ENERGIZING THE FUTURE: INTEGRATION OF RENEWABLE ENERGY TECHNOLOGY ONTO THE TEXAS SYNETHETIC GRID

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

ABSTRACT

Energizing the Future: Integration of Renewable Energy Technology onto the Texas Synthetic Grid

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This research first understands how wind energy has affected the Texas Interconnection over the past ten years and the reasons why the state of Texas has thrived in the wind energy market. Extensive studies and official reports from the Electric Reliability Council of Texas determine that an estimation of 8.6 GW of wind generation will be added onto the grid from the years 2017 through 2019. The next step in this research used a synthetic base case of the Texas grid within PowerWorld that already contained over 2000 busses and 543 generators. Twenty-five new generators with 7.5 MW worth of capacity were added to the Texas Synthetic Grid Case. To fix all overloaded lines, over an estimated $1.03 billion worth of elements such as new transmission lines, high voltage buses, and transformers were added to the case to provide a potential solution. The total project cost over an estimated $12.4 billion which shows how easily costs can accrue in the energy world. This paper illustrates the many variables to take into account when adding new wind generation because one single generator or transmission line can affect the flow of the entire ERCOT system. These are the problems real utilities deal with every day when discovering how their new generation mix affects the grid and how generators, transmission lines, and distribution lines must be built to compensate for added load.

ACKNOWLEDGEMENTS

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NOMENCLATURE

CEO	Chief Executive Officer
CREZ	Competitive Renewable Energy Zones
DOE	Department of Energy
ERCOT	Electric Reliability Council of Texas
GIS	Generation Interconnection Status
GW	Gigawatts
ISO	Independent System Operator
MW	Megawatts
REC	Renewable Energy Credit
REP	Retail Electric Provider
RPS	Retail Portfolio Standard
TSGC	Texas Synthetic Grid Case
WECC	Western Electricity Coordinating Council

CHAPTER I

INTRODUCTION

Background of Texas Wind Development

There has been an extreme push for renewable energy technology around the world to increase the world's renewable energy portfolio. According to the Department of Energy (DOE), "wind power additions continued at a rapid pace in 2016, with 8,203 MW of new capacity added in the United States and $13 billion invested. Cumulative wind power capacity grew 11% bringing the total to 82,143 MW [1]." Furthermore, "Texas installed the most capacity in 2016 with 2,611 MW [1]" which means that nearly one-third of the total wind installed in 2016 was in the "Lonestar" State. With the size of Texas and the vast space in the North and the West, this state has the potential to add gigawatts worth of new, clean energy onto the Electric Reliability Council of Texas (ERCOT) grid. According to a presentation given by ERCOT's CEO in February of 2017, the estimation of total wind capacity installed by 2018 reaches upwards of 18 Gigawatts [2]. Just one gigawatt equals about 500 utility-scale wind turbines estimating that each turbine has 2 megawatts of capacity [3]. Heavy increases in renewable energy technology corresponds with ERCOT's mission "to serve the public by ensuring a reliable grid, efficient electricity markets, open access and retail choice [2]."

Strategies of Wind Farm Placement

Power engineers should take into account several factors when deciding location, design, and size of a wind farm, the most obvious being the assurance of steady wind measurements. According to an NREL study, "recent advances in supercomputing technology as well as sophisticated atmospheric measurement capabilities and large sets of data from turbine based systems provide the ability to study the wind and wind turbine interactions as never before [4]." This leads to accurate data to quote in proposals for potential wind capacity installations. Accurate estimation of wind patterns in the region allows cost analysis for return on investments. Figure 1 below represents Texas' annual wind speed at 80 meters which highlights the portions of Texas where wind speed is highest, both mid-west and the panhandle being regions with the highest speeds.

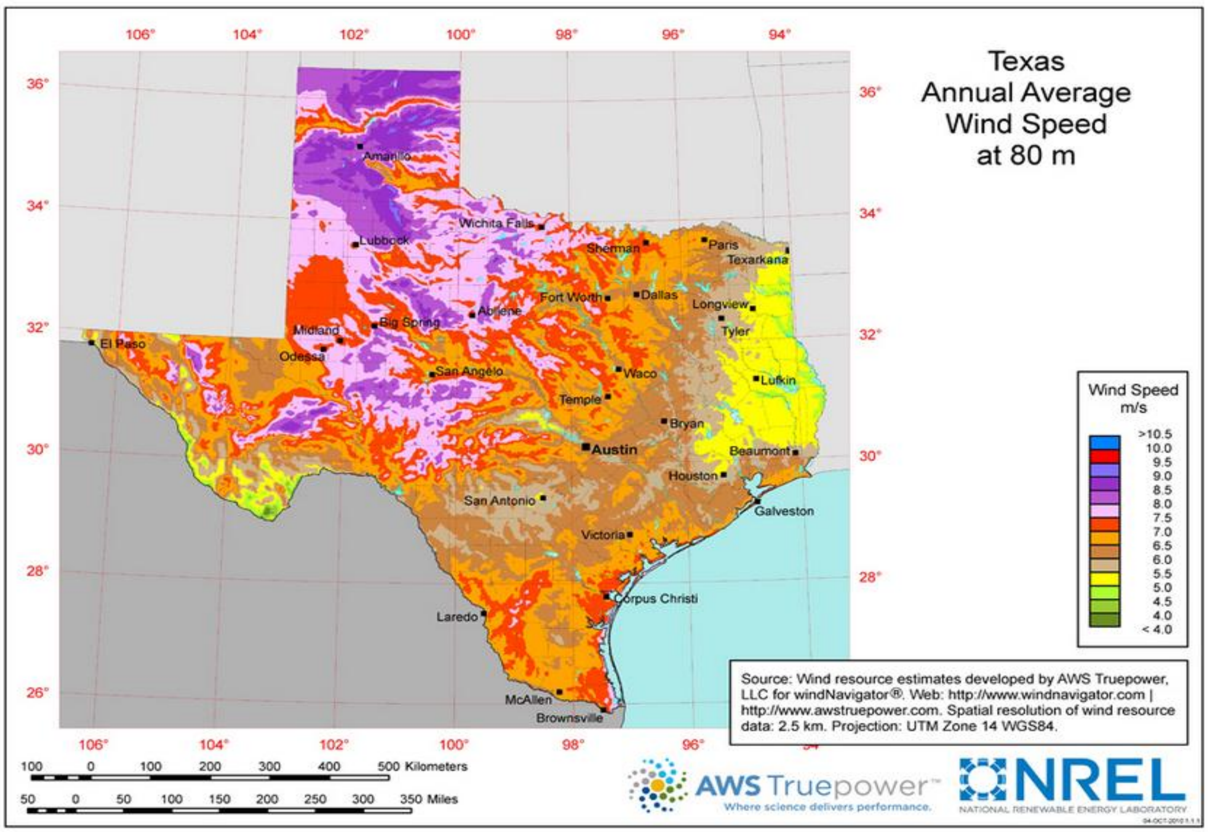

Figure 1. Texas 80 Meter Wind Resource Map [5]
Image Credit: U.S Department of Energy (DOE)/NREL/ALLIANCE

Weather is not the only important limitation of building new wind farms. Senior meteorologist, Scott Haynes, claims that the spatial design of wind farms are based on "property boundaries, environmentally sensitive areas, wildlife, turbine fall distances, government regulations and more internal guidelines." He even states that "current industry standards are likely based on landownership, not wind characteristics [6]." No matter how much space West Texas or the Panhandle has to offer, there will always be government regulations, land restrictions, and citizens against the noise the turbines make and their seemingly unpopular aesthetics. Hopefully the thought of green energy overshadows such issues and all parties involved cooperate to create a healthier planet.

Last, but certainly not least, there exists the issue of adding transmission lines to reach the wind farms. Texas, at least, has an advantage with being the only state with its own grid, ERCOT, which prevents the concern of crossing transmission lines across state borders. The disadvantage, though, has to do with how remote the wind locations are from high consuming cities which leads to the critical need for large-scale transmission projects [7]. This decreases the odds for stakeholder investments to build the farms in parts of the state without existing lines which means proposals must go beyond just the cost of the farm itself. Fortunately, the Public Utility Commission of Texas (PUCT) was so motivated to take advantage of West Texas's high average wind speed that, in 2008, they "studied the areas with the most wind energy projects and potential and established a series of Competitive Renewable Energy Zones (CREZs). PUCT then used these zones to plan a highly efficient series of more than 3,000 miles of transmission lines to reliably transfer renewable energy generated in western Texas to help power eastern markets. By December 2013, the project was largely completed, reducing the need to limit the amount of wind energy entering the grid. The bottom line: clean energy is now accessible to the entire state

[8]." This certainly laid the groundwork for Texas to be the leader in installed capacity of wind power. In 2008, ERCOT almost doubled its installed capacity from 4.7 GW in 2007 to over 8 GW at the end of the year [2]. After 2008, a steady growth continued with upwards of 20 GW of wind energy on the grid by the end of 2016 [1]. Figure 2 below portrays the location of wind power development in Texas in 2016 while Figure 3 illustrates where the transmission lines were added in the CREZ projects.

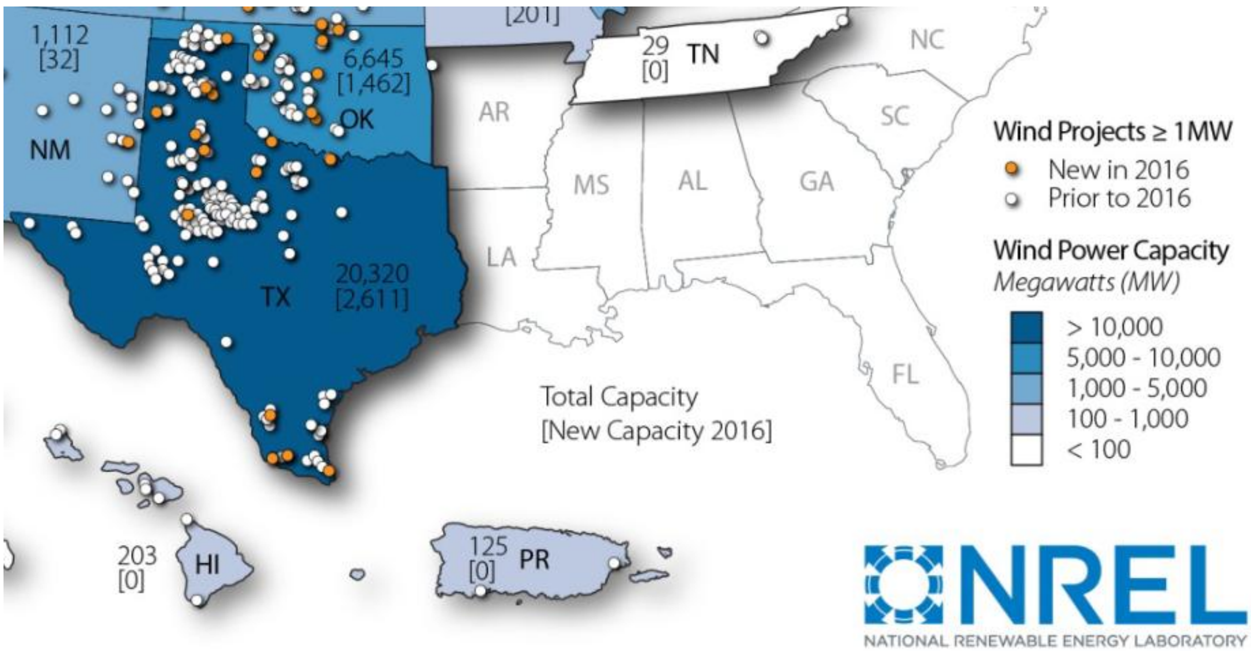

Figure 2. Location of Wind Power Development in United States [1]
Image Credit: U.S Department of Energy (DOE)/NREL/ALLIANCE

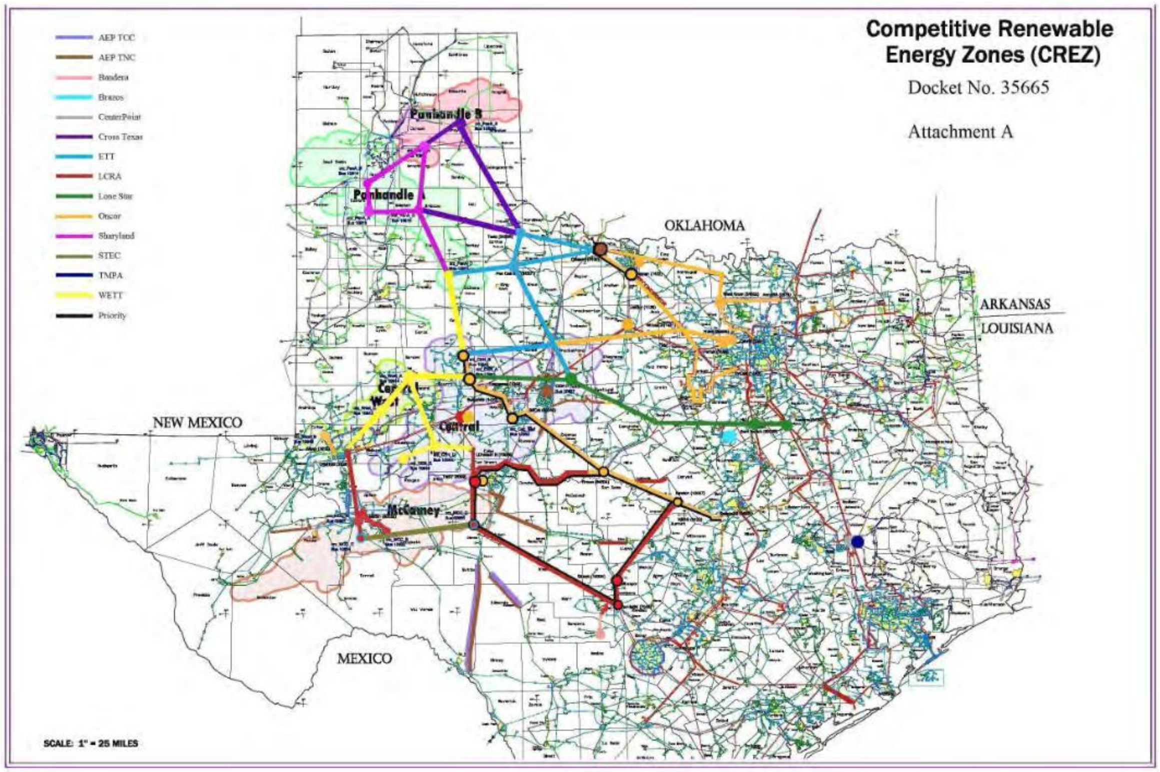

Figure 3. Competitive Renewable Energy Zones: Bringing Wires to Wind [9]
Image Credit: PUCT Docket No. 35665

The Importance of Power Systems Research

After the deregulation of Texas's electric retail market by Senate Bill 7 in 2002, utilities (apart from municipally-owned and electric cooperatives) separated their business activities into 3 categories: a power generation company, a transmission and distribution utility, and/or a retail electric provider (REP) [10]. Customers could now choose who their electric providers are which lead to competitive pricing by these REPs. Senate Bill 7 also contained a document called "The Goal for Renewable Energy" which created a Renewable Portfolio Standard (RPS) for Texas. This also inspired a Renewable Energy Credit (REC) Trading Program that allowed utilities with renewable energy sources providing to a grid to sell their "green energy" to other utilities to take credit for [11]. These competitive programs that occurred because of this bill along with

ERCOT's own goals to provide clean energy to the grid, prompted a huge increase in renewable energy projects. Because of Texas's natural resources, the wind energy market quickly boomed.

It may sound simple to build a wind farm in the regions of Texas where no one lives; it's out of the way, yet provides green energy to better the planet. But as electrical engineers became power engineers, they quickly understood that there is so much more to consider. This research illustrates just a small part of what planning engineers do at ERCOT and other ISOs every day. Power flow analysis tools like PowerWorld and PSSE allow engineers to see the effects of changes to the grid and assists them with discovering a solution, even if found heuristically. The synthetic grids, made from public data to approximate the real load and generation on interconnection systems, have opened up a ground-breaking way to educate students on the function of a power engineer. Adding load and generation on this big on a system from actual reports gives electrical engineering students the opportunity to experience the challenges they will face upon graduation.

This research specifically targets the planned wind energy projects on the ERCOT system from the years 2017 through 2019 and the methodology of transmission planning surrounding the generation additions. The next two sections lay out the methodology and results of adding over 7.5 gigawatts to the synthetic case of the Texas electric grid.

CHAPTER II

METHODS

Texas Synthetic Grid Base Case Overview

The program PowerWorld aids in visualizing electric power systems where users simulate generation, transmission, distribution, load, and many more features that allow the electric power grid to function. Specifically, this research looks at the addition of wind generation onto the Texas Synthetic grid Case, a 2000-bus model of the state of Texas constructed from public data about the ERCOT system.

To illustrate already existing wind generators, all objects were deleted on the TSGC except for the substations and the already existing wind energy. Figure 4 below shows the results of this action.

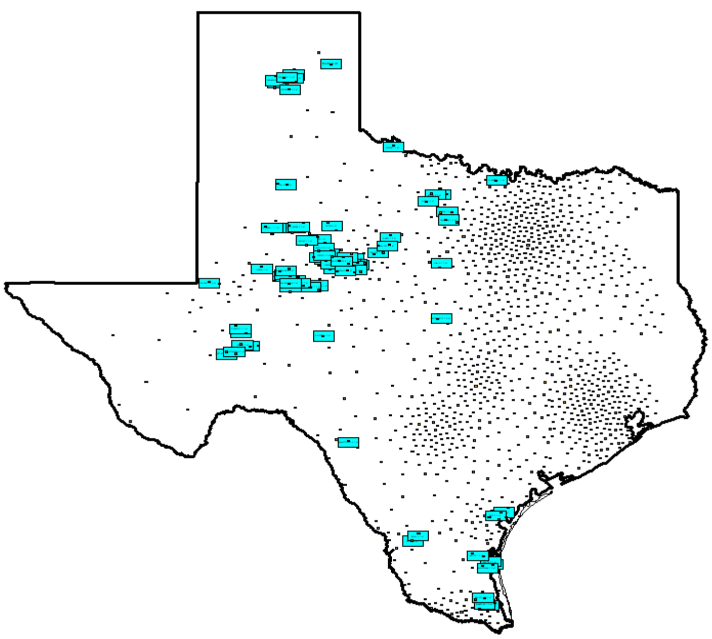

Figure 4. Texas Synthetic Grid Base Case [12]
Image is a derivative of "Texas Synthetic Grid Case" by A. Birchfield. Published with permission.

The blue rectangles portray the wind turbines which range from 7.5 MW up to 216.45 MW with the average wind turbine producing about 2 MW. As Figure 4 above illustrates, most of the wind generation on the synthetic case exists in the Great and Central Plains, also known as the Hill Country and the Panhandle of Texas. A few other farms are scattered throughout the South of Texas along the Gulf shoreline and on the border between Texas and Oklahoma. The total MW capacity on the grid at this point in the base case is 8962.38 MW with the maximum (if the wind was blowing everywhere at its highest speed) just over 12.5 GW.

ERCOT Generation Interconnection Status Report

On the ERCOT website exists a document that they release to the public every year. Until 2014, they called this report the System Planning Division Report and gave it monthly at stakeholder meetings. The last report, given in late October or November, shows the generation interconnections that have been implemented onto the ERCOT system and the planned installments in the near future. Starting in 2014, this report moved under the more organized and thorough Generation Interconnection Status (GIS) Report which has an excel sheet of all planned generators including a “Wind Chart” with all of the wind to be added to the system within the next three years.

In order to insure accuracy and see where ERCOT plans to install wind in the next few years, Figure 5 illustrates the Generator Interconnection Status Report of 2017. Each pin represents the counties where installations are to be completed. The blue pins symbolize those completed in 2017; the red pins, those in 2018; and the purple, those planned for 2019. Of course this report updates every year as new proposals roll in or projects are cancelled, but this gives a realistic estimate of what will be added to the system through 2019. After looking at the report, ERCOT plans to add 8.6 GW between 2017 and 2019. After decreasing these capacities slightly, the total amount of wind energy added to the TSGC for this research will be 7,870 MW.

Figure 5. GIS Report 2017 Future Wind Interconnection Map [13]
Image is a derivative of ERCOT's Generation Interconnection Status Report of 2017.

Adding a New Generator to a Bus

Model Explorer Example

Unit Type	Gen MW Marg. Cost	Fuel Type	Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
W3 (Wind Turbine, Type 3)	0.00	Wind	1082	FORT STOCKTON 2 0	1	Closed	112.50	-21.60	1.00000	NO	YES	45.00	150.00	-21.60	31.95	Cubic	150.00

Figure 6. PowerWorld Model Explorer: Generator [12]

The model explorer contains all of the case information and displays. It can be used to do almost everything in PowerWorld and all the information can be exported and imported from Microsoft Excel allowing easy analysis and automation for additions to the case.

Determining Bus Name and Number

Each new wind generator must be added to a bus which belongs to a larger system called a substation. All elements on the PowerWorld case are placed at geographic coordinates, so each of the county's latitude and longitude will be determined from Google Maps. In order to efficiently add each of the 25 new generators, an excel spreadsheet will calculate the smallest distance from an existing substation to the coordinates within the county. Below indicates this formula:

$$x = \sqrt{(A - C)^2 + (B - D)^2}$$

Where, x = distance, A = latitude of existing substation, B = longitude of existing substation, C = latitude of new generator, and D = longitude of new generator. If the same substation comes up for more than one of the generators, then the second closest substation will be chosen. After that, the network model explorer will determine what bus number belongs to each substation. Some substations have multiple buses, so the bus with the most realistic nominal kV for a wind interconnection will be chosen (usually in the 115-161 kV range).

Other Static Parameters

As seen in Figure 6, more than just the bus name and number is needed to add a new generator. For this research, the following Table 1 illustrates what will be the static parameters for each new generator:

Table 1. Static Parameters

Parameter Name	Value
ID	J
Set Volt	1.02
AGC	NO
AVR	YES
Min MW	0
Min Mvar	(Gen MW*(-.14))
Max Mvar	(Gen MW*(.21))
Cost Model	Cubic
Part. Factor	n/a

Other Variable Parameters

The status describes whether the generator is open (no power runs into the bus from the generator) or closed (power equal to the generation MW runs into the system). All 25 new generators are first added as "open" so that power solution does not change. Then, one by one, each generator will be "closed" and the lines that are overloaded will be observed and fixed. The generation MW and generation Mvar tabs will be changed on a case-by-case to see the turning point in line overloads, but the ultimate goal is to have them all running at 75% of their maximum allowing the assumption that the wind is blowing consistently everywhere.

Transmission Planning for Added Generation

Many options to alleviate overloaded lines exist. The first technique in this research will be adding a line in parallel to an overloaded line with the same parameters to solve the issue. This may cause overloads in other lines, though, so analysis to the whole picture must be done to see if this solution works without consequences. Other lines can be added to surrounding substations to fix the problem, but keep in mind the land restrictions in reality. Adding these lines in PowerWorld with the click of a button can be simple to do, but as discussed in the background section, "property boundaries, environmentally sensitive areas, wildlife, turbine fall distances, government regulations and more internal guidelines [4]" exist to prevent adding transmission with ease.

If just adding lines with similar parameters does not correct the overloading, sometimes just upgrading the conductor in the existing line works because it increases the MVA limits. Yes, this can mean rebuilding the line, but the hardware to hold the line already exists and the permission to build that line has already been granted. Although, upgrading the conductor type may not do enough which may mean adding a separate line with a higher voltage. The cost of building another bus and transformer comes with adding a high voltage line to come out of the system. It may even require building a bus and transformer on the other side of the line depending on the distance to another bus with the same nominal voltage. This has high costs, but getting power from these wind generators out in West Texas to the big cities with more dense population can sometimes only be done by building more high voltage lines.

No optimal solution exists in transmission planning because adding just one line affects the entire system. The engineer must take into account both the cost restrictions and land restrictions which means the best solution may not even be pliable.

Cost Analysis Strategy

The most important metric for the cost of constructing a wind farm comes from the Department of Energy's Wind Technologies Market report stating "the capacity-weighted average installed project cost within the 2016 sample stood at roughly $1,590/kW [1]." The report includes cost by region, installed capacity, and number of projects per region of the United

States. Fortunately, the interior region of the U.S., which includes Texas, has the lowest cost, so this research can assume the installed project cost to be approximately $1,500 per kW [1].

Transmission costs must also be taken into account. The following Table 2 and Table 3 contain data from a 2014 study done by Black and Veatch on Capital Costs for Transmission and Substations for the Western Electricity Coordinating Council. They did not include the price of 115 kV and 161 kV line costs or the 161/230 kV and 161/500 kV transformers therefore an educated estimation was put forth and will be used for the cost estimates in the results section.

Table 2. Baseline Transmission Costs [14]

Line Description	Line Cost Estimate ($/mile)	
115 kV Single Circuit	$	800,000.00
161 kV Single Circuit	$	900,000.00
500 kV Single Circuit	$	1,919,450.00

Table 3. Baseline Transformer Costs [14]

Transformer Type	Cost per XFMR	
161/500 kV	$	10,875.00
115/500 kV	$	10,350.00
161/230 kV	$	7,250.00
115/230 kV	$	7,250.00

After all simulations run and all objects are accounted for, the results section will illustrate an estimation of costs for this research project.

CHAPTER III

RESULTS

New Generators

After observing the GIS report of December 1st, 2017 and making adjustments to the capacity, twenty-five total new generators were added to the TSGC totaling 7,870 MW. The Table 4 below illustrates each new generator, the bus number they are located on, the region they are located in, and their generation capacity.

Table 4. New Generators Added to TSGC

Number of Bus	Name of Bus	Region	Gen MW
1016	GARDEN CITY 0	Far West	300
1044	BIG LAKE 0	Far West	350
1055	ODONNELL	Far West	350
1091	RALLS 2 0	Far West	350
2012	PANHANDLE 2 1	North	600
2029	SILVERTON 0	North	300
2041	PANHANDLE 3 0	North	350
2048	CROSBYTON 0	North	300
2049	ELECTRA 0	North	210
2093	PANHANDLE 5 0	North	500
2123	PANHANDLE 1 0	North	350
2130	HASKELL 0	North	500
3024	ELDORADO 0	West	300
3035	CHEROKEE 0	West	410
3144	ROWENA 0	West	210
3146	JUNCTION 0	West	320
4053	ARMSTRONG 2 0	South	300
4104	TAFT 2 0	South	200
4128	RIO GRANDE CITY 0	South	350
4150	CORPUS CHRISTI 15 0	South	200
4175	LAREDO 2 0	South	400
4184	SAN PERLITA 1	South	450
5046	STEPHENVILLE 1	North Central	100
5102	COMANCHE 0	North Central	300
7253	ANGELTON 1	Coast	250

The generators were tested by region. Having all of the generators on at once without making changes creates an immediate blackout. All of the generators were turned on at 75% of their maximum generation and each region's issues were solved one-by-one until there were no line overloads on the system as a whole. The following subsections describe what new objects were added to each.

Far West Region

1.35 GW of power was added to the far west region. The following Figure 6 shows the overloaded lines when all generators are "Closed." A similar figuration happens in each region when the generators are turned on. The red circles on the lines means they are ≥100% over their MVA limits.

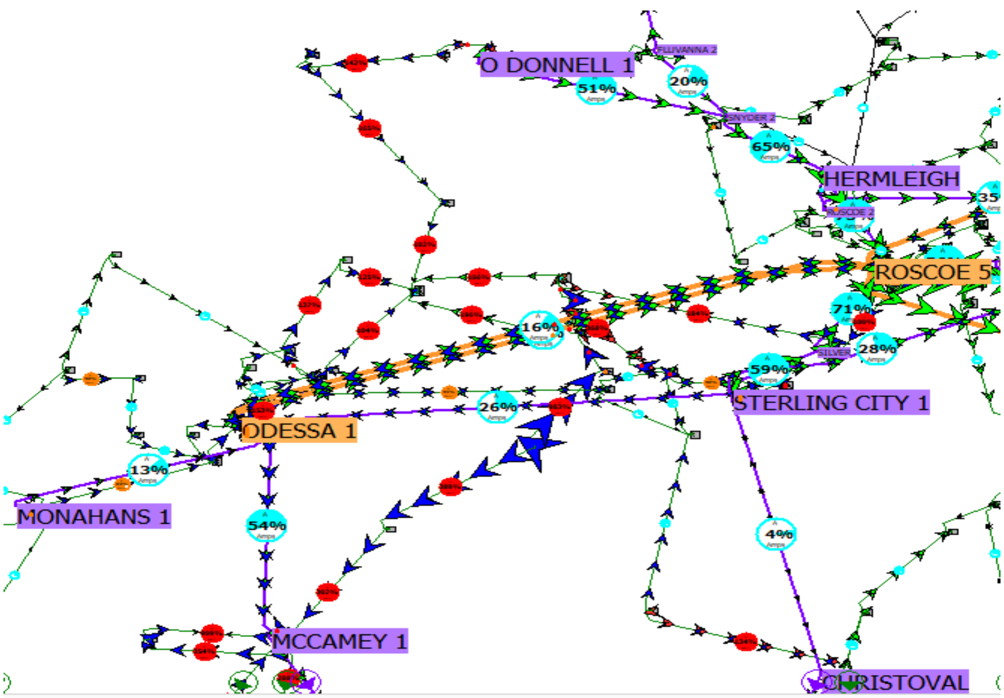

Figure 6. Example of Overloaded Lines [15]
Image is a derivative of "Texas Synthetic Grid Case" by A. Birchfield. Published with permission.

The following table shows what objects were added to fix these line overloads.

Table 5. Far West Region Additions

Generator's Bus Name	Objects Added	Reason
Garden City 0	1. Added 27.18 km line from Garden City 0 to Big Spring 2 (115 kV) 2. Added parallel 13.71 km line from Big Spring 4 to Big Spring 7 (115 kV)	1. Prevented overloading of Garden City 0 to Big Spring 4 2. Prevented overloading of existing line from Big Spring 4 to Big Spring 7
Big Lake 0	1. Added parallel 51.46 km line from Big Lake 0 to Christoval 1 (115 kV) 2. Updated existing 51.46 km line from Big Lake 0 to Christoval 1 to 221 MVA limit (115 kV), 3. Added parallel 35.22 km line from San Angelo 1 0 to San Angelo 2 0 (115 kV)	1. Prevented overloading of existing line from Big Lake 0 to Christoval 1 2. This allowed for less overloading on the line because it was able to handle more MVA capacity 3. Prevented overloading of existing line from San Angelo 1 0 to San Angelo 2 0
Odonnell 0	1. Upgraded 10.91 km line from Odonnell 0 to Odonnell 1 to 221 MVA limit (115 kV) 2. Added parallel 10.91 km line from Odonnell 0 to Odonnell 1 (115 kV)	1. Allowed for less overloading on the line because it was able to handle more MVA capacity 2. Prevented overloading of existing line from Odonnell 0 to Odonnell 1
Ralls 2 0	no additions	N/A

As seen in the chart above, some transmission lines were upgraded to have a higher MVA limit. This might mean rebuilding the whole line to upgrade the conductor, but in order to maintain this much wind generation out in the Far West, lines will need to be upgraded to move this much power. No high voltage lines had to be added in this region because the simpler techniques controlled the overloads.

North Region

A total of 3,110 MW were added to the North region which includes the panhandle, an area with a fast growing number of wind mills. Table 6 shows the additions suitable for solving the overloaded lines in this region.

Table 6. North Region Additions

Generator's Bus Name	Objects Added	Reason
PANHANDLE 3 0	1. Created 500 kV bus, then added two 161/500kV transformers to Panhandle 3 2. Added 98 km line from Panhandle 3 to Miami (500 kV)	1. Needed a 500 kV line because of so much generation added to the panhandle area; Adding 161 kV lines did not solve issues 2. See reason 1; Miami substation had closest 500 kV bus
CROSBYTON 0	1. Added parallel 69.44 km line from Crosbyton 0 to Paducah 0 (161 kV) 2. Added 2 161/230kV transformers from Ralls 1 1 to Ralls 1 2 3. Added 13 km line from Ralls 1 to Ralls 2 (161 kV) 4. Added 48.64 km line from Paducah 0 to Vernon 2 (161 kV)	1. Prevented overloading of existing line from Crosbyton 0 to Paducah 0 2. Prevented overloading of existing transformer from Ralls 1 1 to Ralls 2 2 3. Prevented overloading of existing line from Ralls 1 to Ralls 2 4. Prevented overloading of existing line from Paducah 0 to Vernon 2
ELECTRA 0	1. Added 500 kV bus and 161/500kV transformer to Electra 2. Added 61.63 km (500 kV) line from J Electra to Wichita Falls 1 3. Added 500 kV bus and 161/500kV transformer to Vernon 2 4. Added 67 km line from J Vernon to J Electra (500 kV) 5. Added 152 km (500 kV) line from Ralls 1 to J Vernon 2	1. Needed a 500 kV line because of connection to panhandle region 2. See reason 1; Wichita Falls substation had closest 500 kV bus 3. Needed a 500 kV bus to connect panhandle generation over towards Oklahoma border 4. See reason 3 5. Helped relieve overloaded lines
PANHANDLE 5 0	1. Added 27.44 km line from Panhandle 5 to Panhandle 4 (115 kV) 2. Upgraded existing 27.44 km parallel line to 220 MVA limit (115) 3. Added 161/500kV transformer to Panhandle 4	1. Prevented overloading of existing line from Panhandle 4 to Panhandle 5 2. Allowed for less overloading on the line because it was able to handle more MVA capacity 3. Prevented overloading of existing transformer
PANHANDLE 1 0	1. Added 12.37 km line from Panhandle 1 0 to White Deer 0 (115 kV)	1. Prevented potential overloading of existing line from Panhandle 1 to Deer 0
HASKELL 0	No additions	N/A

500 kV lines were added to this region because of the amount of generation. Using a heuristic approach, two 500 kV buses were added to be able to connect from panhandle towards the boarder of OK. The growth of wind energy in this area definitely calls for more 500 kV lines, but the specific placement is dependent on other variables in reality. For this case, the new J Vernon and J Electra buses added major relief to the system.

West Region

The west region received 1,240 MW worth on new generator capacity. Since this area has a spread out population, new transmission was needed to compensate. Table 7 illustrates what new objects were needed.

Table 7. West Region Additions

Generator's Bus Name	Objects Added	Reason
Eldorado 0	1. Added 500 kV bus and 2 115/500kV transformers to Menard 2. Added 70 km line from J Menard to J Rowena (500 kV) 3. Upgraded 46.68 km Eldorado to Menard line to 250 MVA limit (115 kV)	1. Alleviated 6 surrounding lines of Menard due to Eldorado generator 2. See reason 1 3. Allowed for less overloading on the line because it was able to handle more MVA
Cherokee 0	1. Upgrade 35.29 km line to 220 MVA limits Cherokee to Llano (115 kV)	1. Allowed for less overloading on the line because it was able to handle more MVA
Rowena 0	1. Added 500 kV bus and 115/500kV transformer to Rowena 2. Added 115.66 km line from J Rowena to Goldthwaite 1 (500 kV)	1. Alleviated 9 surrounding lines of Rowena 2. See reason 1
Junction 0	1. Added parallel 48.79 km line from Junction 0 to Menard 0 (115 kV)	1. Prevented potential overloading of existing line from Junction 0 to Menard 0

The 500 kV line from J Menard to J Rowena alleviated Eldorado 0→Christoval 0, Menard 0→Goodfellow AFB, Menard 0→Mason 0, Eden 0→Rowena 0, Cherokee→Llano, and Coleman 0→Santa Anna 0. The 500 kV line from J Rowena to Goldenthwaite alleviated lines similar to the J Menard to J Rowena line. Once again, this may not be the optimal solution, but it provided relief to the system and gives the potential more generation with these high voltage lines.

South Region

The total addition to the South Region is 1,900 MW. Closing all 6 generators made major changes to the lines overloading them in a range from 82% up to 288%. The following table 8 shows what objects were added to fix these line overloads.

Table 8. South Region Additions

Generator's Bus Name	Objects Added	Reason
Armstrong 2	1. Added 26.33 km line from Sarita 1 to Sarita 2 (115 kV) 2. Added 2 115/230kV transformers to Armstrong 1 substation	1. Provided relief for Armstrong 1 transformers 2. Provided relief for existing Armstrong 1 transformer
Taft 2 0	No additions	N/A
Rio Grande City 0	1. Added 28.47 km line from Rio Grande City 0 (115 kV) to Edinburg 3 0	1. Prevented potential overloading of existing line from Rio Grande City 0 to Edinburg 3 0
Coprus Christi 15 0	No additions	N/A
Laredo 2 0	1. Added a 41.9 km line from Laredo 2 to Encinal 0 (115 kV) 2. Added a 31.56 km line from Laredo 2 to Oilton 2 (115 kV) 3. Added parallel 25.68 km line from Laredo 2 to Laredo 3 (115 kV) 4. Added parallel 23.7 km line from Laredo 3 to Laredo 6 (115 kV)	1. Prevents overloading of lines from Laredo 2 to Laredo 3 2. See reason 1 3. See reason 1 4. Prevented potential overloading of existing line from Laredo 3 to Laredo 6
San Perlita 1	No additions	N/A

The biggest issue was in the Laredo Generator. Creating a transformer within the substation to be able to connect a 230 kV line out only created more contingencies. Although adding four new transmission lines can be costly, updating multiple substations with a 230 kV bus and building high voltage lines would be more costly therefore this solution was chosen. Another slight issue was at San Perlita because two lines going from San Perlita to Sebastian substation were loaded to 87% capacity. Because this is on the high side, it was also tested at maximum MW output of 450 MW, and the lines still did not overload therefore no new objects were economically sensible.

North Central Region

This region was done last and therefore needed no additions. Both Stephenville and Comanche generators (400 MW total) were successfully implemented onto the grid without line overloading issues.

Coast Region

The only generator added to the Coast Region is a 250 MW generator to Angelton 1 bus. When closing just this generator, there were no overloads on any surrounding lines.

Cost Estimation

Going back to the methods section about cost estimation, the cost per kilowatt of wind energy added to the grid was estimated at $1,500/kW. Since 7,870 MW worth of wind generation was added to the grid, this puts the total cost of the wind energy project at $11,805,000,000.

Tables 9 and 10 below illustrate the total costs for the components added to the TSGC. Although these numbers are not exact due to difference in line voltages in reality versus this synthetic case and lack of other values such as pole costs and conductor types, this gives a good idea of how easily transmission costs can accrue quickly.

Table 9. Line Cost Estimations

Line Type	Total Distance (Miles)	Cost
115 kV line	363.78	$ 286,576,305
161 kV line	81.45	$ 73,304,379
500 kV line	350.43	$ 672,629,771

Table 10. Transformer Cost Estimations

Transformer Type	Total Number	Cost
161/500 kV	5	$ 54,375
115/500 kV	3	$ 31,050
161/230 kV	2	$ 14,500
115/230 kV	2	$ 14,500

After all of the costs, the total estimate for adding this generation at 75% of capacity comes out to be over $12.4 billion.

CHAPTER IV

CONCLUSION

Real World Application

With the windy panhandle, central plains, and coast of Texas, deciding wind generation belongs here is the easy part. Planning a generation interconnection, new transmission lines to transport added power, and the upgrades at each substation affected takes multiple teams of highly trained engineers, permission from landowners and environmental agencies, and regulatory government approval. This research took 7.5 GW of new wind generation and, with the click of a button, added it to a synthetic model of the Texas electric grid. With careful methodology and thoughtful strategy, a solution to the newly overloaded grid was put into place by adding new transmission lines, transformers, and line upgrades. PowerWorld made visualizing the complete picture possible and allowed for mistakes to be erased without consequences. In reality, planning for the future of the grid is not as simple as creating a viable solution in PowerWorld, but using this tool to understand the system and how it should function theoretically has revolutionized the industry forever.

What Does This Mean for the Future of Wind Energy in Texas?

As long as the wind does not stop blowing, Texas will not stop building windmills. Not only do they provide power to the grid with little ongoing cost, but they even help with frequency deviations in the ERCOT system. CREZ has allowed wind generation to be built in the far west region of Texas as well as the panhandle which is essential to the load growth issues arising as population in cities like Dallas and Austin rapidly increases. Technology like

PowerWorld and other power flow software are being used by ERCOT as this paper is being written allowing the future of the grid to be planned as never before.

REFERENCES

[1] R. Wiser, M. Bolinger, "2016 Wind Technologies Market Report", U.S. Department of Energy, Lawrence Berkeley National Laboratory. DOE-GO/102017-5033, August 2017.

[2] Magness, Bill (2017). *CEO Perspectives* [PowerPoint slides]. Retrieved from www.ercot.com.

[3] M. Mueller, "How Much Power is 1 Gigawatt?" *Office of Energy Efficiency and Renewable Energy."* Oct. 21, 2016.

[4] K. Dykes, M. Hand, T. Stehly, P. Veers, M. Robinson, E. Lantz, R. Tusing, "Scientific Challenges in Wind Energy and the A2e Applied Research Program" in *Enabling the SMART Wind Power Plant of the Future Through Science-based Innovation*, Aug 2017, pp 5.

[5] AWS Truepower, National Renewable Energy Lab, "US 80-m Wind Resource: Land." 2010. https://www.nrel.gov/gis/wind.html

[6] S. Haynes, "Wind Farm Design" from *Iberdrola Renewables.* Jan 2013. https://www.nrel.gov/wind/assets/pdfs/07_3_haynes_nrel_systems _ engineering.pdf

[7] J. Clemente, "The Great Texas Wind Power Boom" in *Forbes Magazine*, Oct 2016. https://www.forbes.com/sites/judeclemente/2016/10/11/the-great-texas-wind-power- boom/#619f4e6ac6aa

[8] The Climate Reality Project, "6 Reasons Why Texas Leads the Nation in Wind Power", in *EcoWatch,* July 2016. https://www.ecowatch.com/6-reasons-why-texas-leads-the-nation-in-wind-power-1906696525.html

[9] Public Utility Commission of Texas. (2016, July 5). Competitive Renewable Energy Zones (CREZ). Docket No. 35665.Available:http://puc.texas.gov/ industry/maps/maps /CREZ_Map_Attach_A.pdf

[10] T. Hunter, "History of Electric Deregulation in Texas," Public Utility Commission of Texas, April 17th 2012.

[11] Public Utility Commission of Texas, "Electric Substantive Rules: Chapter 25", §25.173- Goal for Renewable Energy, January 2 2009.

[12] A. Birchfield, ACTIV_SG_2000_AUG-29-2017. PowerWorld Version 20, Aug 2017.

[13] ERCOT, "Generator Interconnection Status Report November 2017", http://www.ercot.com/gridinfo/resource.

[14] A. Birchfield, ACTIV_SG_2000_MAR-14-2018. PowerWorld Version 20, March 2018.

[15] Black & Veatch, "Capital Costs for Transmission and Substations: Updated Recommendations for WECC Transmission Expansion Planning," B&V Project No. 181374, Feb 2014.