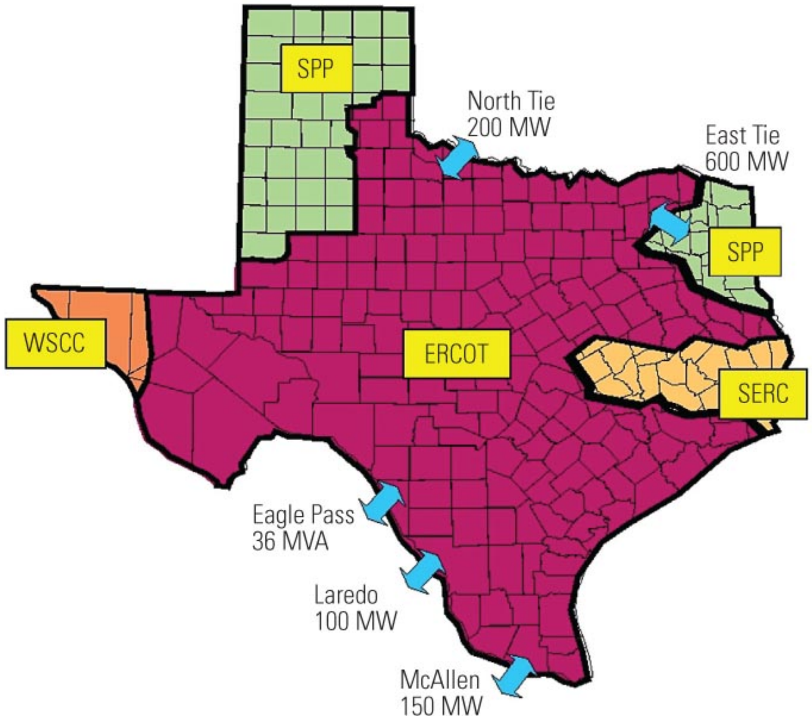

Figure 1 ERCOT Service Area (Power Magazine, June 2010)

ERCOT's formal market. Consumers can know why the pay such amount of the ancillary services and decide whether to join the supply-side operating reserves in the future if possible. Load-serving entities including the Retail Electric Providers, municipal utilities, and rural electric coops can then decide whether to rely upon ERCOT's formal market to procure AS or obtain their AS requirements through some other means such as self-arrangement, if they own generating capacity or have interruptible loads; or by contracting with a generator outside of ERCOT's formal market. Generators can make decisions regarding whether to offer generating capacity into AS markets, use that capacity to generate energy for sale into ERCOT's energy market, or provide it to a load-serving entity outside of a market. Government can also know the policies influence on the price and decide how to make market rules more friendly to customers, how to invest different generation resources, etc.

RESEARCH QUESTIONS

This work mainly focus on how well do generation levels of wind, coal, nuclear, gas, quantities of ancillary services required by ERCOT, Day Ahead Market price of electricity and changes in market rules explain changes in prices among a set of operating reserves Regulation Up, Regulation Down, Responsive Reserves, and Non-Spinning Reserves in ERCOT.

To be specific, for the generation level part, this research studies how a change in energy generation of wind, coal, nuclear and gas affect the prices of various operating reserves and studies whether the prices of certain ancillary services are more sensitive to these generation levels than other ancillary services. This work also studies the ancillary services that might fluctuate with respect to the quantity required by ERCOT, even though AS are specified as completely inelastic demand at most of the time. Finally, this work finds an answer of how have some specific changes in market rules affect prices in the markets for ancillary service.

THESIS STRUCTURE

The remainder of this study is organized as follows. Chapter 2 introduces four different types of Ancillary Services in ERCOT, starts from the market process, generation resource, required response time and concludes with a discussion of the difference between each other. Also, this part explained the reason why the following regression analysis treats Regulation Down separately. Chapter 3 presents the data and descriptive analysis of the data used in this research. It also include the introduction of the selected policy included in the regression analysis. The three methods to do the regression analysis are covered in Chapter 4. Chapter 5 presents the output from different regression models and the interpretation of the results. The details about the calculations performed are presented in an appendix at the end of the document. Finally, Chapter 6 synthesizes and presents major findings and conclusions of the regression review.

Chapter 2: Ancillary Services Description

INTRODUCTION OF ANCILLARY SERVICE

Electric power systems have two unique requirements which must be continuously satisfied in order to maintain overall system stability and reliability: (1) maintaining a constant balance between generation and load, and (2) managing power flows within the constraints of individual transmission facilities (Heffner 2007). The system operator must keep the system in balance, keep the voltage at the right level, and restart the system when it suffers a complete collapse. Load and generation are constantly changing, due to daily load patterns, instantaneous load variation, changes in variable generation output and generators tripping offline, so the system operator carries out these basic functions by purchasing what are called “ancillary services” (Stoft, 2002). The FERC has defined ancillary services as those “necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system” (FERC 2002; see Orders 888,889, and 2000).

Generation units in a power system are also major providers of an array of ancillary services that support system reliability. Energy storage and demand response resources can also provide ancillary services, but currently do so to a lesser extent than supply -side resources in most power systems. The specific services offered and exact definitions of each service vary from market to market. In general, market operators procure ancillary services from market participants according to reliability standards established by the North American Electric Reliability Corporation (NERC) and/or regional Coordinating Councils. Winning bids for energy and ancillary services are mutually exclusive, but a generator can be compensated for both generation and ancillary service provision in the same period as long as the capacities allocated to each do not overlap (ANL, 2016).

Power is the primary service, but ancillary services are needed to ensure reliable, high-quality power, efficiently produced. While there is considerable functional similarity in ancillary services across markets, there is also significant variation in the services response time and generation resources. There are six discrete ancillary services that are necessary in power systems, irrespective of market structure and design has been identified in (ORNL, 2007), but this work will only focused on four used in ERCOT.

ERCOT currently serves approximately 90% of the electrical load in Texas and, as its service territory is entirely within the state of Texas, is the only ISO/RTO in the United States that is not regulated by FERC. ERCOT operates a DAM for four ancillary services, Responsive Reserves, Regulation-up, Regulation-down, and Non-spinning Reserves. These services are co-optimized along with energy provisions in the DAM and ERCOT has different performance standards[3] on each of them (see Table.1).

Table 1 Summary of ancillary services offered by ERCOT

Product	Description
Regulation-up	Must immediately increase output in response to automated signals to balance Real-Time Demand and Resources
Regulation-down	Must immediately decrease output in response to automated signals to balance Real-Time Demand and Resources
Responsive Reserves	• Each Resource providing RRS must be On-Line

[3] ERCOT Nodal Protocols, *Section 8: Performance Monitoring*, 8.1.1.2.1. March 1, 2018

	• Ramping the Resource's Ancillary Service Resources Responsibility for RRS within ten minutes of the notice to deploy RRS • Immediately responsive to system frequency, and must be able to maintain the scheduled level of deployment for the period of service commitment.
Non-spinning Reserves	•Each Resource providing Non-Spin must be capable of being synchronized and ramped to its Ancillary Service Schedule for Non-Spin within 30 minutes. •Non-Spin may only be provided from capacity that is not fulfilling any other energy or capacity commitment.

MARKET PROCESS

In the DAM (see Table.2), ERCOT[4] establishes an Ancillary Services Plan, publishes relevant system information and identifies the Ancillary Service MW necessary for each hour of the Operating Day by 0600. Each QSE has specific Ancillary Service Obligation allocated to it by ERCOT, they can meet their obligations either through self-arrange from one or more Resources it represents and/or through an Ancillary Service Trade. QSEs must submit their bids and offers for ancillary services by 1000. The day-ahead market is executed between 1000 and at which point results are posted. QSEs then have the opportunity to make bilateral trades with other QSEs based upon the results of the day-ahead market; any such trades must be reported to ERCOT by 1430.

4 ERCOT Nodal Protocols, *Section 4: Day-Ahead Operations*, 4.2.1.1. April 11, 2018

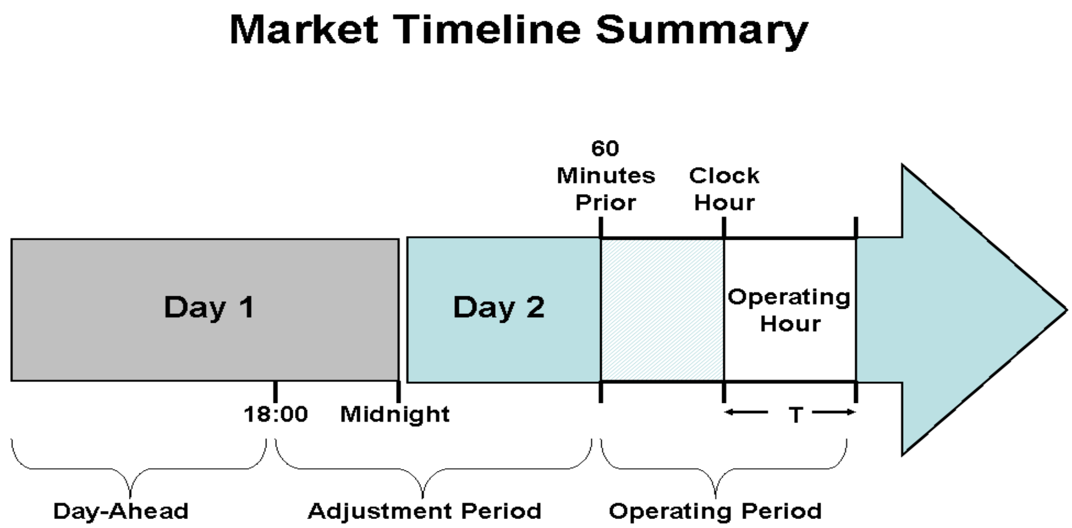

Figure 2 Market Time Summary by ERCOT

During the adjustment period in real-time operations[5], ERCOT shall allow QSEs to request to modify their Ancillary Service positions through a Reconfiguration Supplemental Ancillary Services Market (RSASM). However, this research will only focus on the DAM in this work.

REGULATION-UP AND REGULATION-DOWN

Regulation service is used to balance small fluctuations in supply and demand in real time constantly and spontaneously. It includes two services: Regulation-up and regulation down. They can balance the grid in a near-instantaneous fashion when supply and demand fluctuate due to a variety of factors, such as natural disaster, generation outages, generation intermittency, and transmission outages. This service is primarily provided by a dedicated resource, usually a generator, whose output is adjustable via Automatic Generation Control (AGC) or equivalent so that the dispatcher can

[5] ERCOT Nodal Protocols, *Section 6: Adjustment Period and Real-Time Operations*, 6.4.9.2. March 1, 2018

accommodate the minute-to-minute fluctuations of load and generation. Some markets offer only a single regulation product, while others offer separate products for both of them.

Regulation Services are essential in maintaining system frequency when there are discrepancies between loads and generation. If generation exceeds load, then frequency rises. If load exceeds generation then frequency falls. Although this is not relevant for ERCOT since the interconnection is a single balancing area, Regulation Services are also important in controlling inter-area power flows in the Eastern and Western interconnections. If generation exceeds load within one balancing area, then power will flow over the transmission line ties to adjacent areas. Regulation Services can be dispatched (controlled) based on either frequency or inter-area tie flow or both. In ERCOT, Governor dead bands have recently mostly been tightened in ERCOT to 17mHz from 36mHz through a central AGC which takes both inter-balancing area tie flows as well as system frequency into account. However, the governors mostly only respond when there has been a big contingency.

Regulation Reserves are deployed by ERCOT in response to changes in the system frequency and are used to maintain system frequency close to nominal of 60Hz. ERCOT uses these regulation services every hour of the year is deployed every 4 seconds to maintain frequency. This service is provided by Generation Resources. Resources providing regulation services must respond within seconds to regulation commands and fully comply with ERCOT instructions in less than five minutes.

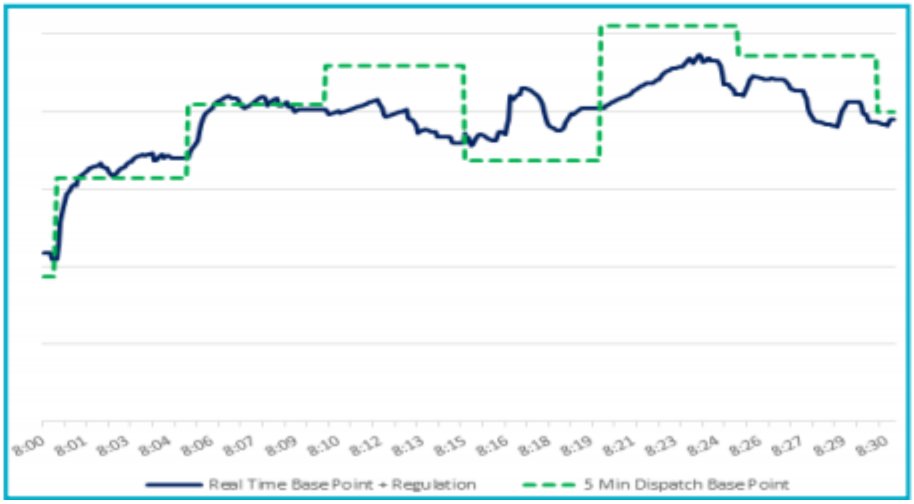

Figure 3 Regulation services performance line (ERCOT 2018)

SPINNING RESERVE – RESPONSIVE RESERVE

Spinning reserves operates to restore the balance between generation and load after the sudden unexpected loss of a major generator or transmission line. Normal system operations are infrequently punctuated by unexpected generator outages and transmission line failures. Planners account for these situations by making sure system operators have a coordinated set of operating reserves that can respond to contingencies without affecting overall reliability. As shown in *Figure 2*, Power system frequency drops suddenly when generation trips. Spinning reserves are provided by generation units that are online but are not generating at full capacity and can therefore increase their output quickly to provide additional capacity to the system. In ERCOT, RRS may be provided by: Unloaded Generation Resources that are On-Line; Load Resources controlled by high-set under-frequency relays; Hydro RRS; or Controllable Load Resources.

The concept and application of spinning reserves is relatively consistent across electricity markets, although the exact requirements like the response time, duration, and volume vary. Since there is insufficient time for energy markets to react, the dispatcher must have enough Spinning reserves available to compensate for the worst credible event, or contingency. For example, in the Texas power system, the simultaneous loss of two nuclear plants is recognized as the worst credible event and ERCOT maintains ~2600 MW of Spinning reserves, called responsive reserves in ERCOT. As shown in *Figure 3*, typically, generation units providing spinning reserves must be able to fully ramp up their generation to deploy the reserves within 10 minutes of receiving instructions to do so, although this requirement varies somewhat depending on the details of the market. Demand-side resources can also provide spinning reserves if they are able to similarly reduce their load within 10 to 15 minutes of receiving an instruction.

Requirements for Responsive Reserves in ERCOT are calculated in four-hour blocks on the basis of forecasted load and wind patterns. This service is provide by Capacity reserved from online Generation, Resources to provide Governor Response (all generators, including renewables, must have governor-like response).Up to 50% can be provided by load with under-frequency relays and the quantity required varies by inertia on system.

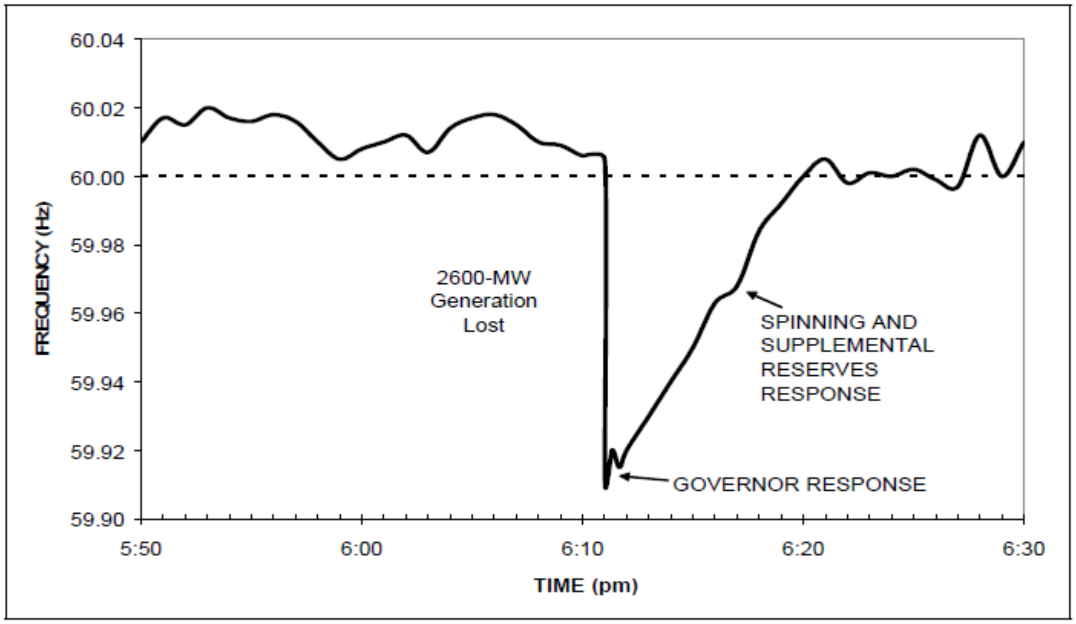

Figure 4 Use of Spinning Reserves to Restore Stability

OPERATING RESERVE – NON-SPINNING RESERVE

Non-spinning reserves are also intended to help the system recover from unplanned contingencies. However, non-spinning reserves can also be provided by generation units that are offline, as long as they are able to start up and increase their output to the target level within a predefined period of time, usually 10 to 30 minutes, depending on the market. Online units with available capacity can also provide non-spinning reserves. Therefore, the amount of non-spinning reserve capacity in a system is often calculated inclusive of any surplus spinning reserve capacity.

As shown is *Figure 4*, Non-Spining reserves in ERCOT are procured/used to ensure sufficient capacity is available to cover large Load/Wind/Solar forecast errors, or replace deployed responsive reserves. ERCOT maintain responsive reserves and non-spinning reserves at essentially all times. Responsive reserves are deployed whenever there is a contingency. Non-spinning reserves are deployed to allow for deployed reserves to be backed off so that they can be deployed again for the next contingency.

Resources providing Responsive Reserves must increase output in compliance with ERCOT instructions in less 10 minutes; those providing Non-spinning Reserves must comply in less than 30 minutes. The system requirement for Non-spinning Reserves is determined by first calculating the 95th percentile of net load[6] uncertainty from both the previous 30 days and the same month of the previous year. ERCOT then subtracts the Regulation-up requirement from this 95th percentile to obtain the Non-spinning Reserves requirement. During on-peak hours (hours 0700 through 2200 Central time, ERCOT also maintains a minimum Non-spinning requirement that is equal to the largest single unit in the system. The Non-spinning requirement is also never permitted to exceed 2000 MW during all hours of operation.

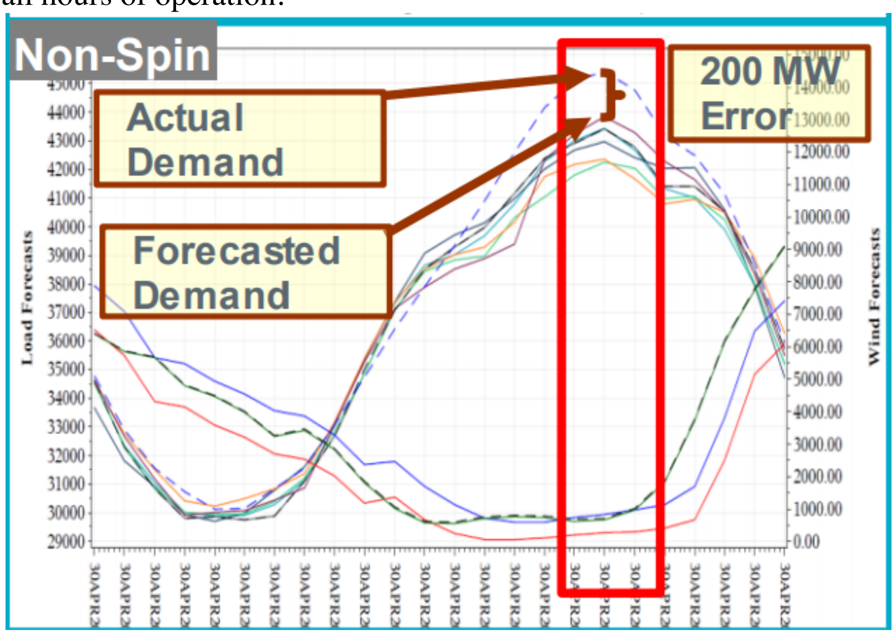

Figure 5 Non-spinning reserves service time (2018 ERCOT)

[6] Net load is defined as total load minus wind generation, and net load uncertainty is defined as the difference between the realized net load and forecast net load.

THE DIFFERENCE BETWEEN ANCILLARY SERVICES IN ERCOT

From Figure 3 and 4, we can tell the ancillary services are not only different in the definition but also show discrepancy in prices and quantity. August 2011 was an extremely hot month during a very warm summer season and energy price is extremely high, and so are the ancillary services prices. ERCOT has traditionally had the highest prices for Responsive Reserves amongst all ISOs, including several periods of sustained high prices between 2011 and 2012. This can be explained in part by the lack of a capacity market and high offer caps. ERCOT has also traditionally had the highest price for Non-spinning Reserves, as experienced several periods of prolonged high prices since their inception, an occurrence that has not been regularly seen in other markets.

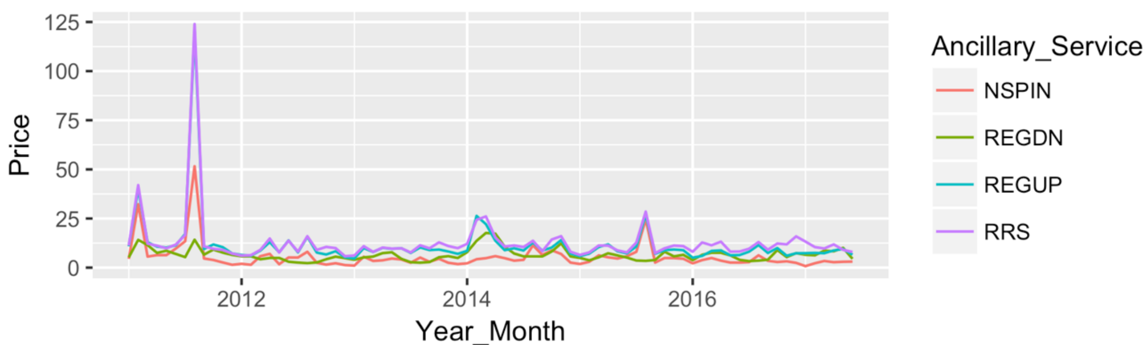

Figure 6 Average hourly Ancillary Services Price in each Month (unit: ($/MWh)

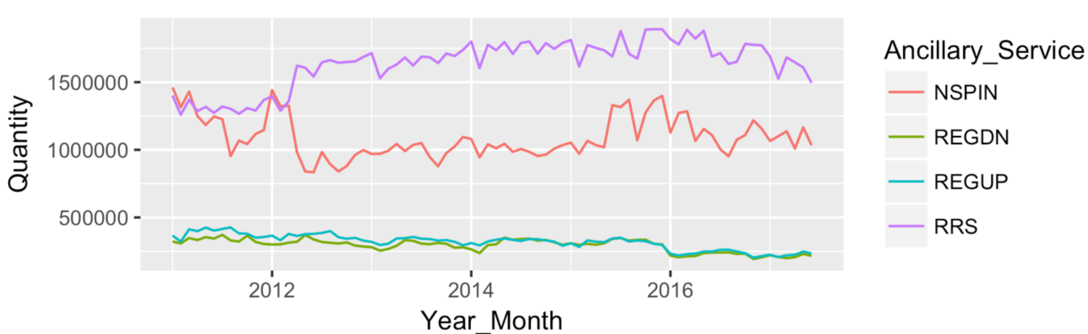

Figure 7 Sums of quantity of each Ancillary Services in each Month (unit: MW/day)

From the market rules, we can know that the production plus Regulation-up plus Responsive Reserves plus Non-spinning Reserves should be greater or equal to minimum capacity, and the production minus Regulation-down should be smaller or equal to maximum capacity. This means that production, regulation up, responsive reserve, non-spinning reserve will have prices that are related to the max capacity constraint being binding and prices will be higher during high demand, whereas regulation down prices will be high during low demand. From the Figure 5 [7]and 6, we can tell this directly, in peak times, like in summer, when the weather is hot and people turn on the air-conditioners, fans to cool off, and at 8pm, people come back home, turn on TVs, lights and begin cooking, the average prices of, regulation up, responsive reserve and non-spinning reserve also arrive at the highest value, whereas regulation down prices tell a different story. From all above, we would treat regulation down differently in our following up in the following research.

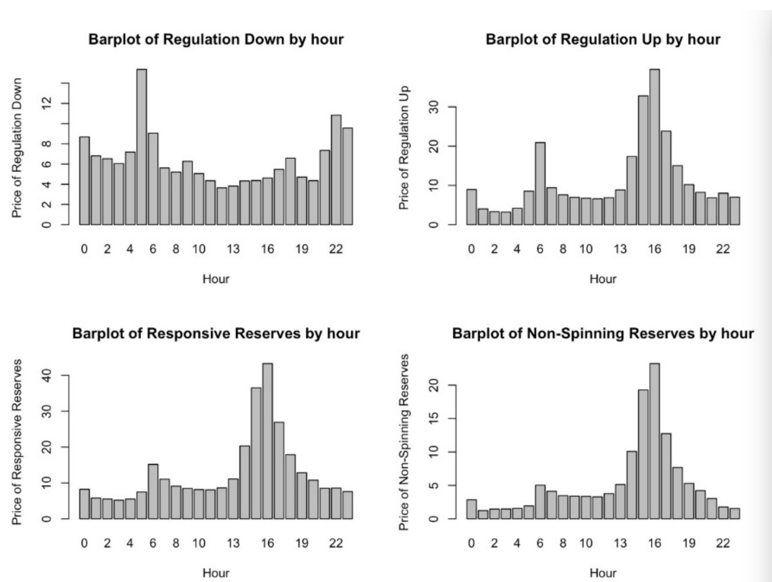

Figure 8 Hourly Average Ancillary Services Price from 2011.1-2017.6 (unit: ($/MWh)

[7] The data comes from ERCOT official website in 2018

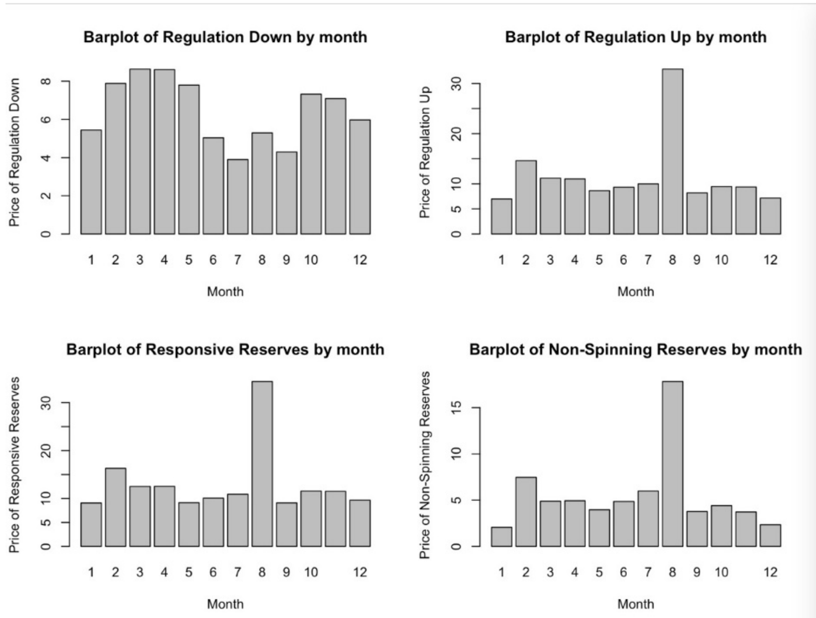

Figure 9 Monthly Average Ancillary Services Price from 2011.1 to 2017.6 (unit: ($/MWh)

Chapter 3: Data

This study focuses on the period of time from when ERCOT changed from zonal to nodal market in Jan, 2011 to June, 2017. To study the influence of policies on AS price, this work includes three influential policies (Andrade, 2017) in the regression models. This data combines analysis of qualitative and quantitative data.

QUANTITATIVE DATA

This study uses quantitative data from the ERCOT official website. The dataset is based on the ancillary service price data structure for 60-minute intervals (24 intervals per day). Ancillary service quantity data and DAM prices can be integrated as they have the same time structure. However, the data on generation levels have 15-minute interval, and 96 intervals per day. Then generation levels are summed and DAM prices averaged in each hour to align with the ancillary service price structure. Thus, the original dataset includes 56,872 observations in 2,370 days. Table 2, 3 and 4 summarize and describe the cleaned data set.

Generation Levels

This data includes the largest four sources of electricity generation (see Figure 8) by energy (unit: MWh), namely, gas (combining "gas" and "gas-cc" together as one variable), coal, wind, and nuclear, all together accounting for more than 98% of the electricity generation in ERCOT. As shown in Figure 9 and Table 2, natural gas is the dominant contributor to electricity generation in all analyzed years, but the specific generation value varies greatly around 16317.92 MWh/hour. Coal's generation is similar to natural gas in the beginning of 2012, and drops significantly since 2015, becoming the second largest contributor to total generation, but moves recently rebounded in 2017.

Generally, it is the second largest contributor to total generation, and the hourly generation fluctuates around 12954.22 MWh/hour. Nuclear and wind are similar to each other, but wind generation shows a rising trend in the end of 2015. Relatively speaking, nuclear and wind have a smaller contribution, and are less variable. Nuclear generation shows a much more stable trend, as the lowest average hourly generation range is 2693.4 MWh/hour in 2015 and the highest is 6641.5MWh/hour in 2011. Wind generation level increased suddenly from 2015 to 2017, the mean hourly generation increased from 4659.18 MWh/hour to 7919.81MWh/hour in only two years. The wind generation shows an inverse relationship with the other three types, generating at its peak when others hit the bottom and vice versa.

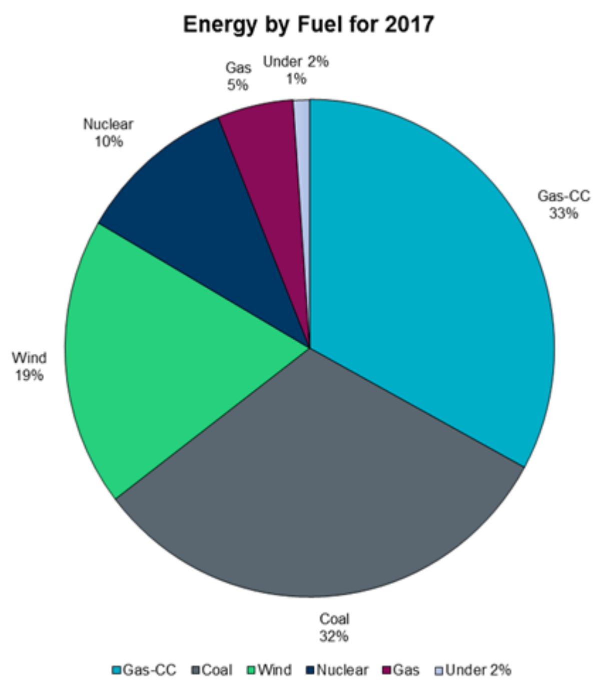

Figure 10 ERCOT latest generation by fuel pie chart (ERCOT, 2017)

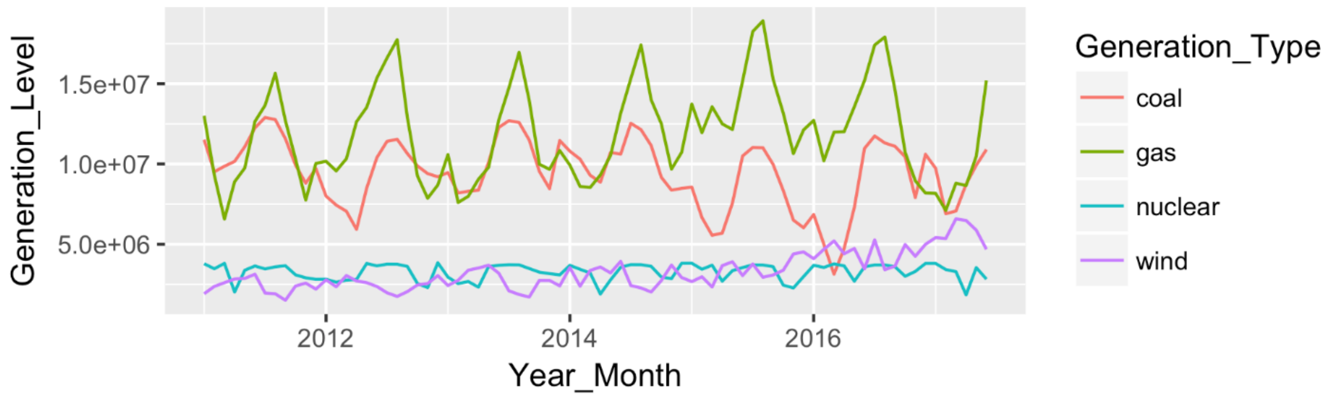

Figure 11 Monthly average generation level of different sources (unit: MWh/day)

The Day-ahead Market Price

The day-ahead market price ($/MWh) [8] are prices at every node or bus in ERCOT. These zones are the load zones, which are load-weighted averages of locational prices in each zone. This work uses the price weighted by the electricity generation in each zone and corresponding price as the data used in the following model. Then the mean value of DAM price in 2011, which is 45.74$ /MWh, is the highest in the study period, and the mean value of DAM price shows an apparently downward trend since 2014 to 2016. From the skewness of this data, we can tell it shows a stable trend recently, as the skewness is only 5.75 in the whole year of 2016.

Prices of Ancillary Services

ERCOT website includes hourly prices[9] of ancillary services in the nodal ERCOT market. It is a nicely-organized clearing price set. As shown in Figures 9 & 10 and Table

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[8] **Data source:**
http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13060&reportTitle=Historical%20DAM%20Load%20Zone%20and%20Hub%20Prices&showHTMLView=&mimicKey

[9] Data Source:
http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13091&reportTitle=Historical%20DAM%20Clearing%20Prices%20for%20Capacity&showHTMLView=&mimicKey

2. Ancillary Services price variance is large, and they are very expensive in the first year of the study period and become stable and cheaper recently. Responsive Reserves price is always the highest, followed by Regulation-Up, then Regulation-Down, and Non-Spinning Reserves price is the cheapest among them. Even though both belong to Regulation services, Regulation -Up and Regulation-Down's price have significant difference, but the difference become smaller as year goes by.

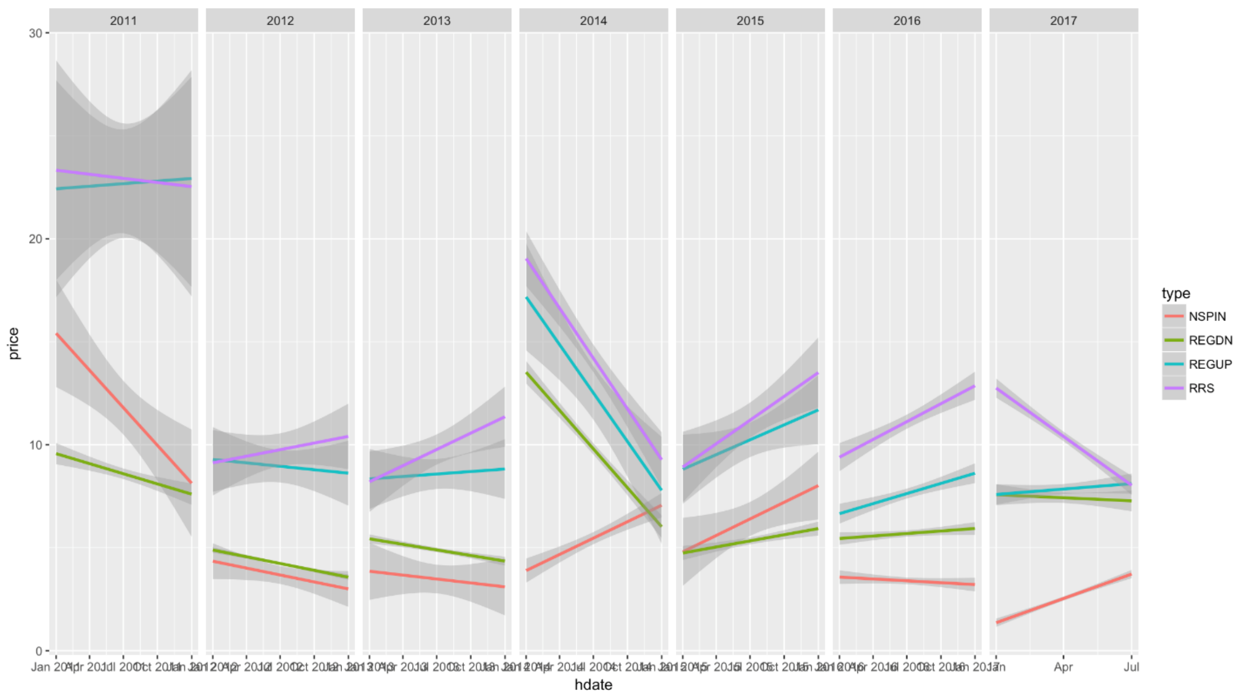


Figure 12 Average hourly Ancillary Services Price in each year (unit: $/MW)

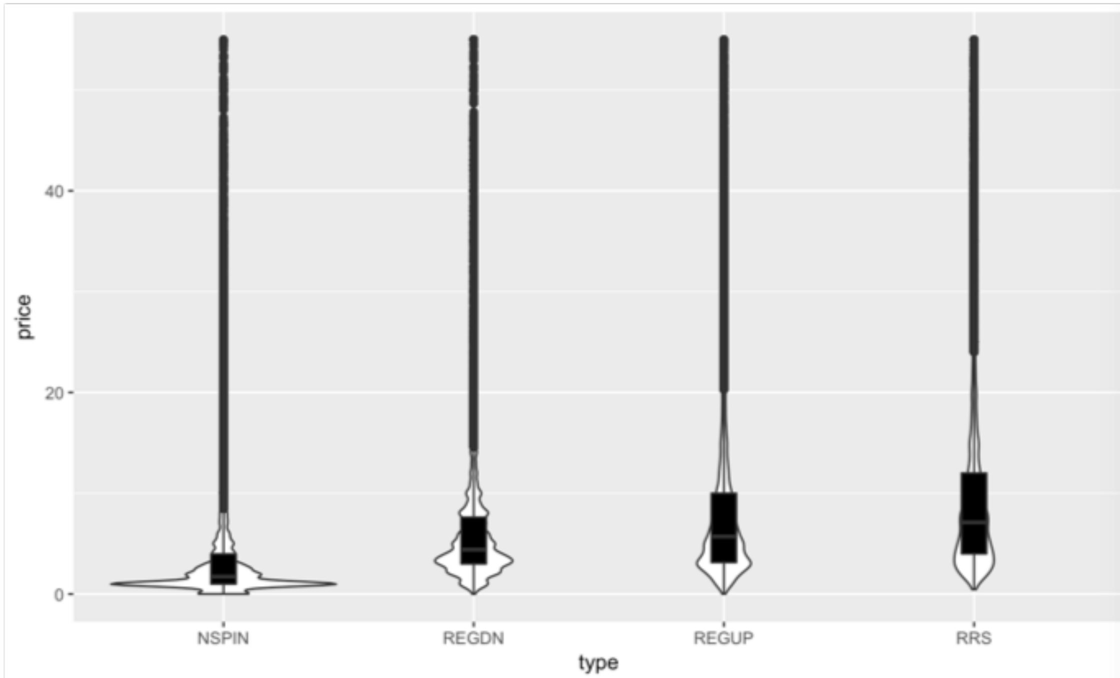


Figure 13 Ancillary Service Price Violin Plot

Table 2 Descriptive table of coal, gas, nuclear, wind generation levels and Day-ahead Market Price

	Coal (MWh/hour)							Gas (MWh/hour)						
	n	mean	sd	min	max	range	skew	n	mean	Sd	min	max	range	skew
All	56872	12954.22	3500.84	2162.66	25372.85	23210.19	-0.36	56872	16317.92	7071.67	1270.78	42991.16	41720.38	0.76
2011	8758	14851.68	2262.14	2702.7	24559.27	21856.57	-0.37	8758	14875.93	6534.83	1270.78	35431.72	34160.94	0.49
2012	8759	12490.96	3078.79	4831.3	25372.85	20541.55	0.03	8759	16515.11	6902.15	4320.56	42135.04	37814.48	0.98
2013	8735	14076.25	2908.06	5829.3	20164.6	14335.3	-0.01	8735	15330.62	7006.71	4362.7	39653.57	35290.87	1
2014	8758	13982.7	2630.14	6088.6	19575.61	13487.01	-0.12	8758	15956.7	7231.76	4030.31	40788.73	36758.42	0.75
2015	8735	11155.27	3550.63	3286.2	20073.16	16786.96	0.37	8735	19173.46	6684.07	6225.48	42991.16	36765.68	0.75
2016	8784	11512.36	4513.96	2162.66	19607.8	17445.14	-0.12	8784	17476.21	7189.92	3821.09	42807.58	38986.48	0.7
2017	4343	12265.85	3161.72	4545.1	19457.5	14912.4	0.01	4343	13456.26	6349.5	3350.69	38952.4	35601.71	1
	Nuclear (MWh/hour)							Wind (MWh/hour)						
	n	mean	sd	min	max	range	skew	n	mean	Sd	min	max	range	skew
All	56872	4494.51	801.5	948.72	7590.22	6641.5	-1.1	56872	4482.29	2991.98	8.47	15918.95	15910.48	0.82
2011	8758	4526.6	789.25	948.72	7590.22	6641.5	-1.06	8758	3230.25	1786.06	28.28	11659.07	11630.79	0.08
2012	8759	4374.8	857.07	1346.83	5187.2	3840.37	-0.91	8759	3391.32	2061.17	8.47	8532.6	8524.13	0.22
2013	8735	4378.64	776.55	2455.93	5400.6	2944.67	-0.68	8735	3726.19	2313.57	14.24	9542.38	9528.14	0.48
2014	8758	4484.84	811.52	2358.7	5149.9	2791.2	-1.08	8758	4125.19	2557.78	20.88	10935.3	10914.42	0.43
2015	8735	4498.62	803.86	2446.8	5140.2	2693.4	-1.16	8735	4659.18	2883.6	37.9	13725.68	13687.78	0.46
2016	8784	4792.32	556.04	2410.87	7405.67	4994.8	-1.94	8784	6050.92	3380.67	127.15	15727.39	15600.24	0.28
2017	4343	4313.16	969.15	2061.45	5130.79	3069.34	-0.81	4343	7919.81	3822.67	106.28	15918.95	15812.67	-0.08

Day-ahead Market Price ($/MWh)						
n	mean	sd	min	max	range	skew
56872	32.26	57.07	1.19	2636.12	2634.94	28.03
8758	45.74	125.27	8.56	2636.12	2627.56	14.56
8759	29.18	40.69	8.05	1531.6	1523.54	22.89
8735	33.5	17.04	11.6	551.29	539.69	10.98
8758	39.68	35.39	5.02	1352.3	1347.28	18.21
8735	26.25	40.13	4.15	2244.3	2240.14	33.64
8784	22.82	14.27	1.19	281.03	279.84	5.75
4343	24.95	9.74	2.08	103.24	101.16	2.03

Table 3 Descriptive table of Ancillary Service Price

	Regulation-Down Price($/MW)							Regulation-Up Price ($/MW)						
	n	mean	sd	min	max	range	skew	n	mean	sd	Min	max	range	skew
All	56872	6.49	9.14	0	593	593	14.35	56872	11.46	60.97	0.01	4999	4998.99	34.39
2011	8758	8.58	12.26	0.14	593	592.86	20.93	8758	22.67	125.63	0.47	2584.94	2584.47	14.38
2012	8759	4.23	3.23	0.01	150	149.99	13.18	8759	8.95	37.5	0.01	1456.49	1456.48	26.16
2013	8735	4.89	5.17	0.01	150	149.99	8.36	8735	8.58	34.57	0.01	3000.5	3000.49	75.19
2014	8758	9.77	13.23	0.5	310.08	309.58	7.93	8758	12.48	61.95	1	4999	4998	62.59
2015	8735	5.34	8.08	0	240	240	12.25	8735	10.25	39.95	0.01	2241.46	2241.45	34.75
2016	8784	5.69	7.31	0.61	216.38	215.77	7.35	8784	7.63	11.49	0.01	246.87	246.86	8.13
2017	4343	7.42	8.53	0.36	80.83	80.47	3.36	4343	7.85	8.25	0.94	200	199.06	5.73
	Responsive Reserve Price ($/MW)							Non-Spinning Reserve Price ($/MW)						
	n	mean	sd	min	max	range	skew	n	mean	sd	min	max	range	skew
All	56872	12.95	58.13	0.45	3000	2999.55	29.34	56872	5.46	33.42	0.01	3000	2999.99	38.22
2011	8758	22.93	127.28	0.67	2605.75	2605.08	14.27	8758	11.77	62.23	0.01	1500	1499.99	14.58
2012	8759	9.76	37.86	0.45	1461.06	1460.61	25.56	8759	3.67	20.76	0.01	1310.54	1310.53	37.61
2013	8735	9.78	34.87	0.84	3000	2999.16	73.25	8735	3.48	33.04	0.9	3000	2999.1	85.62
2014	8758	14.16	31.82	2	1285.73	1283.73	21.98	8758	5.48	14.03	0.77	435.7	434.93	14.01
2015	8735	11.21	40.72	0.97	2255.06	2254.09	33.81	6.41	39.31	0.71	2241.47	2240.76	36.66	0.42
2016	8784	11.13	16.34	1	485	484	14.12	8784	3.39	7.85	0.01	190	189.99	10.99
2017	4343	10.39	7.89	1.29	73.16	71.87	2.25	4343	2.54	3.42	0.01	43.5	43.49	3.48

Quantities of Ancillary Services

The procured quantities[10] of the ancillary services data is the total number by adding Generation Resource and Load Resource together. Regulation Services are mostly procured from Generation Resource, however a good portion of Responsive Reserve is procured from Load resource. Figure 11& 12& 13 and Table 2 show that the quantity of ancillary services procured through the DAM are much more stable, having smaller standard deviation so it shows a more constant trend. Responsive Reserve accounts for nearly 50% of the total amounts ERCOT procured. Non-Spinning Reserve takes up more

[10] Ancillary services quantities required =amounts self-arranged + amounts procured through a day-ahead market + amounts procured through any supplemental ancillary services market

than 30 percent, Regulation-Up and Regulation-Down occupies the remaining 20% equally.

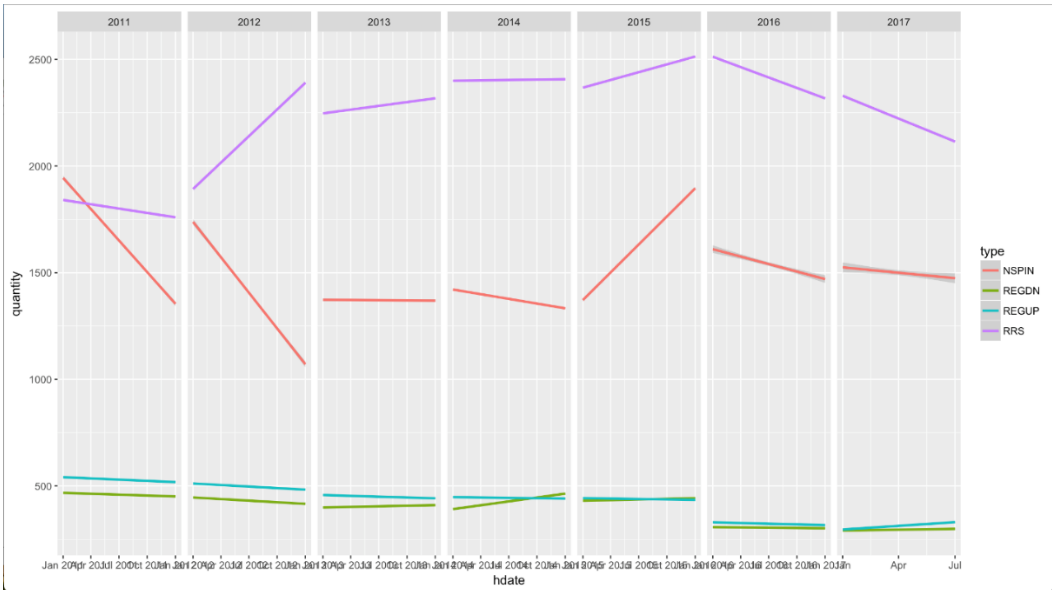


Figure 14 Average hourly Ancillary Services quantity procured through the DAM in each year (unit: MWh)

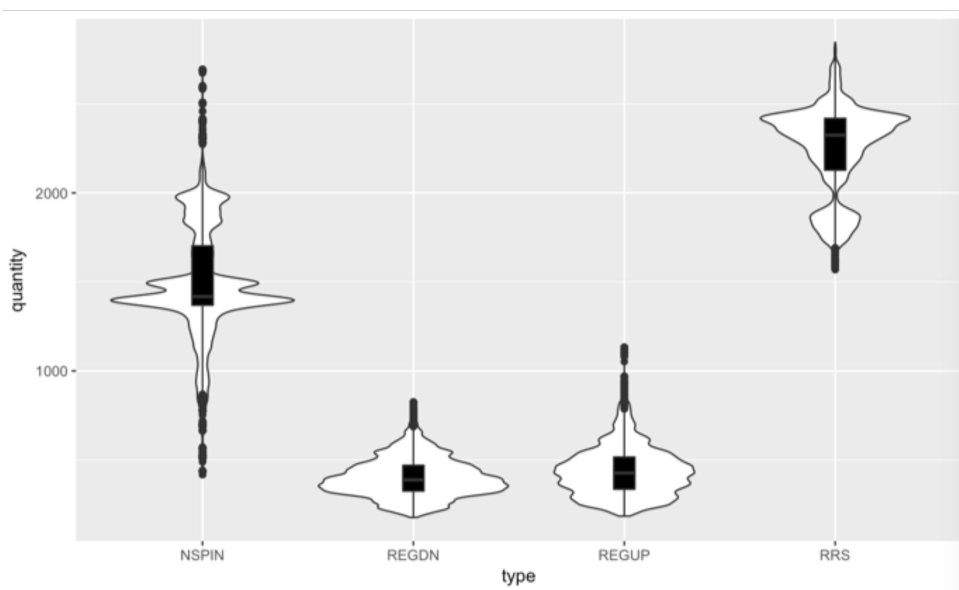


Figure 15 Ancillary Service Quantity Violin Plot

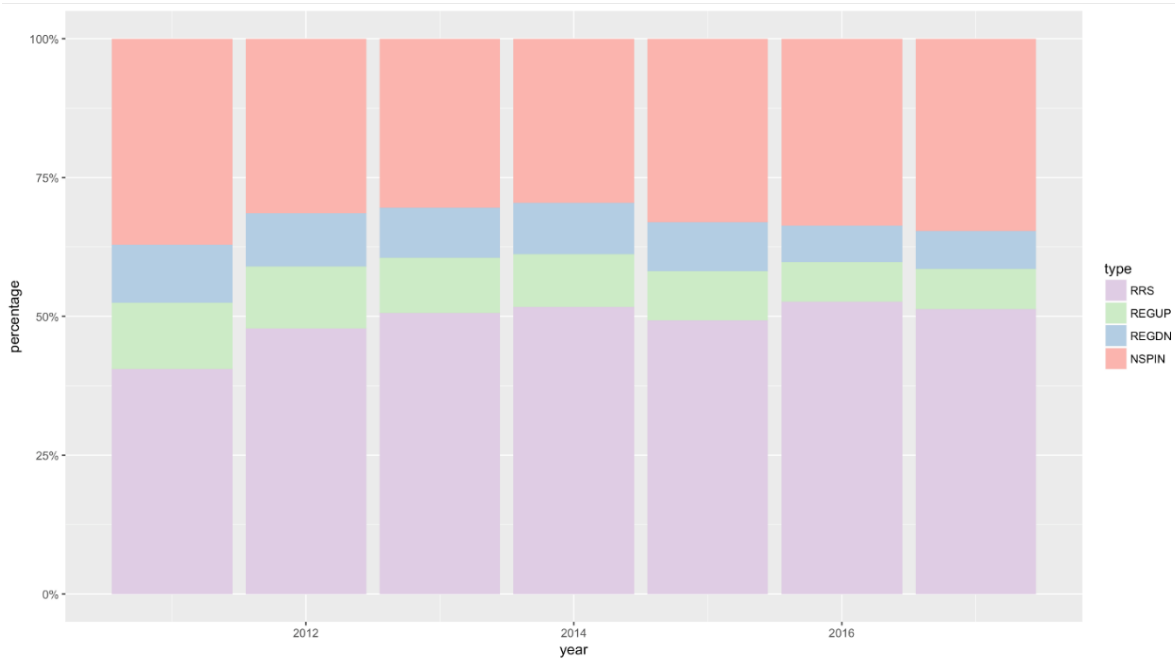


Figure 16 Percentage of Ancillary Services procured through the DAM in each year

Table 4 Descriptive table of ancillary amounts procured through the DAM

	Regulation-Down Quantity (MWh/hour)							**Regulation-Up Quantity (MWh/hour)**						
	n	**mean**	**sd**	**min**	**max**	**range**	**skew**	**n**	**mean**	**sd**	**min**	**max**	**range**	**skew**
All	56872	401.8	109.16	177.7	826.8	649.1	0.52	56872	436.84	137.87	184.8	1133.6	948.8	0.73
2011	8758	459.36	97.64	249.9	824.6	574.7	0.45	8758	529.64	141.3	204.9	1133.6	928.7	0.69
2012	8759	431.09	99.26	246.1	826.8	580.7	0.94	8759	497.17	131.89	184.8	938.5	753.7	0.39
2013	8735	404.68	95.68	237.3	814	576.7	0.91	8735	449.8	117.47	215.1	809.4	594.3	0.55
2014	8758	427.86	95.34	267.6	815	547.4	0.87	8758	444.2	114.85	238.7	1131	892.3	1.28
2015	8735	436.79	91.18	295.4	728.5	433.1	0.91	8735	438.93	113.54	252	897.8	645.8	1.12
2016	8784	304.39	82.47	177.7	613.1	435.4	1.23	8784	323.05	94.9	188.5	693.1	504.6	1.17
2017	4343	294.99	82.84	181.7	564.8	383.1	1.02	4343	313.11	91.71	190.5	693	502.5	1.64
	Responsive Reserve Quantity (MWh/hour)							**Non-Spinning Reserve Quantity (MWh/hour)**						
	n	**mean**	**sd**	**min**	**max**	**range**	**skew**	**n**	**mean**	**sd**	**min**	**max**	**range**	**skew**
All	56872	2245.09	248.83	1568.7	2844.9	1276.2	-0.76	56872	1496.19	317.63	418.1	2693.1	2275	0.05
2011	8758	1800.19	76.32	1568.7	1944.2	375.5	-0.7	8758	1648.99	299.92	773.1	1994.4	1221.3	-0.67
2012	8759	2141.25	198.11	1652.4	2548.5	896.1	-0.37	8759	1404.58	372.16	418.1	1994.8	1576.7	-0.5
2013	8735	2282.24	91.64	1995.3	2495	499.7	-0.6	8735	1370.86	162.12	838.3	1514.8	676.5	-1.48
2014	8758	2403.44	57.08	2162.6	2646.7	484.1	-1.14	8758	1376.94	92.81	806.3	1500.4	694.1	-3.27
2015	8735	2440.31	131.07	2013.7	2844.9	831.2	0.25	8735	1633.79	241.19	1142.9	2000.2	857.3	0.25
2016	8784	2414.67	142.19	1925.1	2792.1	867	-0.41	8784	1540.26	419.1	663.5	2693.1	2029.6	0.31
2017	4343	2221.96	106.84	1827.2	2427.3	600.1	-1.49	4343	1499.55	389.58	686.3	2418.1	1731.8	-0.14

QUALITATIVE DATA

Andrade.et al’ s previous research, which obtains the impact significance of changes in nodal protocol revisions as well as changes in installed generation of wind power, shows that better prediction of wind generation, fewer regulation services will be procured through the DAM?, or will requirements increase?. This work takes the significant three policies in that research and sets corresponding dummy variables into the regression model to test whether they show same significant influence on ancillary service price. Regarding network protocol revisions purely associated to wind power in their research, the three significant policies are listed in Table 5.

Table 5 Policies selected to do the regression

Stage	No.	Name	Description	Start	Before[11]	After[12]
Stage1	**NPRR352**	Real-Time HSL Telemetry for WGRs	It is related with improvements in the prediction of the maximum sustained energy production capability of a wind generator after curtailment.	6/1/2011	3647	53225
Stage2	**NPRR361**	Real-Time Wind Power Production Data Transparency	It requires the submitting of 5 min resolution wind data for real time purposes.	9/1/2011	5855	51017
Stage3	**NPRR460**	WGR Ramp Rate Limitation	It increases the wind powered generation resource ramp rate limitation from 10% per minute of nameplate rating to five minute average of 20% per minute of nameplate rating with no individual minute exceeding 25%.	12/1/2012	16797	40075

[11] Number of observations before the policy issued At what point in time do your observations begin and end?

[12] Number of observations after the policy issued

Chapter 4: Methodology

VARIABLES SELECTION

This work tries to include ancillary services related variables as much as possible. After tests including the residuals linear relationship with all the variables, multicollinearity, and autocorrelation within residuals. This work removes variables such as the natural gas price as measured at Henry Hub in Louisiana, total electricity generation and keeps the following variables in all the regression models: generation level of coal, gas, nuclear and wind, quantity of ancillary services procured through the DAM, DAM price and three related market changes.

To be specific, endogeneity needs to be considered since the quantities of the ancillary services procured through the DAM may be affected by the market prices of ancillary services. In the models presented here, the quantities of ancillary services procured through the DAM are assumed to be exogenous. Yet, if they are truly endogenous (i.e., if anticipated market prices may affect a load-serving entity's decisions regarding whether to either self-arrange or rely upon the DAM to procure these services), then the estimated coefficients representing the quantities procured will be biased. However, to simplify this process, this work tests whether there is linear relationship between all the variables, by using Pearson's product-moment correlation method to calculate the simple correlation coefficients between each of the independent variables and the residuals, instead of the Hausman test, which would more rigorously test for endogeneity. The null hypothesis for this test is that the true correlation is equal to 0, results marked as yellow in Table 6 mean that it failed to reject the null hypothesis, which means a linear relationship exists between the residuals and the independent variables. As shown in Table.5, there is no linear relationship between the residuals of General Linear

Regression models and other variables. However, there are linear relationships between residuals in the panel data model with coal, gas, nuclear, wind and quantity. We currently do not know how to interpret the correlations, since the residuals have two dimensions rather than one dimension. We keep the model in the analysis and will do more research in the future. The linear relationship also exists between the residuals and the quantity in the SUR model. This correlation may suggest that the price and the quantity of the AS which is procured are endogenous. This means that there is feedback among the price and quantity. This makes sense, since it is a market. This is the "identification problem" in economics. Consequently, we must acknowledge that there is some likely bias in the coefficient estimates presented here to quantify the relationship between the prices of ancillary services and the quantities of ancillary services procured through the DAM.

Table 6 All residuals relationship in different Mode

Pearson's product-moment correlation-P Value										
Alternative hypothesis: true correlation is not equal to 0										
Method	**Residuals**	**Gas**	**coal**	**nuclear**	**wind**	**DAM**	**Quantity**	**Stage_1**	**Stage_2**	**Stage_3**
General Linear Regression	Regulation Down	1	1	1	1	1	1	1	1	1
	Regulation UP	1	1	1	1	1	1	1	1	1
	Responsive Reserve Services	1	1	1	1	1	1	1	1	1
	Non-Spinning Reserves	1	1	1	1	1	1	1	1	1
Panel Data Model	Pooling-three	0.624	0.0002949	2.67E-10	0.0139	0.283	< 2.2e-16	1	1	1
	Fixed-three	0.7334	0.004424	5.08E-10	0.009184	0.3339	0.2922	1	1	1
Seemingly Unrelated Model-	Regulation UP	1	1	1	1	1	0.000232	1	1	1
	Responsive Reserve Services	1	1	1	1	1	0.001603	1	1	1
	Non-Spinning Reserves	1	1	1	1	1	1.44E-07	1	1	1

The variance inflation factor (VIF) is used to test the multicollinearity in the second step. VIF quantifies how much the variance is inflated, and the variances of the estimated coefficients are inflated (>4) when multicollinearity exists. As shown in Table 6, there is no multicollinearity exist in the remaining variables.

Table 7 Multicollinearity Test-VIF table

The autocorrelation function (ACF) for a time series is used to test the whether the variable has linear dependence with itself at two points in time. Unfortunately, autocorrelation exists in every model this work uses. For example, as seen in Figure 15, the series residuals value is apparently large than the 95% confidence level line (blue line), ACF figures of other models are included in the Appendix. This work try to add season/hour/month impact and auto regression to remove the autocorrelation, but none of them is useful. This implies that none of the models in this work is adequate to analyze the market, but as the market itself is a complicated topic, much more things need to be done in the future. This work just presents what we found and gives a future research direction.

Multicollinearity Test			
	Rugulation Up	Responsive Reserves	Non-Spinning Reservces
coal	1.65081	1.765621	1.690031
gas	1.586875	1.67975	1.683746
nuclear	1.069791	1.067151	1.074818
wind	1.341997	1.33359	1.332303
DAM	1.098958	1.098887	1.099875
Quantity	1.223016	2.893696	1.174225
stage_1	2.571288	2.580819	2.626279
stage_2	3.147968	3.359708	3.18143
stage_3	1.599098	2.5125	1.499606

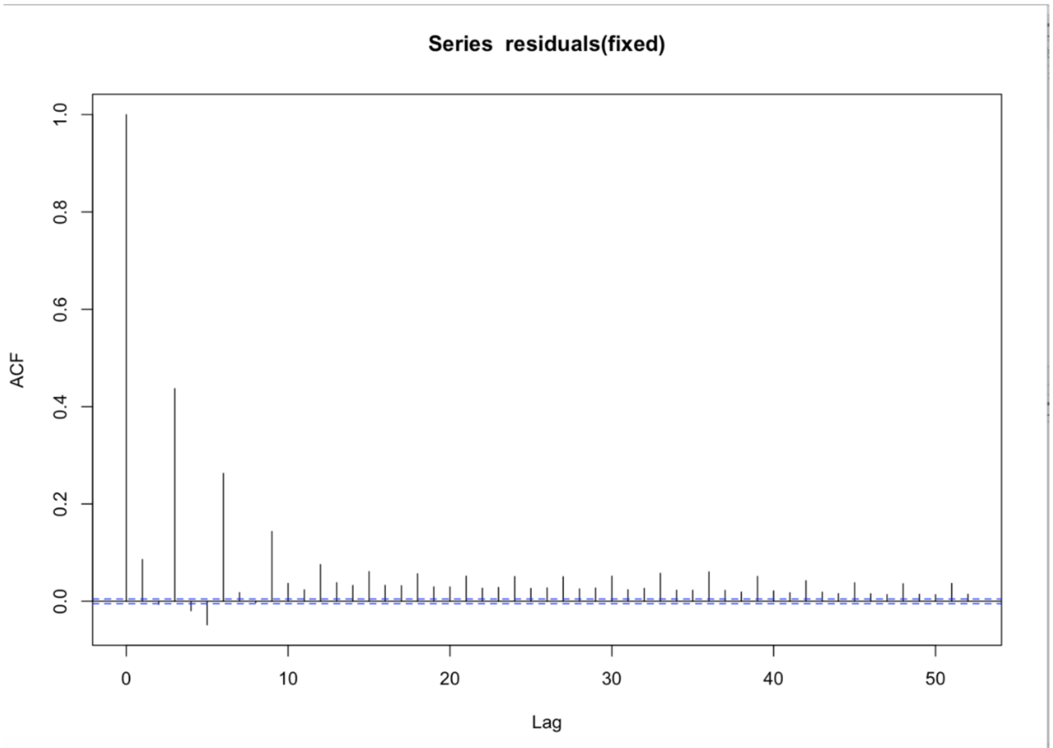


Figure 17 ACF of fixed model in the panel data model

REGRESSION MODELS

This work uses three different models to do the regression: General Linear Regression Model, Seemingly Unrelated Model, and Panel Data Model. This three models are different in how they consider β and random errors. As Chapter 1 mentioned, Regulation-Down is different from the other three Ancillary Services in ERCOT. So this research runs SUR regression and Panel data Model without Regulation-Down.

Generalized linear models

Generalized linear models (GLMs) are a means of modeling the relationship between a variable whose outcome we wish to predict and one or more explanatory variables. The predicted variable is called the target variable and is denoted y. In this study, the target variable is the Ancillary Services price. For quantitative target variables such as those above, the GLM will produce an estimate of the expected value of the outcome. The explanatory variables, or predictors, are denoted $x_1 . . . x_p$., where p is the number of predictors in the model. The random effect is denoted as ϵ_i. The equation used in this works is:

$$\begin{aligned} price_i \; &= \beta_0 + \beta_1 coal + \beta_2 gas + \beta_3 nuclear + \beta_4 wind + \beta_5 DAM + \beta_6 quantity_{i7} \\ &\quad + \beta_7 \mathrm{as.factor(stage1)} + \beta_8 \mathrm{as.factor(stage2)} + \beta_9 \mathrm{as.factor(stage3)} \\ &\quad + \epsilon_i \end{aligned}$$

$i = 1, Regulation - Down$

$i = 2, Regulation - Up$

$i = 3, Responsive\ Reserves$

$i = 4, Non - Spinning\ Reserves$

(1)

Seemingly Unrelated Regression

The seemingly unrelated regressions (SUR) is a model that is usually used in econometrics, and is a generalization of a linear regression model that consists of several regression equations, each having its own dependent variable and potentially different sets of exogenous explanatory variables (Zellner, 1962). Each equation is a valid linear regression on its own and can be estimated separately.

The first assumption of the model is that if $M\ (i = 1,2, \ldots, M)$ represents the equation number (M dependent variables), k independent variables and each equation has $T (t = 1,2, \ldots, T)$ observations, the t should be large. After stacking observations corresponding to the i-th equation into t-dimensional vectors and matrices, then the model can be written in vector form as

$$y = X\beta + u \tag{2}$$

In this form, y is an MT × 1 vector, X is an MT × k matrix, β is a k × 1 and u is an MT × 1 vector of disturbances. The second assumption is that $E(u|X_1, X_2, \dots, X_M) = 0$, $E(uu'|X_1, X_2, \dots, X_M) = \Omega$. The third assumption in SUR is that disturbance terms are uncorrelated with all regressors, so that $E[u_i^T X_i] = 0 \forall i, j$.

The covariance matrix of all disturbances is $E[uu^T] = \Omega = \sum \otimes I_T$, where $\sum = [\sigma_{ij}]$ is the (contemporaneous) disturbance covariance matrix, $\otimes$ is the Kronecker product.

The last assumption is that if all the repressors are exogenous, we can use the seemingly unrelated regression here. As the true covariance matrix of the disturbance terms is generally unknown, Feasible generalized least squares (FGLS) estimation are usually used as the FGLS estimator is based on an estimated covariance matrix of the disturbance terms, it is only asymptotically efficient. These estimators can be obtained by

$$\hat{\beta} = (X^T \widehat{\Omega}^{-1} X)^{-1} \tag{3}$$

The covariance matrix of these estimators can be estimated by $\widehat{COV}[\hat{\beta}] = (X^T \widehat{\Omega}^{-1} X)^{-1}$

Panel data model

A panel data model is used in this research by considering the ancillary services as a group. .Panel data models provide information on individual behavior, both across individuals and over time. The data and models have both cross-sectional and time-series dimensions. It can be balanced when all individuals are observed in all time periods that it will allow the researcher great flexibility in modeling differences in behavior across individuals.

The basic framework for this discussion is a regression model of the form

$$y_{it} = X_{it}'\beta + Z_i'\alpha + \varepsilon_{it} = X_{it}'\beta + c_i + \varepsilon_{it} \tag{4}$$

The individual effects is denoted as $Z_i'\alpha$ where Z_i contains a constant term and a set of individual or group specific variables, which may be observed, all of which are taken to be constant over time t. c_i is usually unobserved. The partial effects can the estimated as

$$\beta = \partial E[y_{it}|X_{it}]/\partial X_{it} \tag{5}$$

There is a strict exogeneity assumption for the independent variables as the current disturbance should be uncorrelated with the independent variables in every period. As this model concerns the heterogeneity, it has an assumption that $E[c_i|X_{i1}, X_{i2}, \dots,] = \alpha$.

Panel data models can be configured to have many model structures. This study examines two different models here:

1. **Pooled Regression**: If Z_i contains only a constant term, then ordinary least squares provides consistent and efficient estimates of the common α and the slope vector β.

2. **Fixed Effects:** If Z_i is unobserved, but correlated with X_{it}, the model should be in this form:

$$y_{it} = X_{it}'\beta + \alpha_i + \varepsilon_{it}, \tag{6}$$

where $\alpha_i = Z_i'\alpha$, embodies all the observable effects and specifies an estimable conditional mean. This will remove the bias and inconsistency in an OLS method when there is an omitted variable This fixed effects approach takes α_i to be a group-specific constant term in the regression model. It should be noted that the term “fixed” as used here signifies the correlation of c_i and X_{it}, not that c_i is nonstochastic.

Chapter 5: Results

GENERALIZED LINEAR MODEL OUTPUT

Table 8 shows the output from General Linear Regression model. As shown in this table, all the variables in the Regulation-Down regression model are significant, but adjusted R-square is only 0.25. That means, the variables in the model do have significant influence on the price of Regulation-Down, but we still miss important variables to explain the price. It is also another evidence to remove its effect in SUR and panel data model.

The adjusted R-square value of the other three models using this regression method are comparatively high, which means variables can explain their price better, with 0.92 in Responsive Reserves, 0.82 in Regulation Up and 0.51 in Non-spinning Reserves. However, NPRR460 does not have significant influence on Regulation UP and Non-Spinning Reserve price as their p-value is larger than 0.1.This study has another regression method-SUR-to study the variables influence on individual ancillary service. We will compare the output and give more interpretation in the following chapter.

Table 8 Output from the General Linear Regression Model

	Regulation Down			**Regulation UP**			**Responsive Reserve Services**			**Non Spinning Reserves**		
	Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)	
Intercept	3.69E+00	< 2e-16	***	-9.64E+00	<2e-16	***	-6.15E+00	1.09E-08	***	-6.72E+00	8.35E-10	***
coal	-2.10E-04	< 2e-16	***	-1.42E-03	<2e-16	***	-1.35E-03	< 2e-16	***	-7.27E-04	< 2e-16	***
gas	-3.26E-04	< 2e-16	***	-3.93E-04	<2e-16	***	-3.00E-04	< 2e-16	***	2.23E-04	< 2e-16	***
nuclear	-2.55E-04	2.93E-09	***	1.44E-03	<2e-16	***	1.22E-03	< 2e-16	***	3.54E-04	0.00543	**
wind	2.47E-04	< 2e-16	***	3.70E-04	<2e-16	***	5.30E-04	< 2e-16	***	1.71E-04	6.4E-06	***
DAM-price	5.20E-02	< 2e-16	***	9.89E-01	<2e-16	***	1.00E+00	< 2e-16	***	4.16E-01	< 2e-16	***
Quantity	2.46E-02	< 2e-16	***	1.52E-02	<2e-16	***	1.45E-03	0.001782	**	4.16E-03	< 2e-16	***
NPRR352	-5.25E-01	0.016	*	-7.13E+00	<2e-16	***	-6.98E+00	< 2e-16	***	-3.12E+00	1.70E-06	***
NPRR361	-2.18E+00	< 2e-16	***	6.65E+00	<2e-16	***	5.77E+00	< 2e-16	***	-1.01E+00	0.0793	.
NPRR460	2.51E+00	< 2e-16	***	1.06E-02	0.972		-7.79E-01	9.14E-04	***	-2.67E-01	0.3115	
Adjusted R-square:	0.25			0.82			0.92			0.51		
Significant Codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**												

SEEMINGLY UNRELATED REGRESSION MODEL OUTPUT

Table 9 shows the output from Seemingly Unrelated Regression model. It shows few discrepancies with the result from General Linear Regression model. The adjusted R-square are the nearly the same (it only drops from 0.82 to 0.81 in Regulation Up). The variables positive and negative influence on each ancillary service price do not change in every variables in each model and the variance of some specific values is very small. Specific significance value changes but all the significance levels do not change. The comparison result between General Linear Regression model and SUR shows that the output is reliable.

Then we can get the conclusion as following: Coal generation and NPRR352 have significant negative influence on all ancillary service price. Wind generation, Day-Ahead Market price and quantity procured for each ancillary service all have significant positive influence on all ancillary service price. Gas generation has significant negative influence on ancillary service price except for Non-Spinning Reserves, on which it has significant positive influence instead. Nuclear generation has significant positive influence on ancillary service price except for Regulation Down, on which it has significant negative influence instead. NPRR361 has significant negative influence on Regulation Down and Non-Spinning Reserves price, and significant positive influence on Responsive Reserve Services and Regulation Up prices. NPRR460 is more complicated, only having significant influence on Regulation Down (positive) and Non-Spinning Reserves (negative) prices.

We will interpret the reason contributing to this output in the following part after comparing the output from Panel Data Model.

Table 9 Output from the Seemingly Unrelated Regression

	Regulation UP			**Responsive Reserve Services**			**Non Spinning Reserves**		
	Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)	
Intercept	-1.14E+01	< 2e-16	***	-1.10E+01	< 2.22e-16	***	-2.66E+00	0.009013	**
coal	-1.45E-03	< 2e-16	***	-1.32E-03	< 2.22e-16	***	-7.69E-04	< 2.22e-16	***
gas	-3.92E-04	< 2e-16	***	-3.15E-04	< 2.22e-16	***	2.47E-04	< 2.22e-16	***
nuclear	1.47E-03	< 2e-16	***	1.21E-03	< 2.22e-16	***	2.92E-04	0.021516	*
wind	3.85E-04	< 2e-16	***	5.34E-04	< 2.22e-16	***	1.72E-04	5.82E-06	***
DAM-price	9.89E-01	< 2e-16	***	1.00E+00	< 2.22e-16	***	4.15E-01	< 2.22e-16	***
Quantity	1.88E-02	< 2e-16	***	3.93E-03	< 2.22e-16	***	2.24E-03	4.44E-16	***
NPRR352	-7.19E+00	< 2e-16	***	-6.83E+00	< 2.22e-16	***	-3.66E+00	1.72E-08	***
NPRR361	6.79E+00	< 2e-16	***	5.20E+00	< 2.22e-16	***	-1.39E+00	0.01557	*
NPRR460	3.28E-01	0.27707		-1.58E+00	7.55E-14	***	-1.80E-01	0.495716	
Adjusted R-square:	0.81			0.92			0.51		
Significant Codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**									

PANEL DATA MODEL OUTPUT

Table 10 shows the output from the two Panel Data model with different model structure. This two model has only one discrepancy in results, as the significance level of wind changes from significant in Pooling Model to not significant in Fixed Effect Model. Coal generation, gas generation, NPRR352 and NPRR460 have significance negative influence on the included three type's ancillary service price. Nuclear generation, Day-Ahead Market price and quantity procured for each ancillary service all have significant positive influence on these price. NPRR361 is not significant.

Table 10 Output from the Panel Data Model

	Pooling Model				**Oneway (individual) effect Within Model**		
	Estimate	Pr(>|t|)			Estimate	Pr(>|t|)	
Intercept	-2.79E+00	2.86E-07	***				
coal	-1.20E-03	< 2.2e-16	***		-0.00102	< 2.2e-16	***
gas	-1.62E-04	< 2.2e-16	***		-2.83E-04	< 2.2e-16	***

nuclear	9.10E-04	< 2.2e-16	***		7.99E-04	< 2.2e-16	***
wind	2.93E-04	< 2.2e-16	***		-2.13E-05	0.43	
DAM-price	8.01E-01	< 2.2e-16	***		8.05E-01	< 2.2e-16	***
Quantity	7.58E-04	< 2.2e-16	***		7.17E-04	< 2.2e-16	***
NPRR352	-1.28E+00	2.75E-03	**		-1.32E+00	0.002	**
NPRR361	4.67E-01	0.208094			3.95E-01	0.284	
NPRR460	-8.94E-01	3.16E-07	***		-4.97E-01	0.004	**
Adjusted R-square:	0.73				0.73		
Significant Codes:	**0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**						

INTERPRETATION

Table 11 summarizes the variables influence on each ancillary services from different models. The significant positive influence Day-Ahead Market price and quantity procured for each ancillary service have on ancillary services can be explained by the market rules easily. Ancillary services are also electricity products, it should follow the electricity price trend. As for the quantity, prices naturally tend to increase with quantity. These rules of Thumb are also used in the following part.

Coal generation shows negative influence on all ancillary service price in the models. That can be explained since the coal price has a close relationship with electricity price (see Figure 18), and coal price is cheaper than other generation resource, then the more generation from coal, the cheaper the whole electricity price would be, and the cheaper the ancillary service would be.

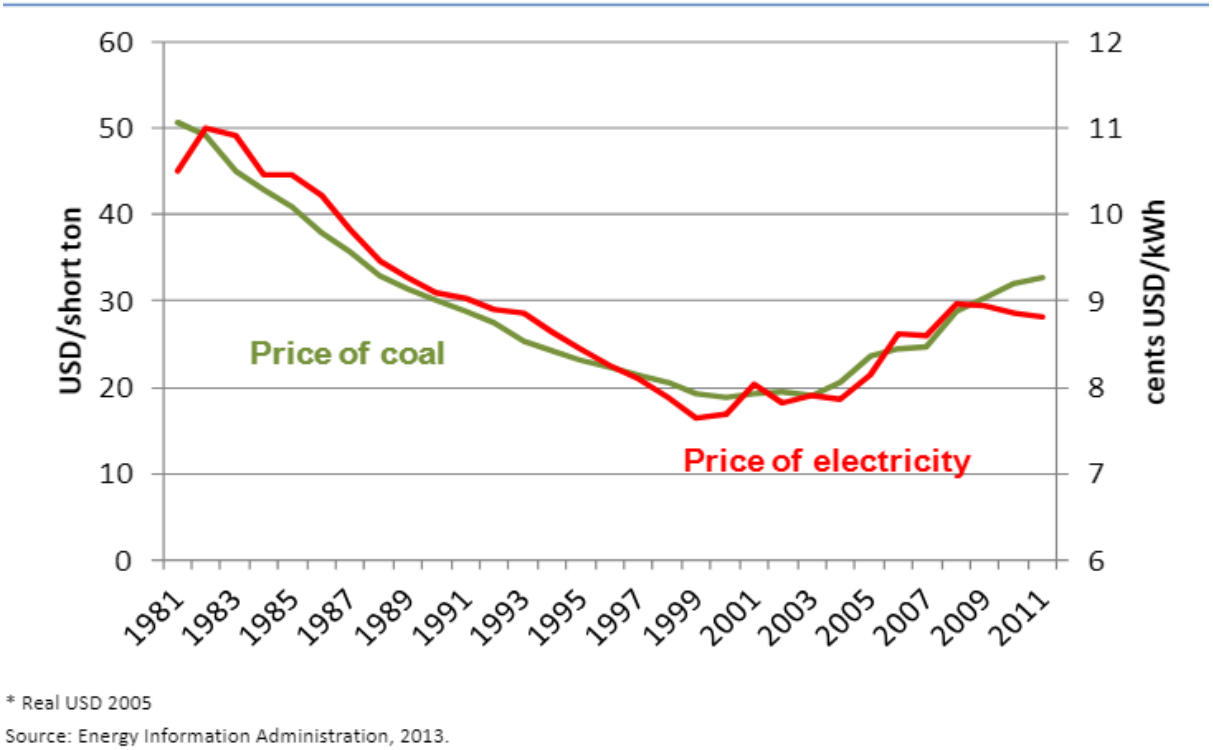


Figure 18 Annual real price of coal, price of electricity for all sectors from 1981 to 2011 (Energy Information Administration, 2013)

Gas generation should have the same effect as coal, because they are the two dominant contributors to total generation in ERCOT. However, from our output, it has a significant positive influence on Non-Spinning Reserve price. We do not have reasonable interpretation for that observation.

Nuclear generation has positive influence on all ancillary service price except for Regulation Down. Even though the operation fee of nuclear energy increases year by year, and is much higher than other generation resources, it could not be the main reason to explain the output.

Table 11 Summary of all regression model output

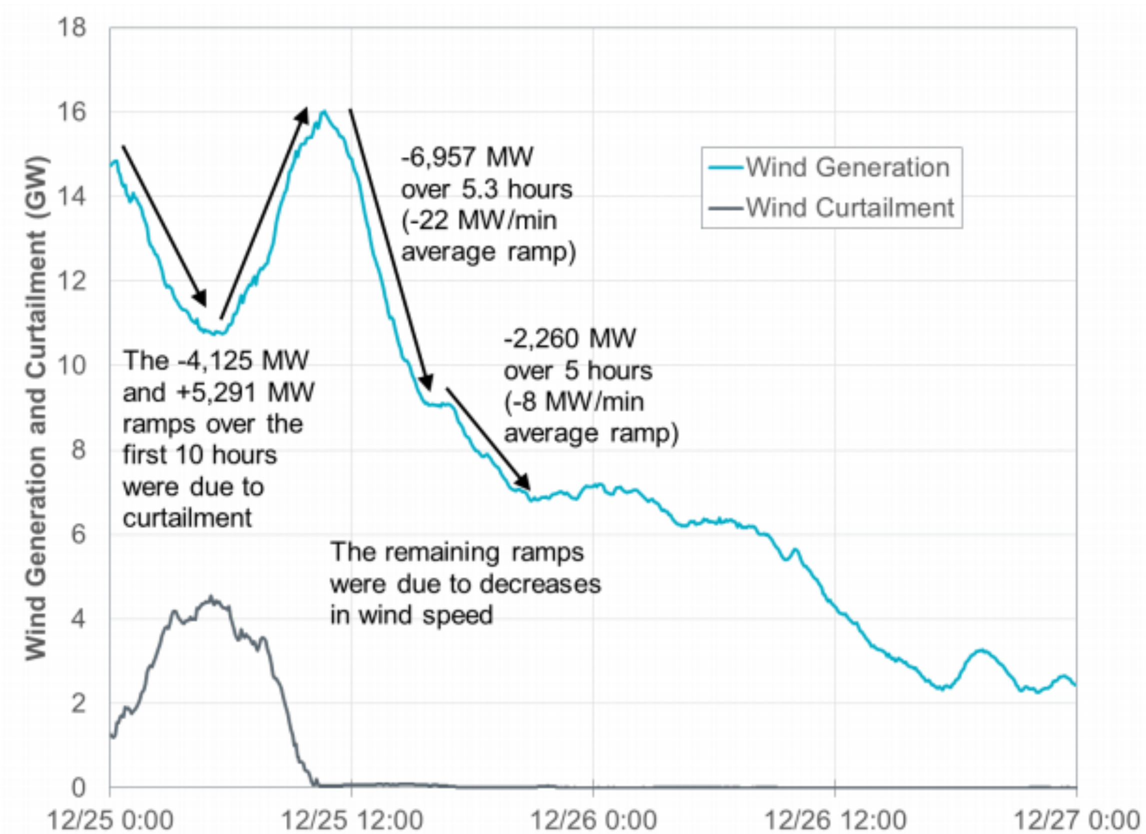
Dataset	Regulation Down	Regulation UP		Responsive Reserve Services		Non Spinning Reserves		Panel Data	
Methods	GLS	GLS	SUR	GLS	SUR	GLS	SUR	Pooling	Fixed Effect
coal	−	−	−	−	−	−	−	−	−
gas	−	−	−	−	−	+	+	−	−
nuclear	−	+	+	+	+	+	+	+	+
wind	+	+	+	+	+	+	+	+	not [13]
DAM-price	+	+	+	+	+	+	+	+	+
Quantity	+	+	+	+	+	+	+	+	+
NPRR352	−	−	−	−	−	−	−	−	−
NPRR361	−	+	+	+	+	−	−	not	not
NPRR460	+	not	not	−	−	not	not	−	−

Wind generation has positive influence on all ancillary service price except in fixed effect model of Panel data model. As shown in Figure 19, wind generation is uncertain and variable. Wind in Texas blows hard nearly 24-hours a day, 365 days a year but it is not a stable resource. Then the more generation comes from wind, the more variability exists, the more regulation services are needed, and the higher the ancillary service price would be. The output from fixed effect model of Panel data model do not make sense.

NPRR352 has negative influence on all ancillary service price. This policy related with improvements in the prediction of the maximum sustained energy production capability of a wind generator after curtailment. The output shows that this policy has apparent benefit to the market as it helps to lower the price. However, this policy was issued on June 1st, 2011, just after the extremely cold winter in Texas, during when the energy price was extremely high. We are therefore not sure about its real effect from this study.

[13] not significant

Figure 19 Large Ramps in Wind Generation (ERCOT, 2018)



NPRR36, which requires submitting of 5 min resolution wind data for real time purposes, is not significant in the two Panel Data Models. But we believe the significant positive influence on Regulation Up and Responsive, and significant negative influence on Non Spinning Reserves confuse the model. According to output from General Linear Regression Model, we can also tell that it has a significant influence on Regulation Down. However, better prediction of wind should have the same impact on Regulation services, which is different from what we find on Regulation Down and Regulation Up. We currently do not understand the reason for this occurrence.

NPRR460 increases the wind powered generation resource ramp rate limitation from 10% per minute of nameplate rating to five minute average of 20% per minute of nameplate rating with no individual minute exceeding 25%. It only has significant negative influence on Regulation Down price, and significant positive influence on Non-Spinning Reserves.

Chapter 6: Summary

CONCLUSIONS

None of the models mentioned in this study is perfect, and not every output can be explained with strong theory from the studies that have been done. This works main findings are:

1. Regulation Down reserves price is different from other ancillary services in ERCOT, more relevant variables need to be added into the regression model to explain its performance.
2. Non-Spinning Reserves price shows discrepancy between Regulation Up reserves and Responsive Reserves price even though it can be better explained as compared to Regulation Down Service.
3. Coal generation has significant negative influence on all ancillary service prices, while nuclear generation, wind generation. Day-Ahead Market price and quantity procured for each ancillary service have significant positive influence on these price.

4. Gas generation influence on Responsive Reserves price is different from its influence on other AS prices; nuclear generation influence on Regulation Down reserves price is different from its influence on others.
5. Policies influence is hard to control and this work does not have persuasive conclusion yet.

FUTURE DIRECTIONS

This model need more relevant variables to have better estimation for Regulation Down and Non-Spinning Reserves at first. The variables could be selected from: 1. the market plan changes of individual ancillary services as shown in Table 12. ERCOT will issue changes to market rules to operate the market better with more diverse generation resource (like more wind and solar). The changes in market rules will also have a significant influence on the price. 2. Meteorological data, like extreme weather, humidity, temperature and so on. Ancillary service, an insurance to the system uncertainty and variability, should be sensitive to these uncertain conditions. An example is 2011, the price of ancillary services are super high as Texas experienced a super cold winter and a following up super-hot summer.

The models are also need to be adjusted. More test need to be done in the variable selection process and more structures in Panel Data Model can be tested.

Table 12 ERCOT Ancillary Service Plan changes

No.	Year	Item	Description
1	2017	Regulation Service	Remove exhaustion rate feedback from the regulation procurement analysis
2		Regulation Service	Estimate 5-minute net load variability by including solar generation (net load = load – wind generation – solar generation).
3		Regulation Service	The annual updates to GE Tables to reflect incremental installed wind generation.
4	2016	Regulation Service	Remove consideration of the last 30 days from Regulation Analysis and instead use the Regulation data using same month of the previous two years.
5		Regulation Service	Use five minute average instead of one minute average regulation deployment for exhaustion rate
6		Regulation Service	Use 95th percentile of 5 minute net load/deployments instead of 98.8th percentile;
7		Regulation Service	Update the GE Tables
8		Regulation Service	Increase CPS1 trigger to 140% instead of 100%.
9		Non-Spin	Remove last 30 days from Non-Spin Analysis and instead use the same month for previous three years;
10		Non-Spin	Use the 3-hour ahead net forecast error instead of 6-hour ahead;
11		Non-Spin	Use net forecast error only on the under-forecast;
12		Non-Spin Analysis	Use dynamic percentile between 70th and 95th percentile based on the risk of net load ramp.
13	2015.1	Regulation Service	Annual update to the factors used to adjust the Regulation Service quantities for additional installed wind generation since June 2013 – Added approximately 988 MW of Wind since last analyses
14		Regulation Service	Reg-Up quantities calculated based on Reg-Up use only, excluding the use of other Ancillary Services during abnormal events, e.g., February 2014
15	2015.6	Non Spin Reserve	Remove transfer of 500 MW of calculated NSRS requirement to RRS – Procure the calculated NSRS amount as NSRS
16		Responsive Reserves	Once annually, ERCOT will calculate and post amounts of RRS to be procured for each hour of the year The calculated quantities of RRS to be procured are based on: – Historic system inertia conditions based on expected load and wind patterns – LRs providing 50% of RRS – Using the Equivalency Ratio between RRS from generation and load – Generating Resources providing capacity that is frequency responsive • No portion of the calculated NSRS requirement will be procured through RRS

Appendix

Appendix 1.Variable Selection Model 1

Table. Positive and Negative Relationship between Ancillary Service and variables in 4 models												
Model 1 and 6	Regulation Down		Regulation UP		Replacement Reserve		Non-spinning Reserve		Model 2 and Model 3		Model 4 and Model 5	
(Intercept)	+	***	−	***	−	**	−	***				
coal	−	***	−	***	−	***	−	***	−	***	−	***
gas	−	***	−	***	−	***	+	***	−	***	−	***
nuclear	−	***	+	***	+	***	+	*	+	***	+	***
wind	+	***	−		+	***	+	**	+	***	−	
DAM	+	***	+	***	+	***	+	***	+	***	+	***
REGDN_Q	+	***	+	***	−		+	***	+	***	+	***
as.factor(stage)2	−	*	−	***	−	***	−	***	−	**	−	**
as.factor(stage)3	−	***	+		−		−	***	−	***	+	.
as.factor(stage)4	+		−	**	−	***	−	***	−	***	+	***
as.factor(stage)5	−	***	+		−		+		−	***	+	***
as.factor(year)2012	−	***	+		+	***	+		+	**	−	***
as.factor(year)2013	−	***	+		+	***	−		+		−	***
as.factor(year)2014	+	***	−	**	−	**	−	***	+	*	−	***
as.factor(year)2015	+	***	+	***	+	***	−	**	+	*	−	***
as.factor(year)2016	+	***	+	***	+	***	−	***	+	*	−	***
as.factor(year)2017	+	***	+	***	+	***	−	***	+	**	−	***
R square	0.2943		0.8192		0.927		0.5085		0.56312		0.73332	
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1												

Appendix 2. Variable Selection Model 2

Table. Positive and Negative Relationship between Ancillary Service and variables in 4 models												
Model 1 and 4	Regulation Down		Regulation UP		Replacement Reserve Service		Non-spinning Reserve Services		Model 2		Model 3	
coal	−	***	+	***	+	***	−	***	−	***	−	**
gas	−	***	+	.	+		−	***	−	***	−	
nuclear	−	**	+	***	+	***	−		+	***	+	***
wind	+	***	+	***	+	***	−	***	+	***	+	***
Henry	+	***	−	***	−	***	−	***	−	***	−	***
Real Market Price	−	**	−	*	+	***	+	***	+	**	+	***
Day Ahead Market Price	+	***	+	***	+	***	+	***	+	***	+	***
The quantity of electricity	+		−	***	−	***	+	***	−	***	−	***
The quantity of relative ancillary services	+	***	+	***	+	***	+	***	+	***	+	***
R square	0.2471		0.8188		0.927		0.5075		0.56397		0.73398	
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1												

Appendix 3. Variable Selection Model 3

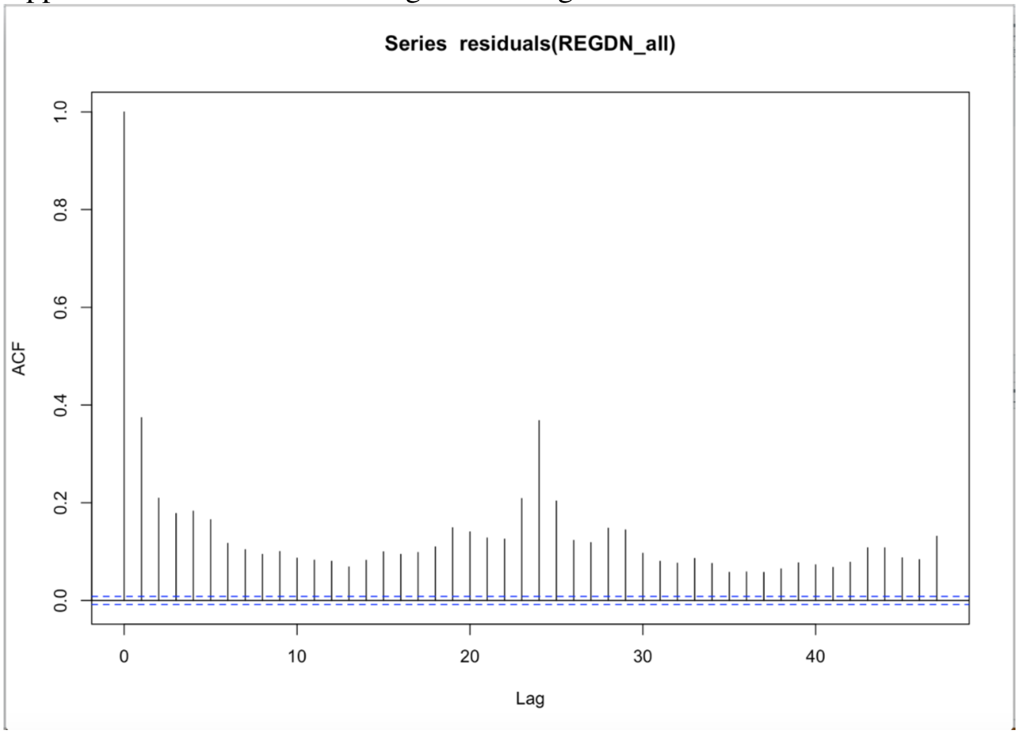
	Regulation Down			Regulation UP					
	General			General			SUR-three		
	Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)	
(Intercept)	1.98E+00	1.22E-08	***	-2.92E+00	0.01	*	-4.47485	5E-05	***
coal	-1.29E-04	< 2e-16	***	-1.74E-03	< 2e-16	***	-0.00175426	< 2.22e	***
gas	-3.26E-04	< 2e-16	***	-4.14E-04	< 2e-16	***	-0.00041128	< 2.22e	***
nuclear	-5.49E-05	2.31E-01		7.36E-04	1.19E-06	***	0.000752916	7E-07	***
wind	2.54E-04	< 2e-16	***	3.19E-04	1.43E-13	***	0.00033334	1E-14	***
DAM	5.16E-02	< 2e-16	***	9.91E-01	< 2e-16	***	0.990517	< 2.22e	***
Quantity	2.47E-02	< 2e-16	***	1.55E-02	< 2e-16	***	0.0185539	< 2.22e	***
stage_1	4.68E-01	0.0453	*	-1.13E+01	< 2e-16	***	-11.2977	< 2.22e	***
stage_2	-2.40E+00	< 2e-16	***	7.96E+00	< 2e-16	***	8.054	< 2.22e	***
stage_3	2.40E+00	< 2e-16	***	4.87E-01	0.113		0.75586	0.013	*
summer	-1.69E+00	< 2e-16	***	6.45E+00	< 2e-16	***	6.45853	< 2.22e	***
autumn	-1.18E+00	< 2e-16	***	3.83E+00	< 2e-16	***	3.87419	< 2.22e	***
winter	-1.07E+00	< 2e-16	***	2.97E+00	< 2e-16	***	3.07554	< 2.22e	***
Adjusted R	0.2484			0.8158			0.8158		

	Responsive Reserve Services						Non Spinning Reserves					
	General			SUR-three			General			SUR-three		
	Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)		Estimate	Pr(>|t|)	
(Intercept)	8.39E-01	0.455		-4.91E+00	1.27E-07	***	-3.13E+00	0.007988	**	9.01E-02	0.9349761	
coal	-1.64E-03	< 2e-16	***	-1.58E-03	< 2.22e-16	***	-9.02E-04	< 2e-16	***	-9.36E-04	< 2.22e-16	***
gas	-2.87E-04	< 2e-16	***	-3.06E-04	< 2.22e-16	***	2.07E-04	< 2e-16	***	2.30E-04	< 2.22e-16	***
nuclear	6.09E-04	5.34E-11	***	6.03E-04	8.59E-11	***	7.53E-05	0.581804		1.72E-06	0.9899549	
wind	5.14E-04	< 2e-16	***	5.18E-04	< 2.22e-16	***	1.40E-04	0.000271	***	1.44E-04	0.0001792	***
DAM	1.00E+00	< 2e-16	***	1.00E+00	< 2.22e-16	***	4.17E-01	< 2e-16	***	4.16E-01	< 2.22e-16	***
Quantity	4.82E-04	0.299		3.37E-03	< 2.22e-16	***	4.20E-03	< 2e-16	***	2.67E-03	< 2.22e-16	***
stage_1	-1.01E+01	< 2e-16	***	-9.90E+00	< 2.22e-16	***	-5.46E+00	4.88E-15	***	-5.85E+00	< 2.22e-16	***
stage_2	6.39E+00	< 2e-16	***	5.77E+00	< 2.22e-16	***	-3.73E-01	0.53561		-7.30E-01	0.2233651	
stage_3	-1.84E-02	0.938		-9.74E-01	5.39E-06	***	5.95E-02	0.82338		1.23E-01	0.644033	
summer	5.35E+00	< 2e-16	***	5.27E+00	< 2.22e-16	***	3.35E+00	< 2e-16	***	3.40E+00	< 2.22e-16	***
autumn	4.35E+00	< 2e-16	***	4.18E+00	< 2.22e-16	***	2.37E+00	1.41E-14	***	2.45E+00	1.55E-15	***
winter	3.60E+00	< 2e-16	***	3.57E+00	< 2.22e-16	***	9.31E-01	0.001575	**	1.19E+00	4.85E-05	***
Adjusted R	0.9238			0.923775			0.5077			0.507547		

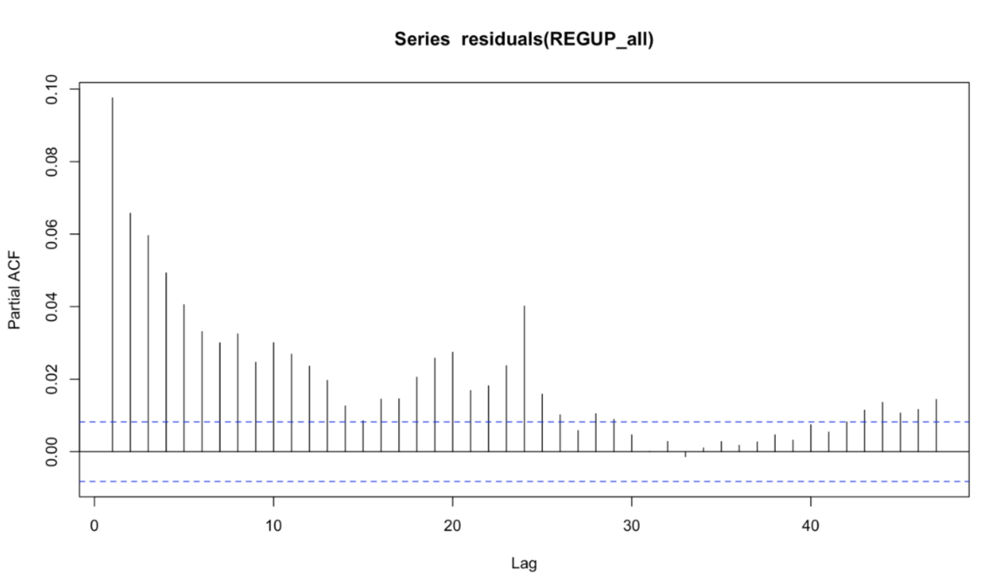
	Pooling Model			eway (individual) effect Within Mo		
	Estimate	Pr(>|t|)		Estimate	Pr(>|t|)	
(Intercept	-2.52E+00	3.921E-06	***			
coal	-1.21E-03	< 2.2e-16	***	-1.03E-03	< 2.2e-16	***
gas	-1.61E-04	< 2.2e-16	***	-2.82E-04	< 2.2e-16	***
nuclear	9.60E-04	< 2.2e-16	***	8.52E-04	< 2.2e-16	***
wind	2.92E-04	< 2.2e-16	***	-2.16E-05	0.4238083	
DAM	8.01E-01	< 2.2e-16	***	8.05E-01	< 2.2e-16	***
Quantity	7.56E-04	< 2.2e-16	***	7.16E-04	< 2.2e-16	***
stage_1	-9.09E-01	0.0491227	*	-9.99E-01	0.0299343	*
stage_2	0.64828	0.1013565		0.57079	0.1473726	
stage_3	-1.0765	1.34E-09	***	-0.66062	0.0001947	***
summer	-0.75143	0.0001275	***	-0.71814	0.0002351	***
autumn	-1.4353	1.213E-13	***	-1.3317	4.86E-12	***
winter	-0.92957	4.192E-07	***	-0.96055	1.503E-07	***
Adjusted R	0.73115			0.73317		

Summary Table				
	SUR AND OLS		Panel	
coal	−		−	
gas	−	NSPIN +	−	
nuclear	+	NSPIN not s	+	
wind	+		+	not significant
DAM	+		+	
Quantity	+		+	
stage_1	−		−	
stage_2	+	NSPIN −	not significant	
stage_3	+	NSPIN not s	−	
summer	+		−	
autumn	+		−	
winter	+		−	

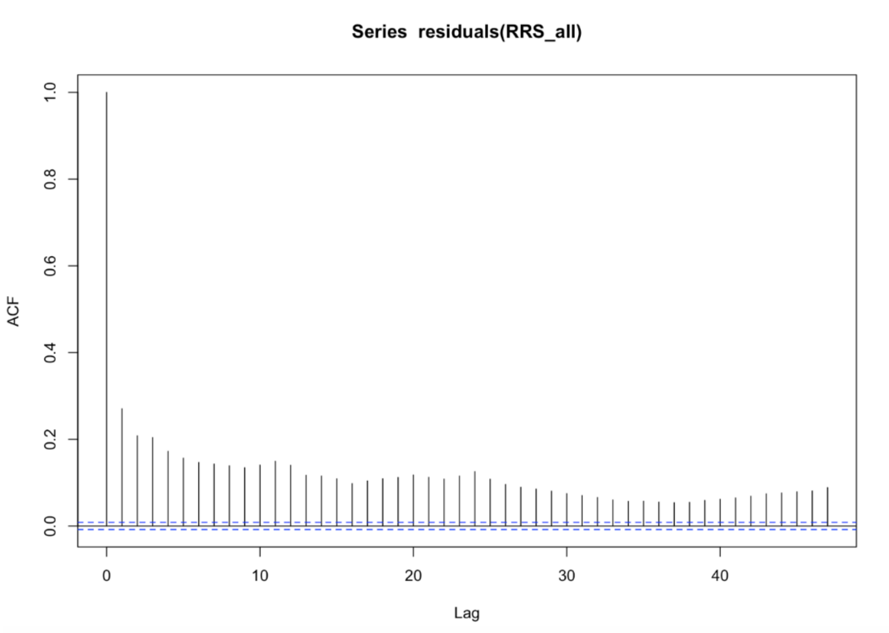
Appendix 4. General Linear Regression-Regulation Down ACF



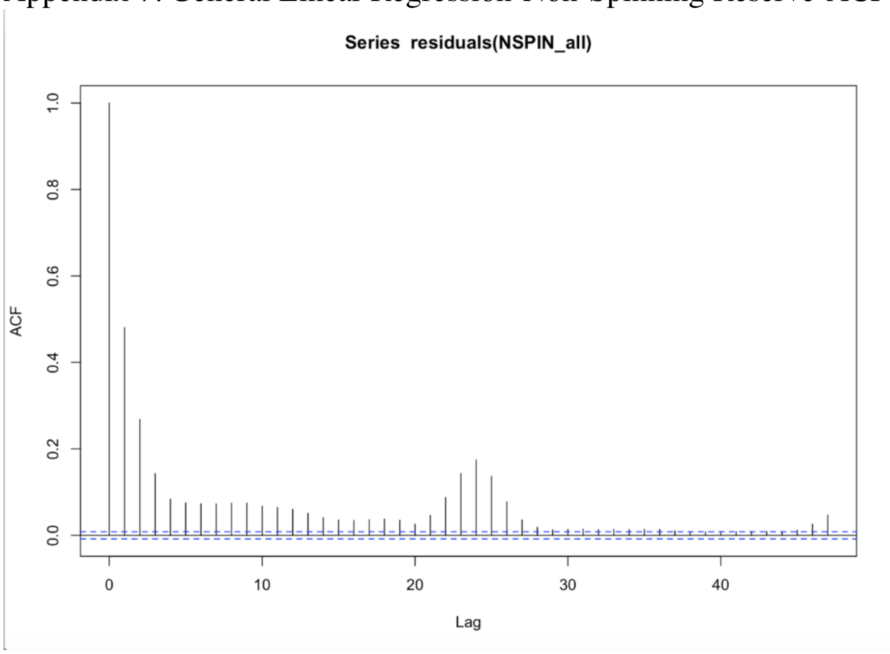
Appendix 5. General Linear Regression-Regulation Up-ACF



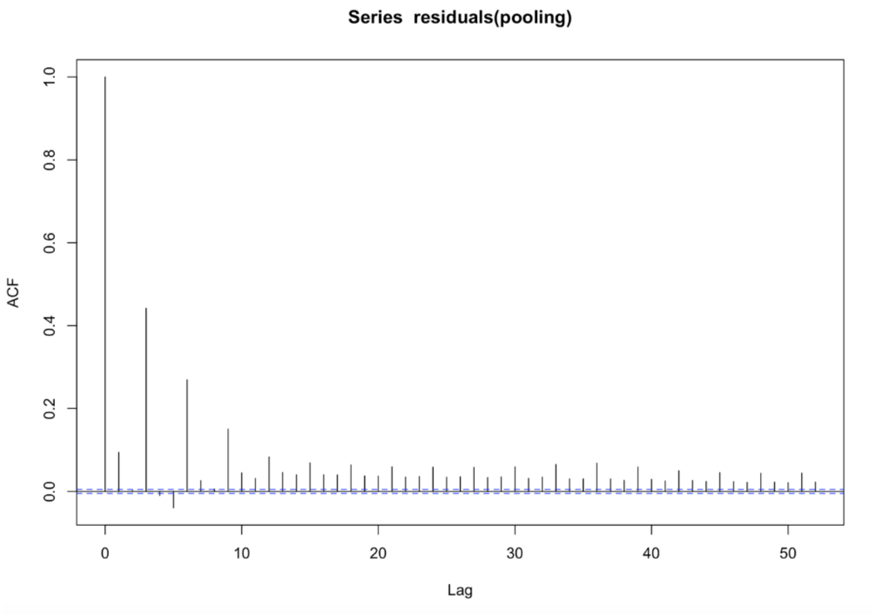
Appendix 6. General Linear Regression-Responsive Reserves-ACF



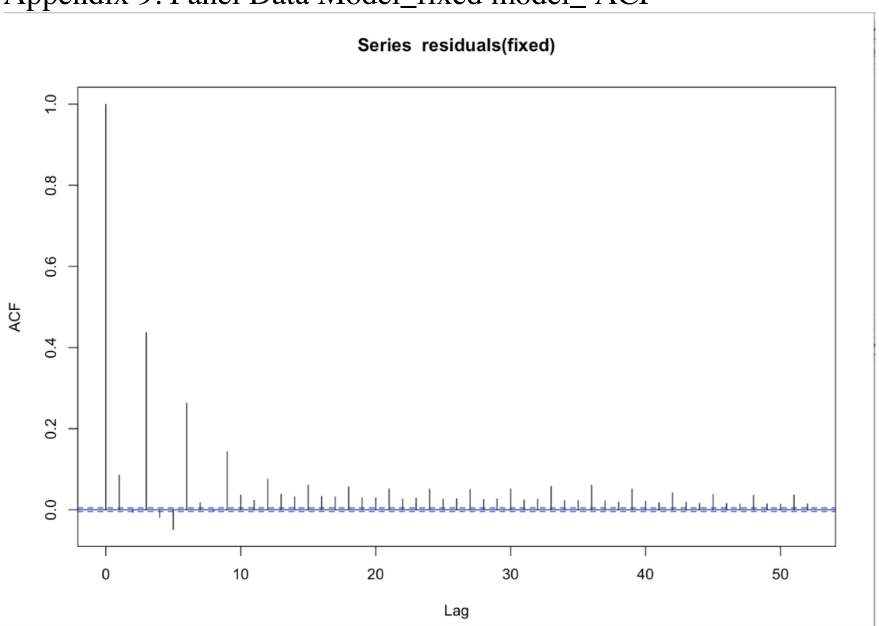
Appendix 7. General Linear Regression-Non-Spinning Reserve-ACF



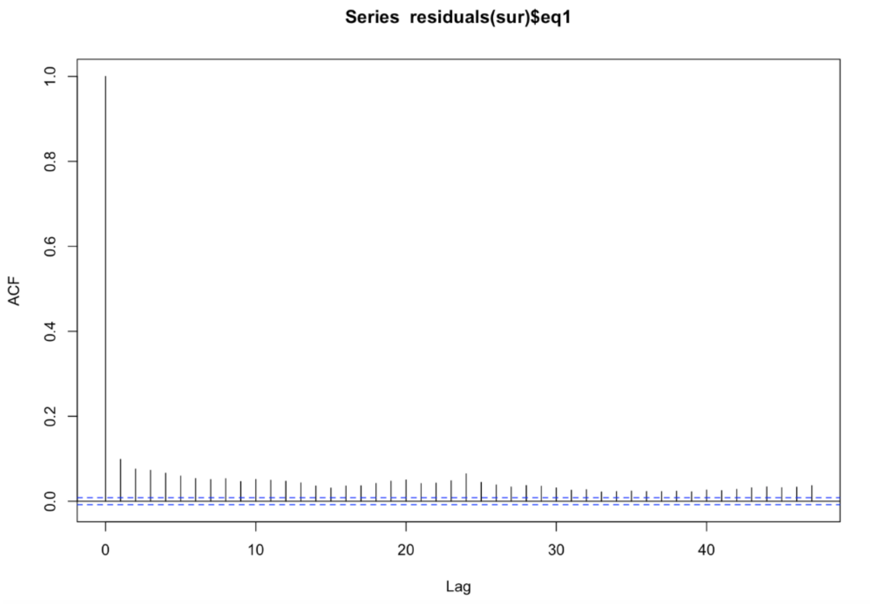
Appendix 8. Panel Data Model_pooling model_ ACF



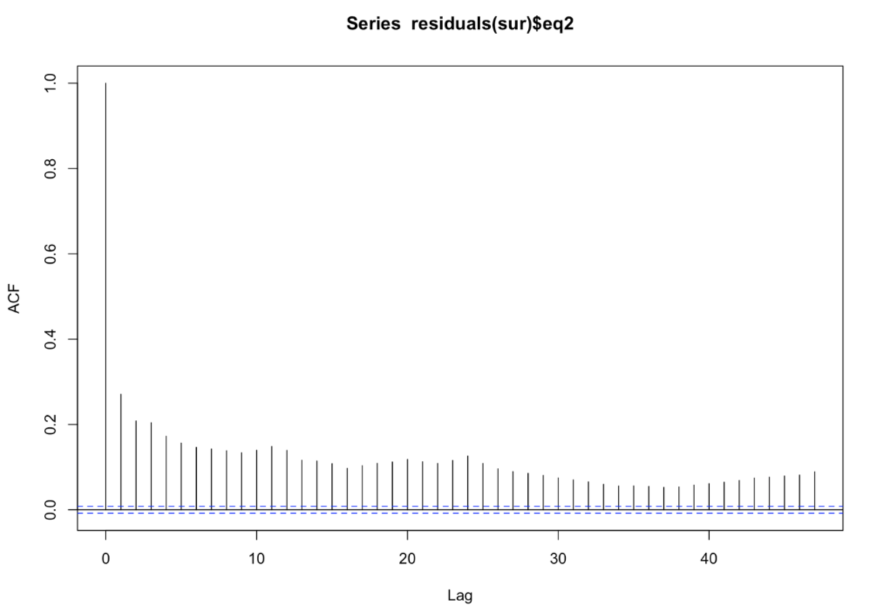
Appendix 9. Panel Data Model_fixed model_ ACF



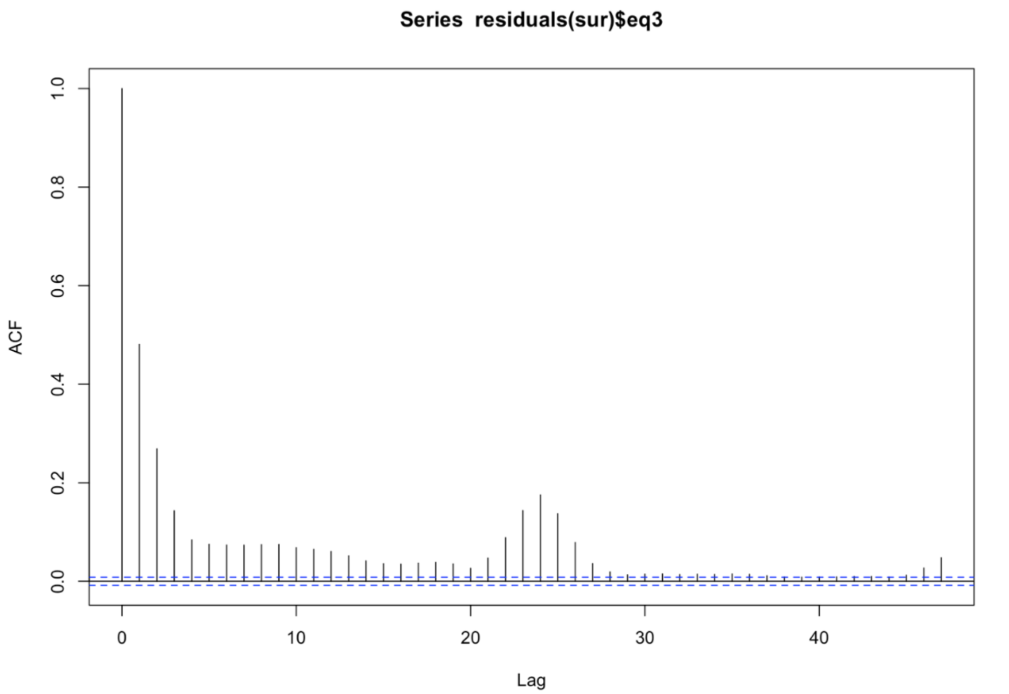
Appendix 10. Seemingly Unrelated Regression-Regulation Up_ ACF



Appendix 11. Seemingly Unrelated Regression-Responsive Reserve_ ACF



Appendix 12. Seemingly Unrelated Regression-Non-Spinning Reserve_ ACF



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