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Wind Turbine Power Production Estimation for Better Financial Agreements

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WIND TURBINE POWER PRODUCTION ESTIMATION FOR BETTER FINANCIAL AGREEMENTS

A Thesis Presented

by

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ABSTRACT

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Wind farm operators utilize various financial agreements to generate revenue and mitigate risk. These agreements are often based on some estimate of the energy production from the wind farm. A power purchase agreement (PPAs), which is a long-term fixed volume fixed price arrangement, was the most common type of agreement for much of the growth of wind energy in the U.S. Recently, wind turbine power production estimations are relying less on fixed production volumes and PPAs as the basis for energy estimation in financial agreements and more on proxy generation, or an estimate of what the wind farm should make given a set of inflow conditions. These newer types of financial agreements are shifting the focus to when power is produced rather than just how much, and so it is imperative to understand and analyze the errors arising in proxy generation and how it may impact the financial agreements that use proxy generation. This work quantifies the errors in proxy generation and compares two methods of estimating power production, examining the financial impacts of both, for one wind project. These two methods are the nacelle transfer function (NTF) method and the reanalysis data method, which may be used if onsite data is unavailable. The different

methods of estimating power production have varying impacts on the financial outcome of the project. Errors in power production estimates that coincide with large price events can result in significant financial impacts for the wind project, and this is more likely to occur with the reanalysis method compared to the NTF method. The results show that the Nacelle Transfer Function (NTF) method of estimating power production via onsite measurements has much less risk of being impacted by a price excursion than the reanalysis data method.

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CHAPTER 1

INTRODUCTION

Wind energy is among the fastest growing sources of energy in the U.S. and globally. In the past 10 years, the installed capacity of wind turbines in the U.S. has increased from 40.18 GW to 113.43 GW, and is projected to reach 224.07 GW by 2030 [1]. As wind energy installations have grown, traditional power purchase agreements have become less common. Wind projects have therefore utilized financial arrangements to guarantee their revenue stream. One of the integral components of these financial arrangements is the concept of proxy generation (PG), which is used to estimate wind farm power production under ideal conditions. To sustain wind energy development, it is critical to understand the interconnections between the production of a wind project and the associated financial arrangement, and thus the revenue and risk of the project.

Traditionally, wind energy developments were financed based on power purchase agreements, which pay a fixed price for every kWh produced. Thus, the expected performance of the project depends solely on the estimated annual energy production (AEP). However, electricity prices are highly variable, especially at daily and annual time scales. Electricity prices, independent of wind, fluctuate significantly from on/off peak prices as well as with the seasons [2]. Power Purchase Agreements (PPAs) shield wind energy developments from these fluctuations. With a continual decrease in the prevalence of PPAs (discussed further in section 2.2.1), financial agreements like the virtual PPA and proxy revenue swap have emerged as viable alternatives (discussed further in section 2.2.2). Using proxy generation, defined as what the wind farm should produce given a set of weather conditions, to estimate wind farm power production allows these agreements to minimize risk to all parties and stabilize cash flow [3].

When extreme price events occur and coincide with large error in wind turbine power production estimation, wind plants can be exposed to substantial price risk. The price excursions that occurred in Texas during February 2021 are a prime example of circumstances that can lead to these price events. Different methods of calculating proxy generation can also have varying impacts on the financial outcome of wind plants. A better understanding of the methods for calculating proxy generation and the associated prediction errors, as well as how PG correlates with electricity pricing, will lead to financial agreements with a more desirable balance of risk for both parties [4]. The objective of this thesis is to compare two power prediction methods and their results, relative to price, in order to better inform financial models that rely on proxy generation.

In an effort to improve the understanding of how different methods of power prediction impact the financial outcome for wind plants, this thesis has the following goals:

- Develop and validate a Nacelle Transfer Function (NTF) model in Python for calculating proxy generation.
- Develop and validate a Reanalysis Data model in Python for calculating proxy generation.
- Compare the Proxy Generation and Proxy Revenue results from both methods.

Chapter 2 provides background on both wind turbine power production estimation as well as wind plant financial arrangements. Chapter 3 outlines the wind plant and other data sets used in this analysis. Chapter 4 and 5 discuss the NTF and Reanalysis Data methods, respectively. Chapter 5 compares the results between the two methods. Chapter 6 summarizes the analysis and provides avenues for future work.

CHAPTER 2

BACKGROUND

2.1 Wind Turbine Power Production

Wind turbine power production is characterized via the power curve (discussed further in section 2.1.1). Combining the power curve with the wind speed distribution (discussed further in section 2.1.2) at the location provides an estimate of the wind energy generated by the farm over the course of a year. This generation estimate, along with a pricing estimate, is the basis of revenue estimation used in financial agreements. The components of wind power production are outlined below along with their difficulties and alternative solutions.

2.1.1 Power Curve

The wind turbine power curve relates the electrical output of a wind turbine as a function of the inflow conditions. These are generated by wind turbine manufacturers, and typically are based on test data, with specifications described in the IEC 61400-12-1:2017 [1]. The International Electrotechnical Commission (IEC) is responsible for maintaining the set of design requirements to verify that wind turbines are built safely and according to specific technical conditions.

Figure 1 below provides an example of a power curve and highlights important sections.

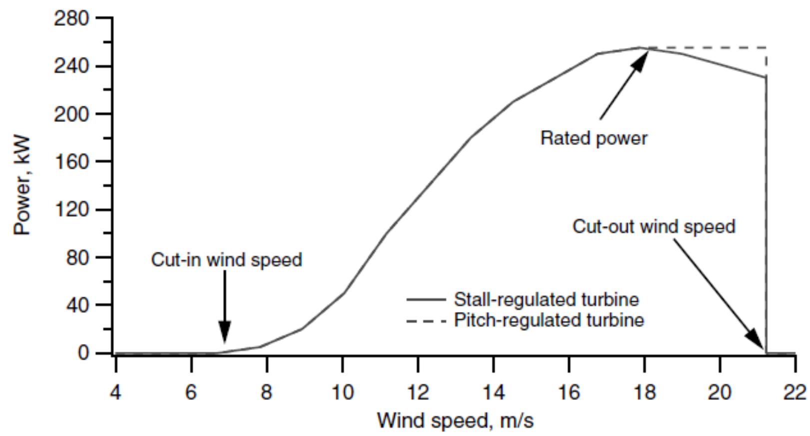


Figure 1: Wind turbine power curve [2]

Power curves are affected by a variety of factors and the reference power curve may only apply to particular climate or terrain regions. There has been significant research on power curve accuracies and the effects of complex wind regimes on turbine performance [3],[4],[5], showing that there is deviation in power production from the predicted values given a manufacturer's reference power curve. Examining the deviation between proxy and actual generation, however, is a new concept.

Deviation in power curves can also arise from factors such as turbulence intensity, wind shear, and terrain [3],[4]. Additionally, different weather phenomena such as the Low-Level Jet experienced in the Great Plains/Midwest region can result in the vertical wind speed and shear profile being inaccurate when estimated through the typical power law relations [5]. Terrain and wake effects also cause complicated wind conditions.

As this research will use manufacturer sales power curves, it is expected that these same factors will impact the results. However, in the context of financial settlements, deviations from the warranty (reference) power curve are considered to be a component of turbine performance, which is partially accounted for in expected operational losses and also categorized as operational risk (discussed further in Section 2.2).

2.1.2 Wind Speed Characterization and Measurement

The wind speed at a location varies over time, and the Weibull distribution is often used to characterize the long-term wind speed probability distribution, as seen in Figure 2. To create this distribution, a time series of measured wind speed at a site is created. It is typical to use a time series with either 10-minute average or 1-hour average wind speeds. A histogram of the measured wind speed can then be created, and fit with a probability distribution, such as the Weibull.

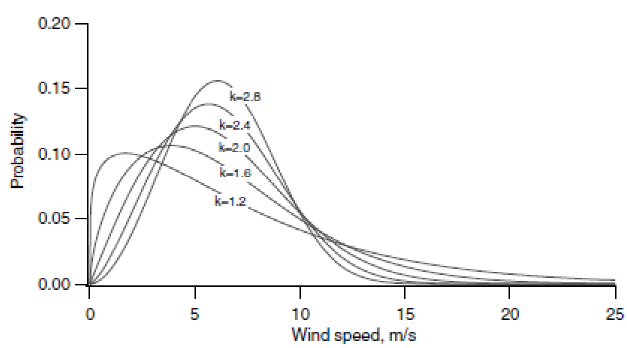


Figure 2: Weibull probability density function for $\bar{U}$ =6 m/s [2]

The Weibull distribution is a 2-parameter distribution, using the scale and shape parameter. These parameters determine the mean and shape of the distribution. Traditionally the estimated energy production of a wind turbine is calculated by integrating the product of the wind speed probability distribution and the turbine power curve over all wind speeds. This produces a long-term estimate of the expected annual energy production (AEP) but does not consider seasonal variations in wind speed. That is, the energy produced during any given season may differ substantially from what would be predicted from the long-term wind speed probability distribution [4]. In addition to seasonal variations, there are also fluctuations on smaller time scales that occur.

Wind speed data can be measured and collected using different approaches, including a nacelle anemometer, a meteorological mast (met mast) or remote sensing devices. Wind condition data can also be estimated using a mixture of observations and models, as is the case with Modern Era-Retrospective analysis for Research and Applications (MERRA) (discussed further in Section 3). This research will examine trends in proxy generation dependent on these different wind speed data sources. Nacelle anemometer wind speeds come from anemometers mounted to the back of the turbine nacelle and require a nacelle transfer function to estimate what the wind speed would have been, in the absence of the rotor, which has uncertainties. Met mast wind speeds come from towers that are not always where the turbines are located, and due to terrain effects may have values that differ from the true wind speed experienced by a turbine. MERRA reanalysis data are a synthesis of world wind observation data, and the use of this data is relatively new for this application [6]. In addition to the variability in data sources already discussed, there are also wake effects from turbine-turbine interactions, resulting in even more variability in the wind speed measurements. This analysis will examine the effects of these different wind speed sources on the accuracy of the proxy generation calculation.

2.1.3 Proxy Generation (PG)

Proxy generation is an idealized production estimate that is based on inflow conditions. Proxy generation can be described below [7].

$$PG(WS) = (PowerCurve_{warranty}\big(WS, NTF(WS)\big) - ExpectedOperationalLosses$$

Where $WS_{nacelle}$ is the nacelle wind speed, NTF is the nacelle transfer function, $PowerCurve_{warranty}$ is the warranty (reference) power curve, and $ExpectedOperationalLosses$ includes power performance losses, wake losses, lockage losses, and transmission losses within the plant. Nacelle wind speed is corrected to "free stream" with the NTF ratio, and the corrected wind speed is then used with the power curve to calculate energy. NTF and Power Curve are both non-linear functions of wind speed.

Some research has begun to examine the error in proxy generation, although it has only been in regard to performance in simple terrain [7]. It has been shown that the uncertainties from NTFs can be 4-8%, with proper management of measurements.

There are many different components that factor into the final PG result, each with their own potential for error. Uncertainty arises in the measurement of wind data. There is also the possibility of failed or faulty instruments, inconsistently mounted nacelle anemometers, or inconsistent turbine controller settings. The nacelle transfer function is derived from project met mast turbine pairs, then applied to other turbines in the wind farm without accounting for wake affects. It is highly dependent on inflow angle, turbulence intensity, and measurement layout mounting. The power curve used in this equation is the contract power curve from the manufacturer, and the actual production will vary as well (as discussed in section 2.1.1). In the expected operational losses, there are site calibration issues and proxy generation is known to underestimate these values [4]. These sources of error all effect the final proxy generation calculation, which will be compared to the actual generated power.

2.2 Wind Energy Financial Models and Agreements

Wind energy financial models have changed significantly since the industry began and agreements are still changing today [8]. Without a financial arrangement, wind farms would sell directly into the electricity market. This merchant structure results in variable cash flow for the project, and wind projects need revenue stability to be viable, which led to the development of traditional PPAs. Due to the lack of buyers driving PPA prices low, they are continuing to be phased out and replaced by swaps, hedges, and virtual power purchase agreements (discussed further in section 2.2.2 and section 2.2.3). This work with proxy generation hopes to allow financial agreements to be robust as the industry continues to grow.

2.2.1 Power Purchase Agreements

Traditional PPAs are long-term fixed price contracts of 15-20 years, typically between a wind project and a utility or end power user [9]. There is a limited pool of buyers (utilities and end users) but many producers (wind project developers), which results in low prices for the agreements of this type. Due to the pricing and lack of buyers, fewer traditional PPAs are being made, as seen in Figure 3. Wind projects are then forced to turn to alternative arrangements, leading to an increase in synthetic PPAs [10].

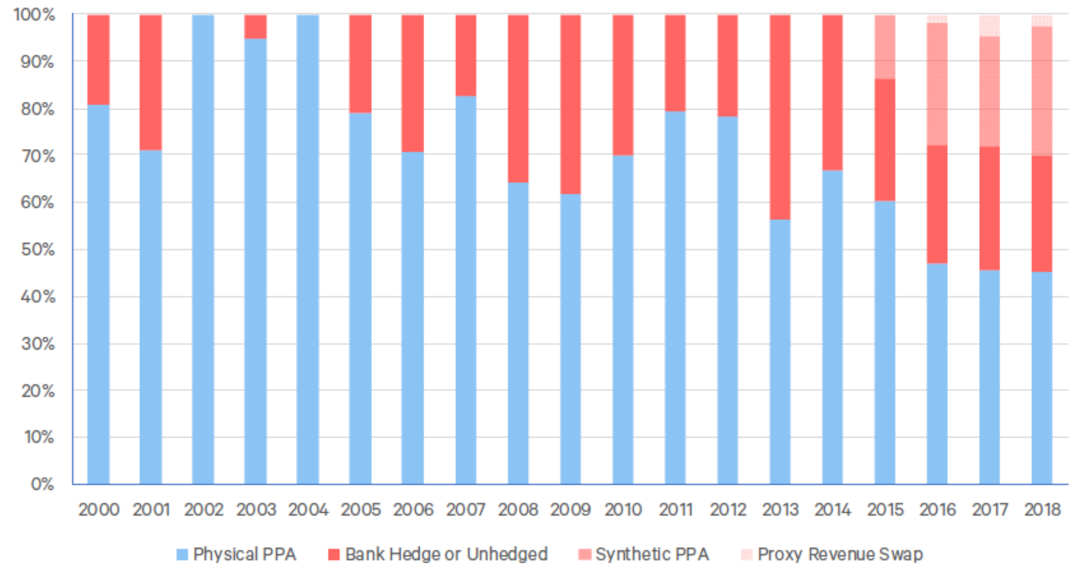


Figure 3: Percentage of US wind capacity installations since 2000, by physical PPA or merchant structure [11]

By charging a fixed price per kilowatt hour in a PPA, this financial arrangement is simplified with respect to the wind's intermittency and unpredictability [12]. However, this forces wind projects to sell power at a lower, albeit guaranteed price potentially resulting in less revenue. Due to the pricing of traditional PPAs decreasing, the industry is moving toward alternative agreements that strive to account for these complexities in wind speed variability and increase revenue while still protecting the wind projects against electricity price fluctuations [11].

2.2.2 Financial Hedging and Strategies

Financial agreements such as hedges and virtual PPAs have been able to stabilize cash flows for wind projects. Virtual PPAs, as described in the name, never actually see an exchange of electrons between the wind farm and the counterparty. Instead, both the wind farm and counterparty buy and sell directly into the wholesale market, and the difference in market and pre-determined fixed price is then settled between the two. Virtual PPAs may also come with the added benefit of Renewable Energy Credits (RECs) for the counterparty [13]. Bank hedges are an arrangement in which the wind farm promises to produce a fixed volume of energy, and the settlement amount varies depending on the market price of energy.

Figure 4 below summarizes how payment is arranged between the wind project (renewable energy system), electricity market (power pool and utility), and hedge provider (business) for a virtual PPA.

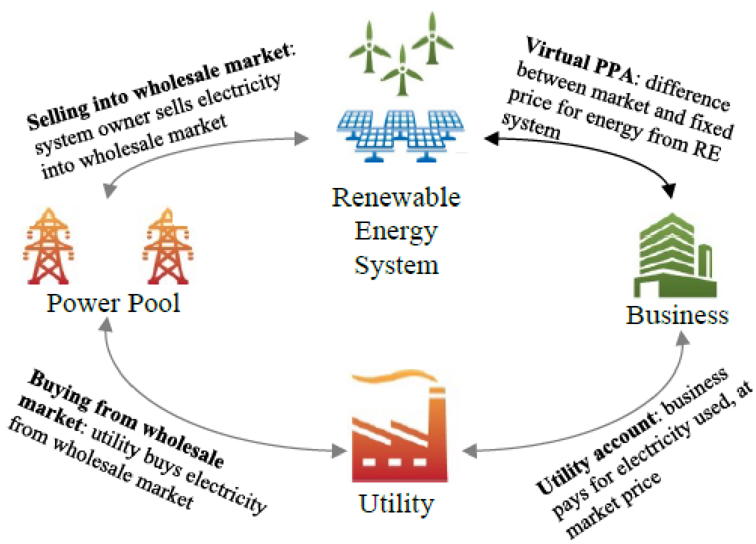


Figure 4: Illustrations of virtual PPA transactions [10]

In virtual PPAs, the Actual Generated Quantity (AGQ) is typically used to determine the fixed price of energy [7]. The AGQ is the amount of energy that the project actually generates. Using AGQ to settle pricing may cause issues for the hedge provider when the generated quantity is not as expected. One factor that may cause an issue is operational risk due to competing interests between the hedge provider and wind farm [14]. AGQ is partially dependent on the quality of wind farm operation (i.e. how well managed and maintained the wind farm is), and the counterparty wants zero exposure to operational risk. Using Proxy Generation (PG) instead of AGQ, which is based on measured input rather than measured output, the operational risk is removed for the hedge provider [15]. PG provides an estimate for the energy that the wind farm should generate given a set of weather conditions, which puts the operational risk on the wind farm - the party responsible for the operation.

For bank hedges, the wind farm is responsible for paying the settlement amount, regardless of how much energy is produced. Wind is a variable resource, but the fixed volume of energy is expected to be delivered regardless, which forces the wind project to be responsible for the weather risk. Proxy Generation mitigates this as it allows for expected energy production to fluctuate depending on the measured availability of the wind resource.

2.2.3 Financial Settlements with PG

Increasing the proxy generation accuracy will provide hedge providers and wind farms with a better estimate of what the project should have produced, which will improve financial agreements for both parties. Wind measurements therefore have the potential to impact project revenue. Wind project financial stability is now dependent on PG, through two primary financial settlements: the Proxy Generation virtual PPA (PG-vPPA) and the Proxy Revenue Swap (PRS). PG-vPPAs operate similarly to virtual PPAs.

PRS have an agreed upon lump sum for a defined period irrespective of the energy quantity or electricity price. This value acts as a benchmark; if the proxy revenue exceeds the benchmark, the project pays the counterparty; if the proxy revenue is short of the benchmark (lower than expected wind speeds or prices), the counterparty pays out to the project [16].

The benefit of PG is that the operational risk is decoupled from the counterparty [11], [7], allowing the party responsible for operations (the wind farm) to handle the risk of operation. Therefore, the wind farm is incentivized to operate at a maximum efficiency due to the structure of the agreement and is flexible as it does not require a fixed volume of power to be generated [11]. PG in the financial settlement also allows for flexibility on the part of the wind farm, as they are no longer responsible for producing a fixed volume of power. The weather risk is the responsibility of the counterparty, which is mitigated with the use of PG-based financial agreements as they are more readily able to absorb these changes in weather [17]. These types of agreements protect both parties compared with previous virtual PPAs and hedge agreements.

Some of the price risks associated with using PG estimates are when wind and price are problematically correlated. As seen in Figure 5, ERCOT South shows a massive uptick in hub price at a low generation level, synonymous with low wind speed. As both the error in PG and price are correlated with wind speed, it is imperative not to just minimize overall error in PG but to understand the underlying trends, specifically at wind speeds of interest.

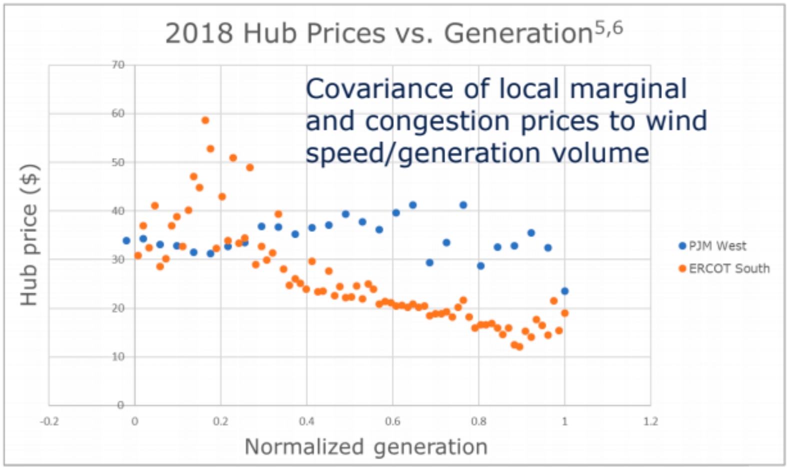


Figure 5: Hub Prices vs. Generation [7]

Figure 5 is an example that occurred during a hot summer day in Texas, when the wind was low and energy demand was high (due to the immense power draw of A/C units). Another striking high price of energy event occurred during the 10-12 February 2021 Texas storm, and the price of energy reached $9,000/MWh. If there is a large discrepancy between proxy and actual generation during these price events, the wind farm is still responsible for paying the settlement. Different methods to calculate proxy generation can therefore have a large impact on the wind farm financial outcome, which will be explored further in Section 6.

CHAPTER 3

SITE OVERVIEW

3.1 Site Overview

The wind plant analyzed for this project is located in north Texas, and the layout is shown in Figure 3-1. Winds are predominantly from the south, with a winter northerly component. Note the 4 met masts represented by triangles:

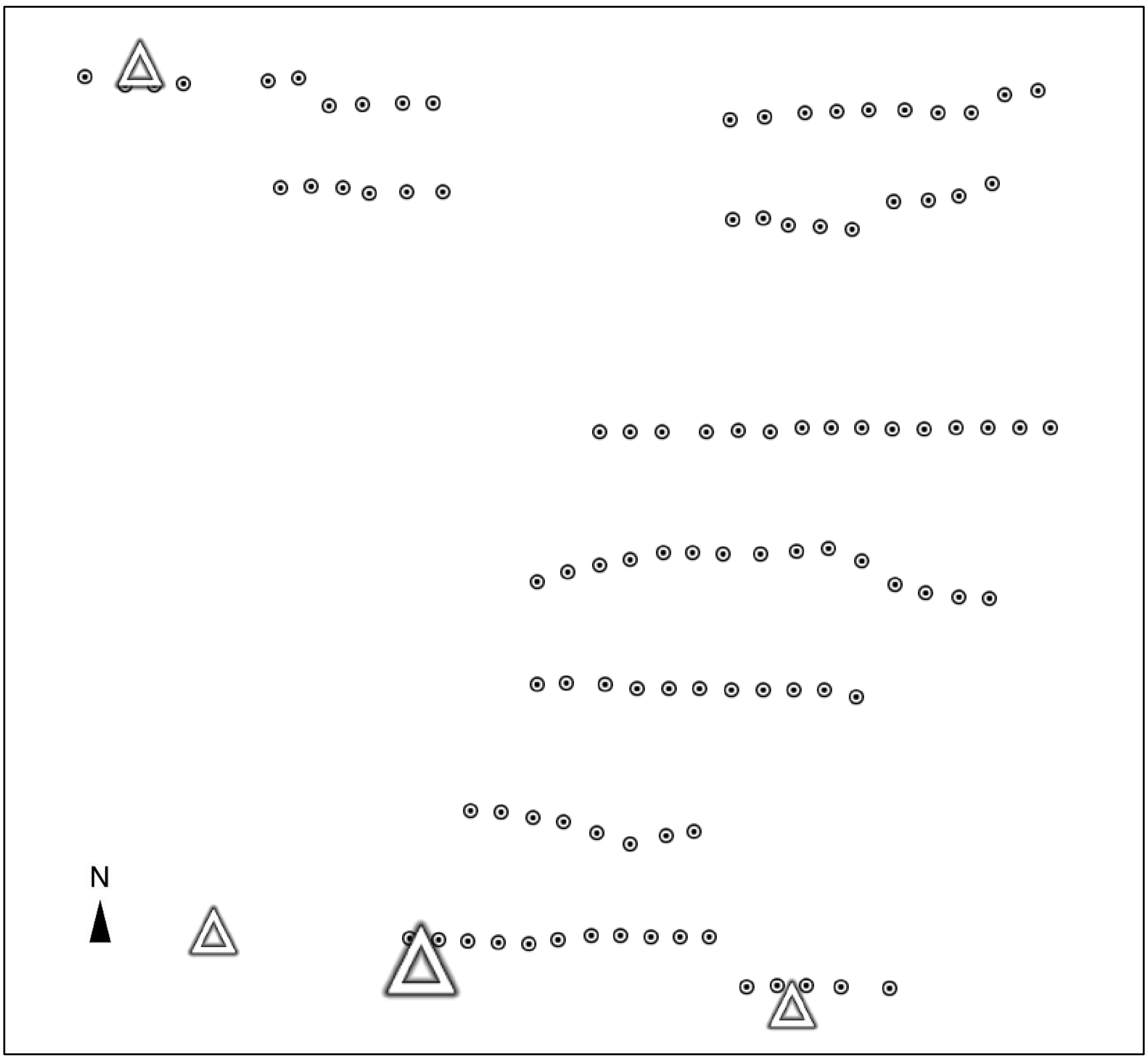


Figure 6: Turbine layout at project

3.2 Dataset

3.2.1 Turbine SCADA data

Turbine SCADA data are provided for all turbines from 12/1/2017-11/30/2018, in 10-minute intervals. This dataset comprises turbine power, nacelle wind speed, rotor position, operating state, temperature, and density corrected nacelle wind speed. Nacelle anemometer wind speeds are not a raw wind speed measurement; instead there is a turbine OEM applied nacelle transfer function that is not site specific. The NTF method allows for an additional, site specific NTF to be applied (discussed further in chapter 4).

3.2.2 Mast data

There were four met masts installed at the site, 3 permanent and one temporary. Masts 9710-9712 comprises data from the SCADA system, and mast 9713 is from the Campbell Scientific data logger in non-SCADA format. Three of them are paired with test turbines, and the fourth one was not used in this analysis.

3.2.3 MERRA-2 Reanalysis data

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) dataset is a long-term global reanalysis project by the Global Modeling and Assimilation Office at NASA. The spatial resolution is about 50 km in the latitudinal direction. Wind condition data are available at 10 m and 50 m heights in 1-hour intervals.

3.2.4 ERCOT Price data

The price dataset for this analysis is from the Electric Reliability Council of Texas (ERCOT) HB_West hub, in 15-minute intervals. The maximum price per MWh during the analysis interval was $1406.43, and the minimum was -$18.40.

3.3 Data Filtering and Analysis

Initial steps with the turbine and mast data involved first filtering the raw data then creating the framework to generate proxy generation values. This was done using Python.

The steps for data filtering are as follows:

1.) Merge turbine and mast data via timestamp according to pairings in Table 2

2.) Calculate air density for each 10 min record in the data period. A single density dataset for the project was used based on the data averaged between Masts 9710 and 9711, due to the flat topography for the region. The equation for calculating air density is as follows (from IEC 61400-12-2 9.1.1 Eq 4):

$$\rho_{10min} = \frac{1}{T_{10min}}\left(\frac{B_{10min}}{R_0} - \phi P_w\left(\frac{1}{R_0} - \frac{1}{R_w}\right)\right) \quad (4)$$

where

ρ_{10min}	is the derived 10 min averaged air density;
T_{10min}	is the measured absolute air temperature averaged over 10 min;
B_{10min}	is the measured air pressure averaged over 10 min;
R_0	is the gas constant of dry air 287,05 J/(kgK);
ϕ	is the relative humidity (range 0 to 1);
R_w	is the gas constant of water vapour [461,5 J/kgK];
P_w	is the vapour pressure [P_a].

P_w = 0,0000205 exp(0,0613846T), where vapour pressure P_w depends on mean air temperature T[K].

3.) Determine turbulence class for power curve (medium). See Appendix for specifics.

4.) Convert ERCOT pricing database from 15 min to 10 min intervals. See Table 1 for details.

Table 1: ERCOT price database conversion intervals

Turbine SCADA Minutes	ERCOT Price Delivery Interval
0	1
10	Average 1 and 2
20	2
30	3
40	Average 3 and 4
50	4

CHAPTER 4

NACELLE TRANSFER FUNCTION (NTF) METHOD

4.1 Model Development

The NTF method uses onsite measurements from met masts and turbine nacelle mounted anemometers to calculate power production for each individual turbine, which is then summed for the site wide value of proxy generation. This site specific NTF provides an additional correction to the nacelle wind speed that aims to capture the terrain effects on the wind speed measurement. These NTFs are generated from data comprised of met mast – turbine pairs using Python scripts. Table 2 below illustrates the turbine/mast coupling:

Table 2: Mast/Turbine Coupling

Mast Name	Test Turbines
9710	1,2
9711	5,6
9712	N/A
9713	3,4

The steps to generate proxy generation and proxy revenue values via the NTF method are as follows:

1. Calculate Nacelle Transfer Functions (NTF) for valid data. The NTF in this case is a reference table that provides the relationship between front-of-rotor, or “free stream” wind speed and nacelle anemometer wind speed (NWS), with the met mast acting as free stream. A period of data was selected where both valid met mast and NWS were available, and processed following guidelines set by the IEC Standard 61400-12-2. This included only using data from

unobstructed direction sectors, with specific constraints found in Appendix E. The binned ratio method was implemented in which the data was grouped into 0.5 m/s bins and the ratio between met mast and NWS were calculated for each bin [18]. An NTF was created using the data from each mast/turbine pair. These provide a conversion ratio to take the measured nacelle wind speed at the particular test turbine and convert it to the free stream wind speed at the corresponding met mast. Mast/turbine pairs are listed in Table 2. In addition to the six mast/turbine pair NTFs, there is a site-wide NTF using the data from all mast turbine pairs averaged together for a total of seven NTFs. These are used to calculate seven different PG results that will be compared in section 4.3.

Table 3 shows an example NTF with the full NTFs found in Appendix . Wind speed bin 2.5 contains the average wind speed across all wind speeds between 2.25 – 2.75. Met Mast is the average wind speed measured at the met mast, and NWS is the average wind speed measured at the nacelle.

Table 3: NTF for Turbine 1

Wind Speed Bin (m/s)	Met Mast (m/s)	NWS (m/s)
2.5	2.734	2.511
3	3.113	3.022
3.5	3.469	3.503
4	3.998	3.998
4.5	4.225	4.492
5	4.725	5.000

2. Apply NTF to all valid nacelle wind speeds from each turbine at the site to determine free stream wind speed using linear interpolation. The equation used is as follows (from IEC 61400-12-2 D.4 Eq D.1 [19]):

$$V_{\text{free}} = \frac{V_{\text{free},i+1} - V_{\text{free},i}}{V_{\text{nacelle},i+1} - V_{\text{nacelle},i}} \times \left(V_{\text{nacelle}} - V_{\text{nacelle},i}\right) + V_{\text{free},i} \qquad \text{(D.1)}$$

where

$V_{\text{nacelle},i}$ and $V_{\text{nacelle},i+1}$	are bin averages of the nacelle wind speed in bin *i* and *i+1;*
$v_{\text{free},i}$ and $v_{\text{free},i+1}$	are bin averages of the met-mast wind speed in bin *i* and *i+1*, flow correction factors shall be applied from the site calibration measurement, if appropriate;
V_{nacelle}	is the measured value of the nacelle anemometer for which we want to estimate the free stream wind speed;
v_{free}	is the free stream wind speed estimated using the measured nacelle and met mast wind speed, corrected for flow distortion due to terrain (V_{nacelle} *and* v_{free}, respectively).

3. Normalize the free stream wind speed to the reference air density of the contract power curve. The equation used is as follows (from IEC 61400-12-2 9.1.1 Eq 6):

$$V_n = V_{\text{free}} \left(\frac{\rho_{10\text{min}}}{\rho_0} \right)^{1/3} \qquad (6)$$

where

V_n	is the normalised wind speed;
V_{free}	is the measured nacelle wind speed, corrected with the NTF, as detailed in Annex D.

4. Apply the power curve to normalized free stream wind speed to determine proxy generation with linear interpolation. We will now have a proxy

generation value for each turbine. See Appendix A for more power curve details.

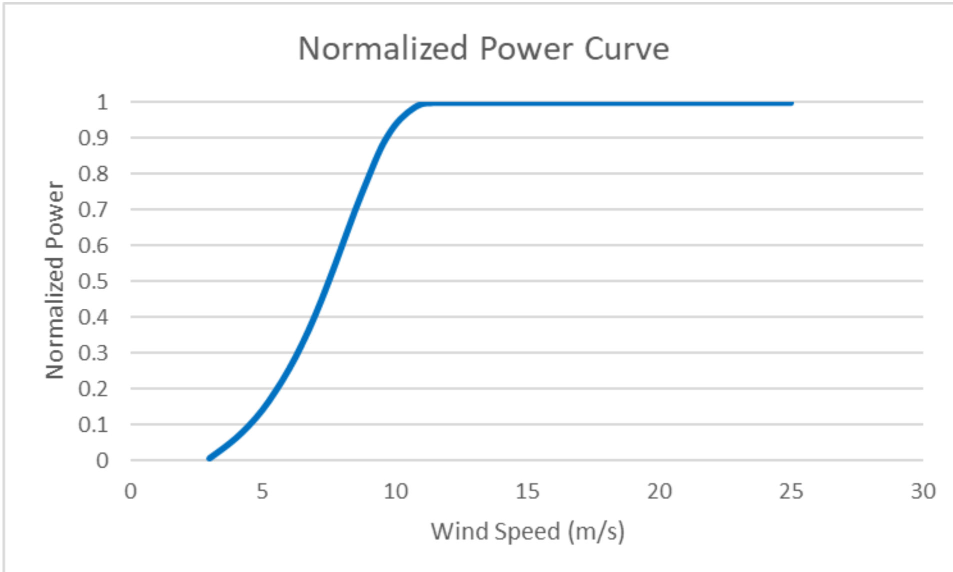


Figure 7: Manufacturer power curve

5. Sum turbine production at each time stamp to get site wide proxy generation

6. Calculate proxy revenue from proxy generation using price data:

$$Proxy\ Revenue = Generation\ (Mwh) * Price\ (\frac{\$}{Mwh})$$

7. Repeat steps 2-6 with the remaining NTFs. There will be seven sets of PG results total, one with each NTF.

8. In order to examine the impact of the site-specific correction, steps 3-6 are completed with the nacelle wind speed in place of the corrected free stream.

4.2 NTF Method Validation

The NTFs generated were then compared with previous analysis. The values appear to match overall, showing that the methods used here work properly and the NTF model is ready to be used for further analysis.

4.3 Error in NTF model

The NTF model relies on onsite measurements, which are expensive and need maintenance and calibration. It is difficult to quantify how many mast/turbine pairs are necessarily to accurately capture the front-of-rotor “free stream” to nacelle anemometer wind speed relationship. By comparing proxy generation results from all mast/turbine pairs, it was possible to examine the potential range of results if different configurations were implemented. An additional nacelle wind speed (NWS) proxy generation result was calculated, which used the nacelle anemometer wind speeds without an additional NTF ratio applied. The impact of onsite measurements and site specific NTFs was able to be analyzed. Figure 8 shows results from six different test turbine NTFs as well as a comparison with NWS and site-wide NTF. The red dashed line has a slope of 1.

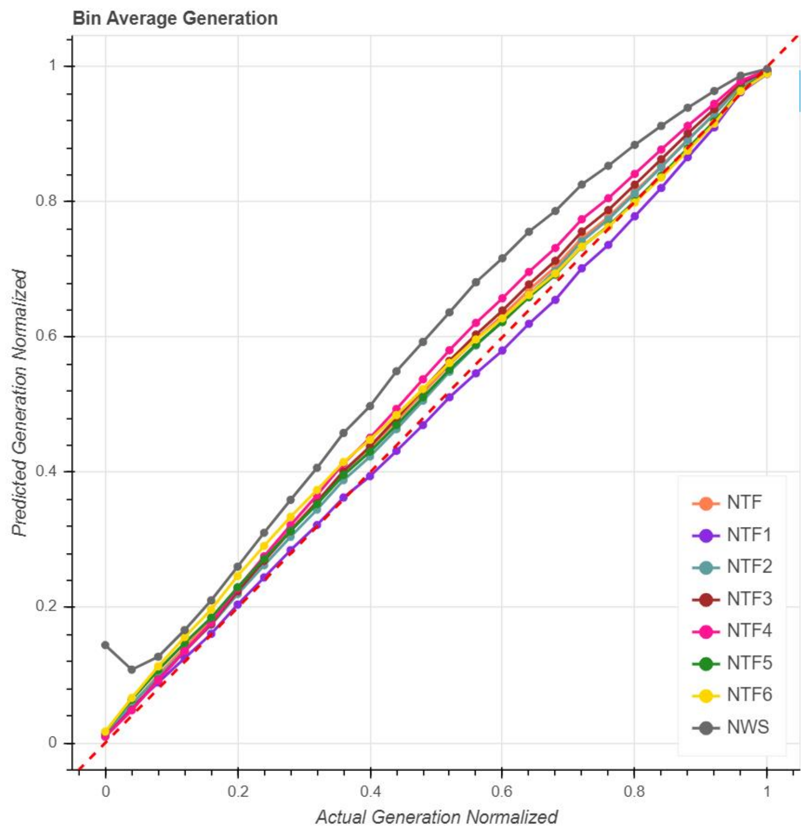


Figure 8: Bin Average Generation for all NTFs

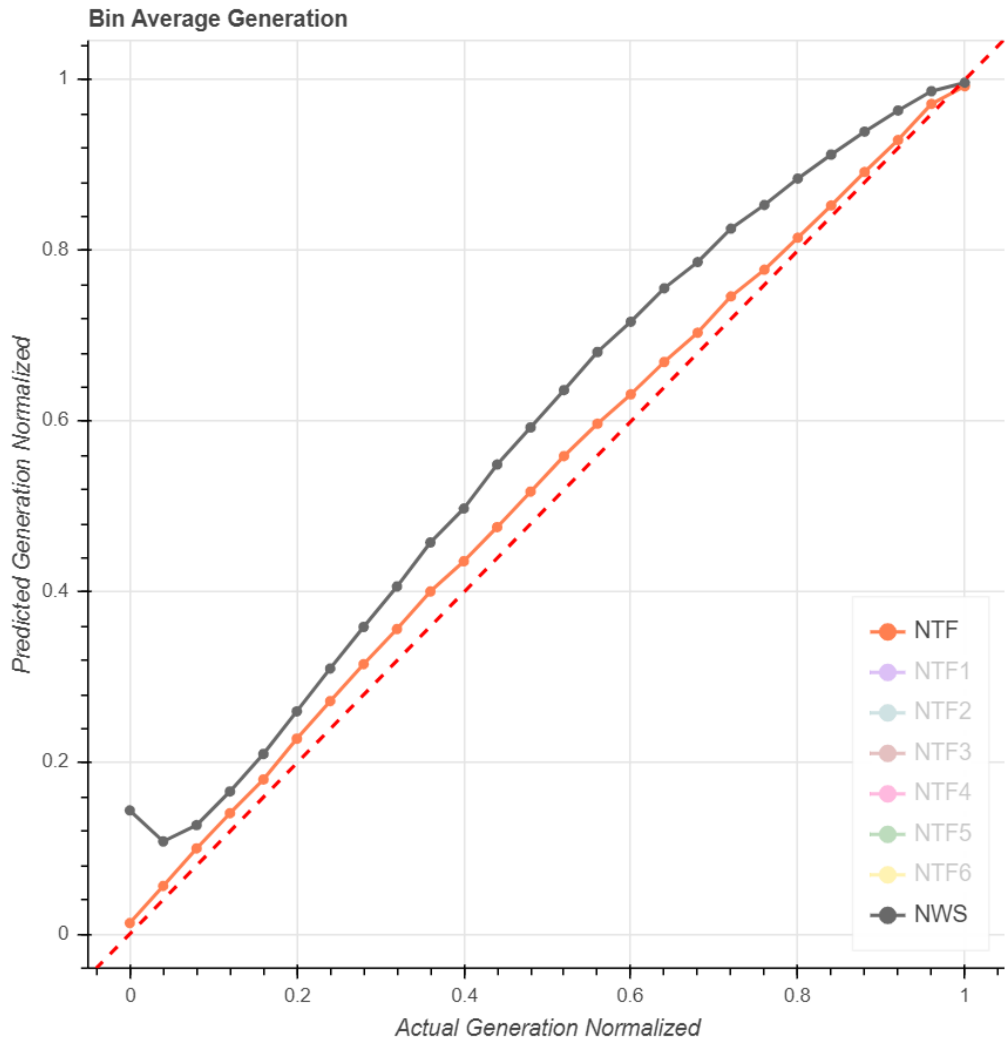


Figure 9: Bin Average Generation for site wide NTF and NWS

Figure 9, above, shows the difference in bin average generation of the site wide NTF and the NWS results. The NWS results overpredict generation much more than the site wide NTF, and this is reflected in the annualized proxy generation calculations shown in Table 4. This figure clearly demonstrates the impact of the site specific NTF.

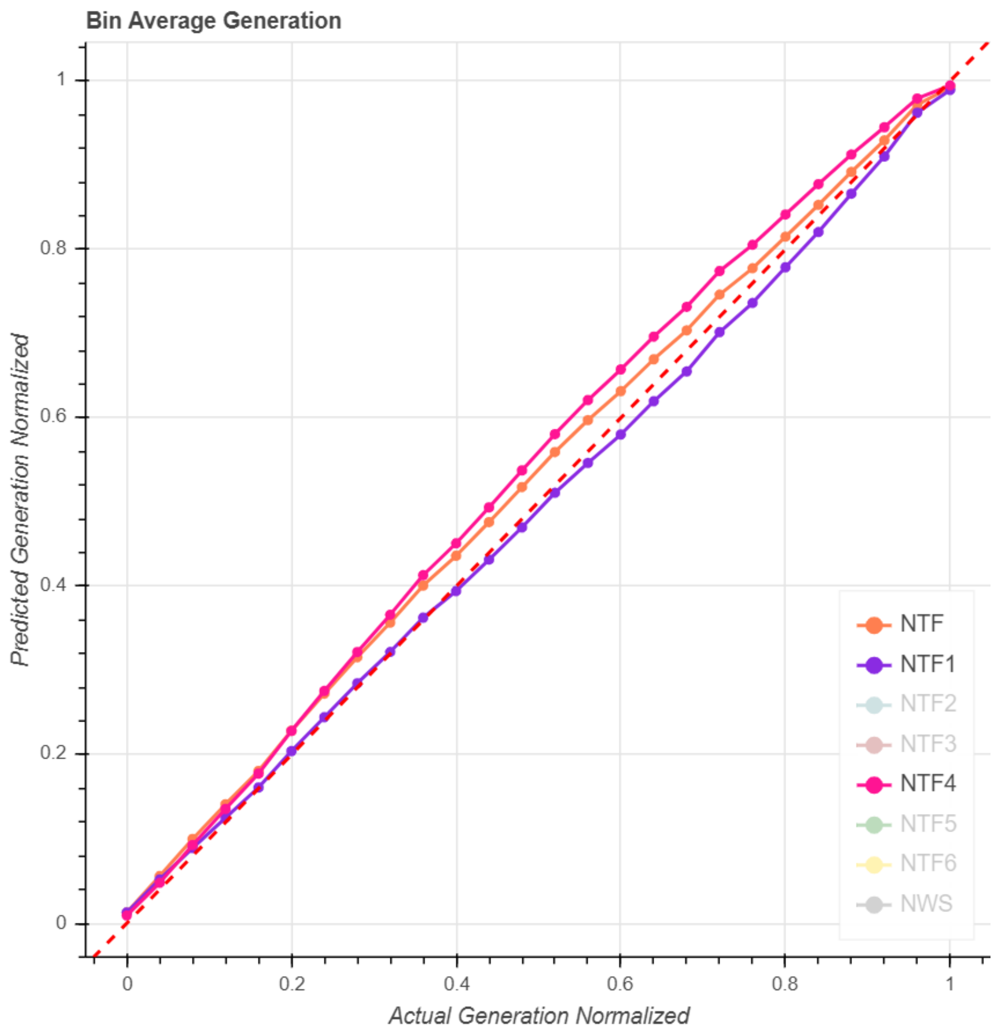


Figure 10: Bin Average Generation NTF method range

Figure 10 shows the site wide NTF results in addition to the largest and smallest NTF mast-turbine pair generation estimates. This demonstrates the "operating envelope" of the different mast-turbine pairs, as well as the range of potential results for situations in which there are fewer mast-turbines pairs at the site. Due to the variability in terrain, different mast/turbine pairs will result in different NTF ratios which ultimately impact the financial outcome of the wind project.

Figure 11 and Figure 12, below, show the mast-turbine pair results for same mast, different turbine sets. Figure 11 shows the largest range between this type of pair, demonstrating that terrain effects and other turbine differences may have an impact on NTF creation, even with the same met tower.

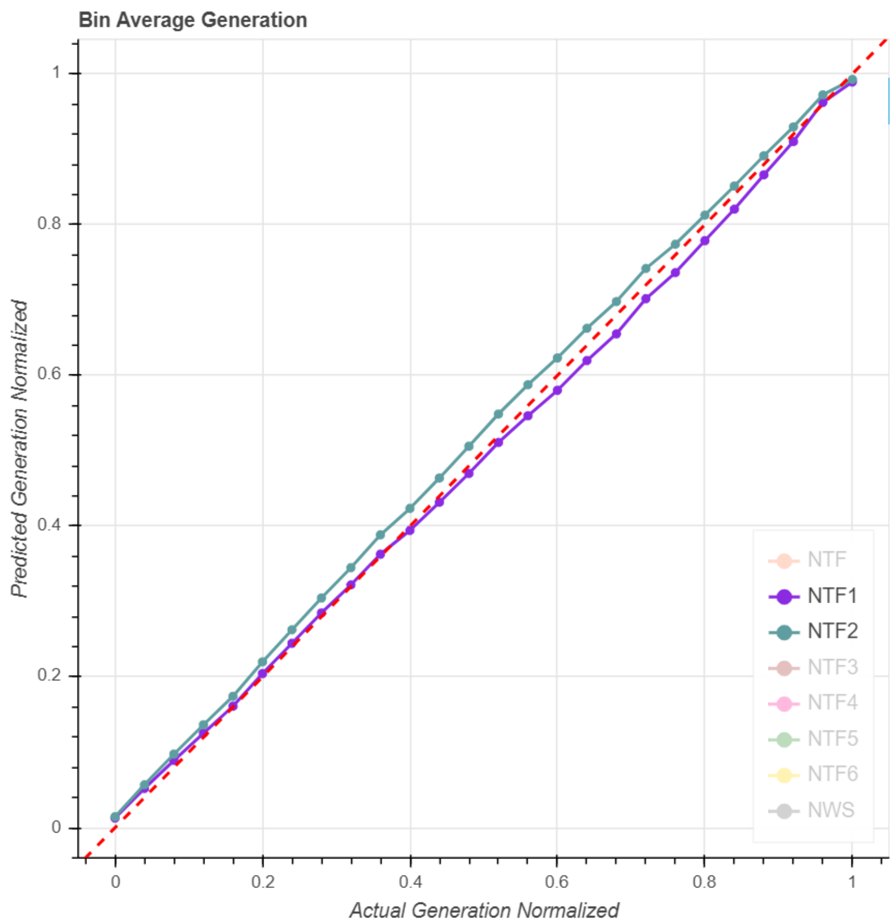


Figure 11: Bin Average Generation mast/turbine pair comparison 1

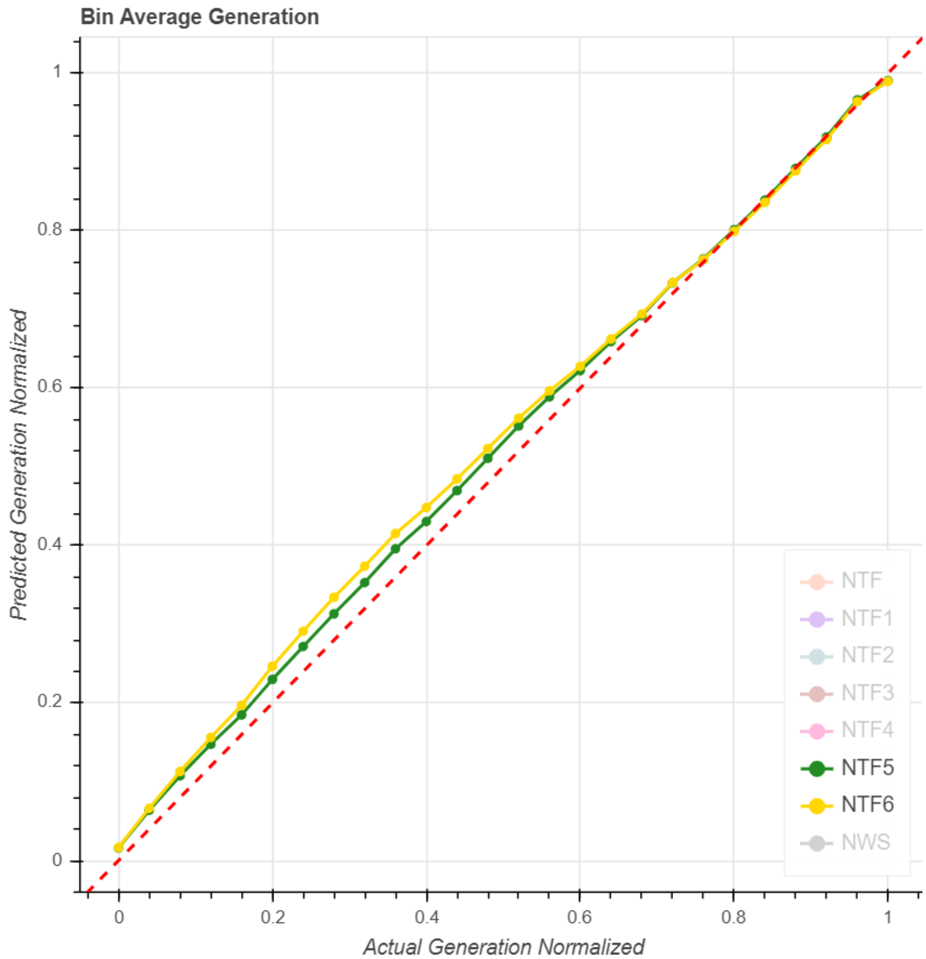


Figure 12: Bin Average Generation mast/turbine pair comparison 2

Table 4 and Table 5 show the proxy generation and proxy revenue results for the NTF method. The NTF comparison for proxy generation has a range of errors from a 3% underestimate to a 10% underestimate, with the site wide average being roughly in the middle. The proxy revenue results have a range from a 9% underestimate to a 1% underestimate.

The NWS model overestimates significantly for both generation at 2% and revenue at 7%, compared to the results with a site specific NTF. This result demonstrates the effect of the site specific NTF on the accuracy of the production estimate. Terrain effects that impact the wind speed are not as well captured by the nacelle anemometer and turbine OEM applied NTF.

Table 4: NTF Proxy Generation

	NTF	NTF1	NTF2	NTF3	NTF4	NTF5	NTF6	NWS
Proxy - Actual Generation % Loss corrected[1], Annualized	-5%	-10%	-6%	-5%	-3%	-6%	-5%	2%
Proxy - Actual Generation Loss corrected[1], Annualized MWh	-51,745	-98,744	-60,135	-48,795	-34,058	-58,230	-47,347	23,892

[1]Where losses were assumed to be 9%

Table 5: NTF Proxy Revenue

	NTF	NTF1	NTF2	NTF3	NTF4	NTF5	NTF6	NWS
Proxy - Actual Revenue % Loss corrected[1], Annualized	-3%	-9%	-4%	-3%	-1%	-3%	-1%	7%
Proxy - Actual Revenue Loss corrected[1], Annualized $	$ -490k	$ -1,560k	$ -700k	$ -520k	$ -220k	$ -540k	$ -210k	$ 1,220k

[1]Where losses were assumed to be 9%

Figure 13 below compares the distance between the test turbine/met mast with the error in PG and Proxy Revenue (PR), with the intention of examining terrain effects and distance of met masts on the accuracy of the PG estimate. As the terrain at the site is composed of relatively flat farm land, it seemed plausible that distance to the met mast would have a larger effect on the differences in the PG results. However, these results do not show a strong causal relationship between the two.

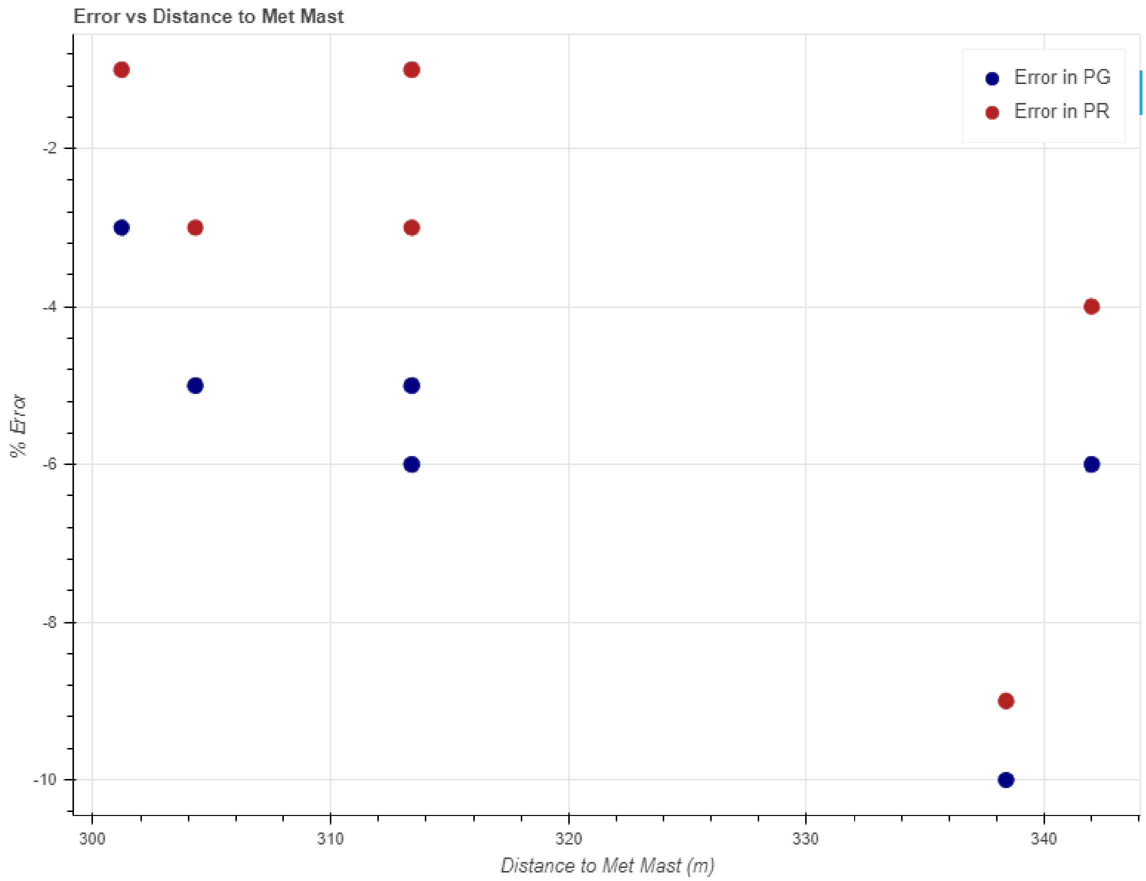


Figure 13: Distance to Met Mast vs Error

CHAPTER 5

REANALYSIS DATA METHOD

5.1 Model Development

The Reanalysis Data method uses a single wind speed and direction pair calculated from the MERRA-2 database to predict site-wide power production. In the event of turbine SCADA or other site measurements being unavailable, the financial arrangement may be settled using the Reanalysis Data method to calculate proxy generation.

Using measured turbine and mast data, a power matrix is created, which is a lookup table of wind speed and wind direction that yields site wide power. Wind speed and direction binning for the power matrix were established through the met masts to account for blockage and array effects.

Table 6: Power Matrix Valid Sector Designations

Met Mast	Valid Sector (°)
Mast 9711	90°-240°
Mast 9710	303°-89°
Mast 9712	241°-304°

The steps to create the power matrix are below:

1.) Power from each individual turbine was summed at each timestamp at which availability was greater than 90% to get site-wide power, and the corresponding met mast wind speed and direction were used.

2.) The power was averaged over wind speed and wind direction to create the power matrix. Manual edits were as follows:

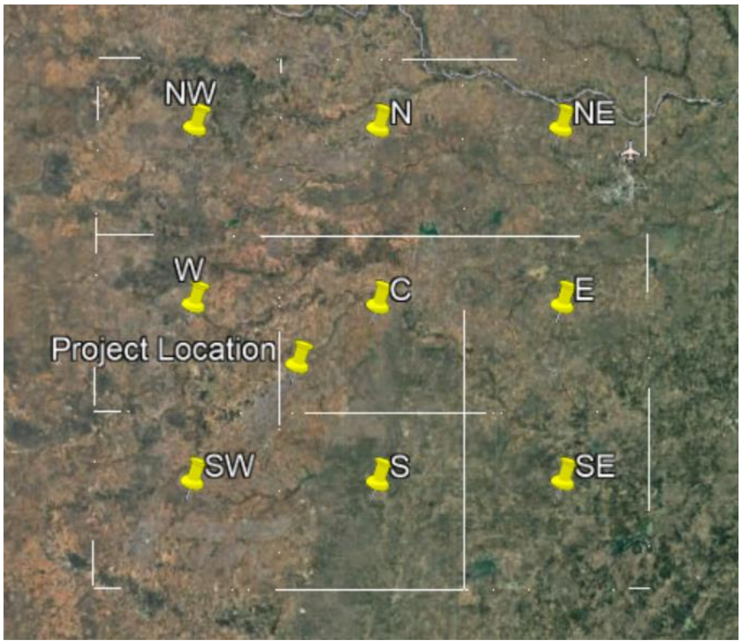
   a. At wind speeds below cut in, power was assumed to be zero based off the warranty power curve.

b. Unfilled bins at wind speeds above rated power up to cut out wind speed were filled with the average site-wide rated power.

The power matrix can be found in Appendix D.

The steps to generate proxy generation and proxy revenue values via the Reanalysis Data method using Python scripts are as follows:

1.) MERRA-2 data for the nine nearest grid points to the wind farm was downloaded from the database. The four nearest to the project were used for this analysis, labeled below as: W, C, SW, S.



2.) MERRA-10 m and MERRA-50 m wind speed values are used with a wind shear extrapolation model to estimate hub height wind speed. The equation used is as follows:

$$W_{HH,i} = W_{50,i}\left(\frac{HH}{50}\right)^{\ln\left(W_{50,i}/W_{10,i}\right)/\ln(50/10)}$$

Where:

$W_{HH,i}$	=	wind speed at Turbine Average Hub Height, during hour i
$W_{50,i}$	=	MERRA-2 grid point wind speed at 50 meters, during hour i
$W_{10,i}$	=	MERRA-2 grid point wind speed at 10 meters, during hour i
HH	=	Turbine Average Hub Height, in meters
ln	=	natural logarithm function

3.) The four geographic neighboring MERRA-2 hub height wind speed points are used to get Estimated Project Wind Speed (EPWS). The equation used is as follows:

$$W_{Proj,i} = \frac{\frac{W_{NW,i}}{r_{NW}^2} + \frac{W_{SW,i}}{r_{SW}^2} + \frac{W_{NE,i}}{r_{NE}^2} + \frac{W_{SE,i}}{r_{SE}^2}}{\frac{1}{r_{NW}^2} + \frac{1}{r_{SW}^2} + \frac{1}{r_{NE}^2} + \frac{1}{r_{SE}^2}}$$

Where:

$W_{Proj,,i}$	=	wind speed at Turbine Average Hub Height for the Project during hour i
$W_{[NW,SW,NE,SE],i}$	=	wind speed at Turbine Average Hub Height for each of the four (4) geographic neighboring MERRA-2 grid points during hour i
$r_{[NW,SW,NE,SE]}$	=	distance from the four (4) geographic neighboring MERRA grid points to the Geographic Center of the Project

4.) The EPWS is normalized to the site air density with the following equation (from IEC 12-2 9.1.1 Eq 6):

$$V_n = V_{free}\left(\frac{\rho_{10min}}{\rho_0}\right)^{1/3} \qquad (6)$$

where

V_n is the normalised wind speed;

V_{free} is the measured nacelle wind speed, corrected with the NTF, as detailed in Annex D.

5.) The normalized EPWS is then corrected with the wind speed data collected at the met mast in the valid sector:

$$Corrected\ Normalized\ EPWS = CNEPWS\ Scale\ Factor \times Normalized\ EPWS^{\ CNEPWS\ Exponent}$$

The CNEPWS Scale Factor and CNEPWS Exponent were calculated by an exponential fit of MERRA and each onsite met mast wind speed. The scale factor and exponents from each of these were averaged. Table 7 below shows the scale factor and exponent result.

Table 7: CNEPWS Scale Factor and Exponent

	Scale Factor	Exponent
Met 9710	1.5892	0.7841
Met 9711	1.6271	0.7507
Met 9713	1.366	0.8264
Average	1.52733	0.787067

6.) The 50 m project wind direction was calculated as a weighted average of the wind vector for each of the MERRA-2 grid points, with each wind vector weighted by the inverse-square distance from the corresponding MERRA-2 grid points to the geographic center of the project site.

7.) The power matrix is applied to the MERRA corrected hub height wind speed and MERRA-50 m project wind direction. At each timestamp, the wind direction was chosen nearest to the value in the power matrix and the wind speed via linear interpolation.

5.2 Error in reanalysis (MERRA-2) model

To examine the error in the MERRA-2 method, there were three components to analyze:

1. Direct parameter comparison of MERRA-2 vs onsite measurements.

2. Proxy Generation comparison to examine errors in power matrix and results after transformation through turbines.
3. Proxy Revenue comparison to examine financial impacts of power matrix method and potential amplification of PG error.

Beginning with the direct parameter comparison of MERRA-2 vs. onsite measurements, Figure 14 below is a scatter plot of MERRA-2 vs wind speeds measured at Met9711. It is clear that MERRA-2 estimates already have large discrepancies from actual wind speeds at the site, with significant spread in the values despite being site corrected (step 5 in Section 5.1). Chapter 6 discusses the proxy generation and proxy revenue comparisons.

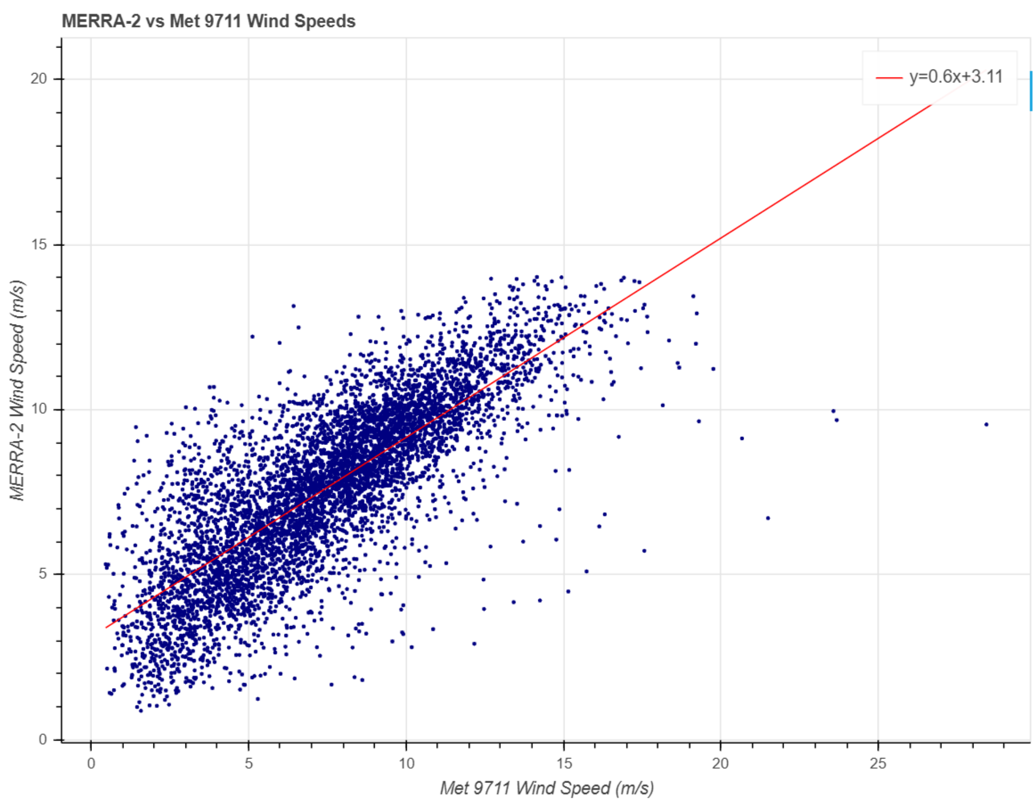


Figure 14: MERRA-2 vs Met 9711 Wind Speeds

CHAPTER 6

MODEL COMPARISONS

6.1 Proxy Generation and Revenue comparisons

Both the NTF method and the MERRA-2 method results were gathered from timeseries data over the course of eight months, from January 2018 to September 2018. By comparing results from the same time frame, it is possible to examine the financial impacts of each power production estimate during this time.

Figure 15 below shows the comparison of MERRA-2 and the NTF method with actual generation. It is immediately clear that the NTF method is much closer to actual generation. The spread of error in the NTF method is much less, and single event risk is overall less. The most important events are large discrepancies between proxy and actual generation, specifically if they coincide with a large price excursion. This appears much more likely with MERRA than NTF.

Figure 16 shows the comparison of MERRA-2 and the NTF method with actual revenue. The MERRA results show significantly more spread in error, especially at higher revenues.

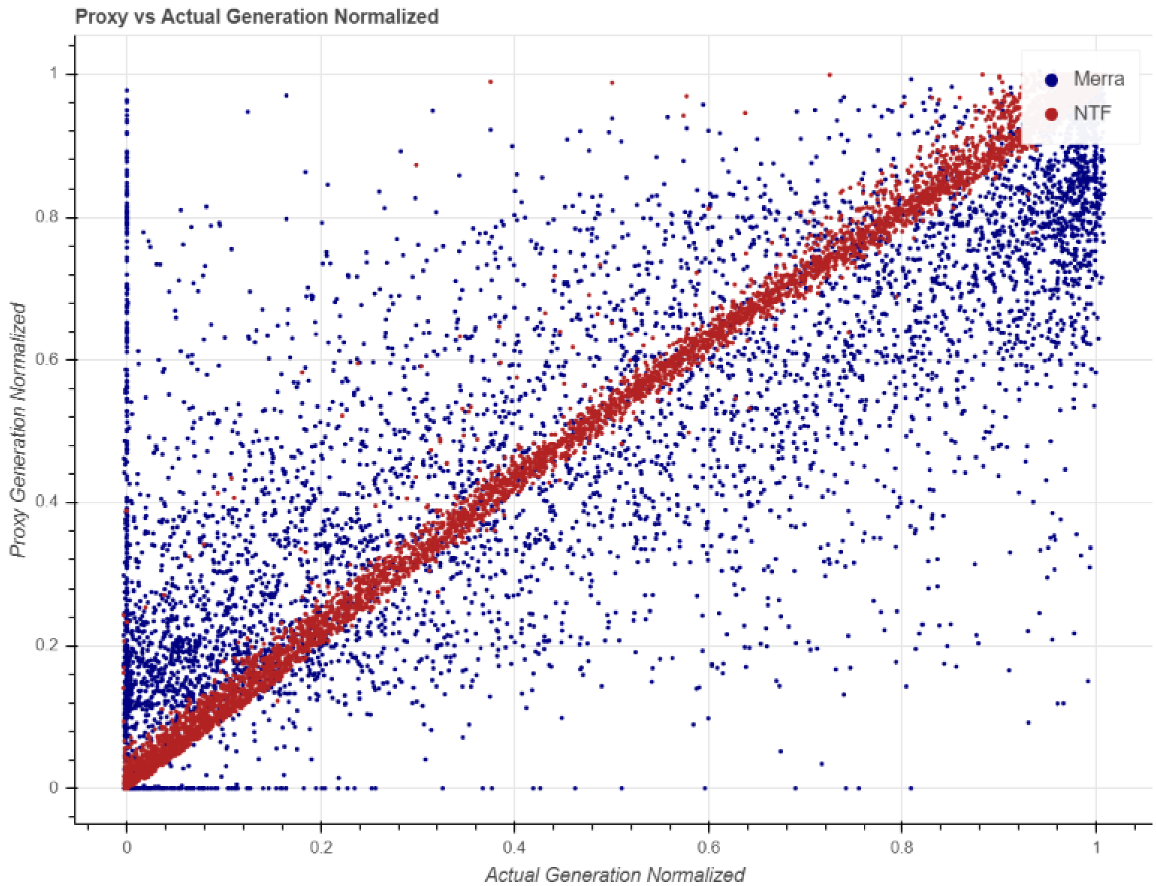


Figure 15: Proxy vs Actual Generation Scatter

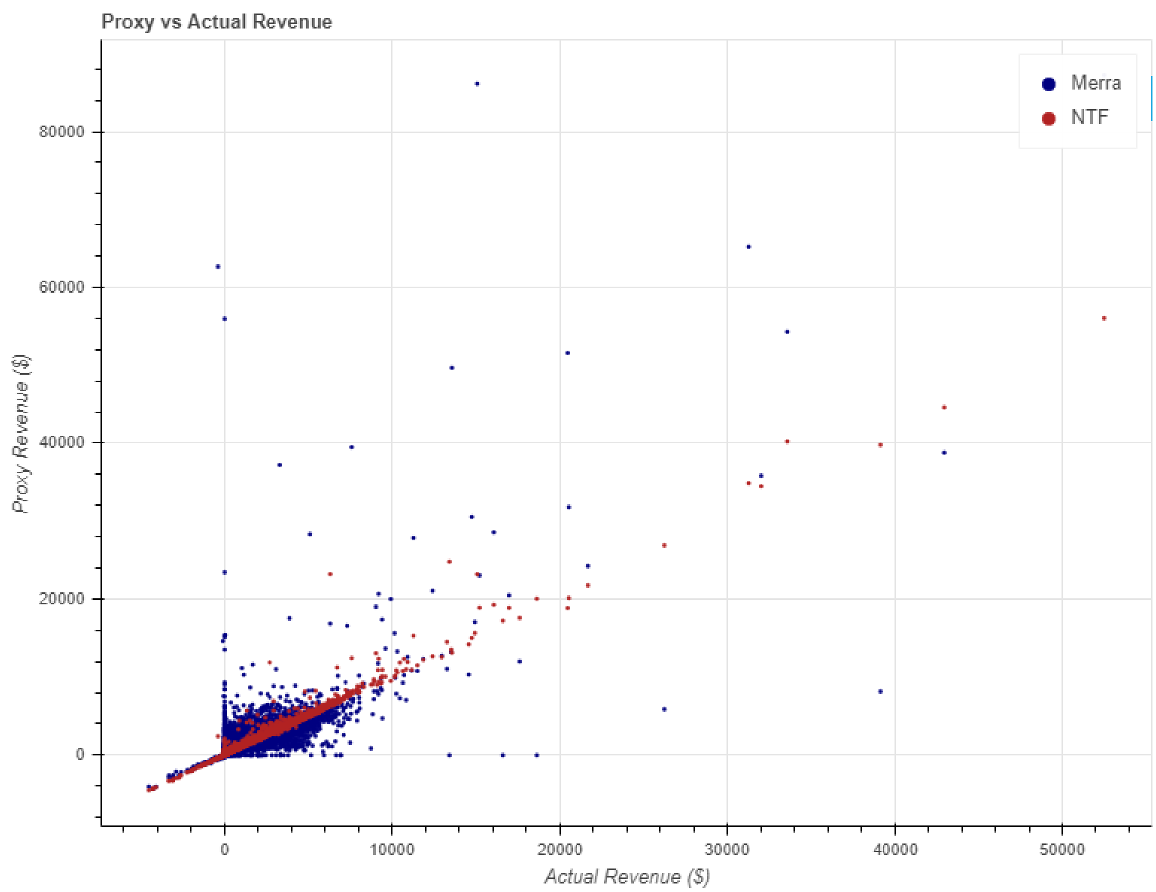


Figure 16: Proxy vs Actual Revenue Scatter

Figure 17 below shows error in generation and revenue as a timeseries. Error in generation here displays the same trends as Figure 15. The spread in error for MERRA is much larger than that of the NTF method. The revenue timeseries tends to magnify events when the error is large and the price of electricity is high.

During the period we investigated, two particular periods stood out. 8 – 10 March 2018 and 19-26 July 2018 the error in MERRA-2 is consistently large and error in the NTF method is approximately zero. Further investigation found that during these times, none of the turbines at the site were in normal operating states, and it is likely that the turbines were shut down for maintenance. Removal of these periods from the dataset had little impact on the final results, so they were kept.

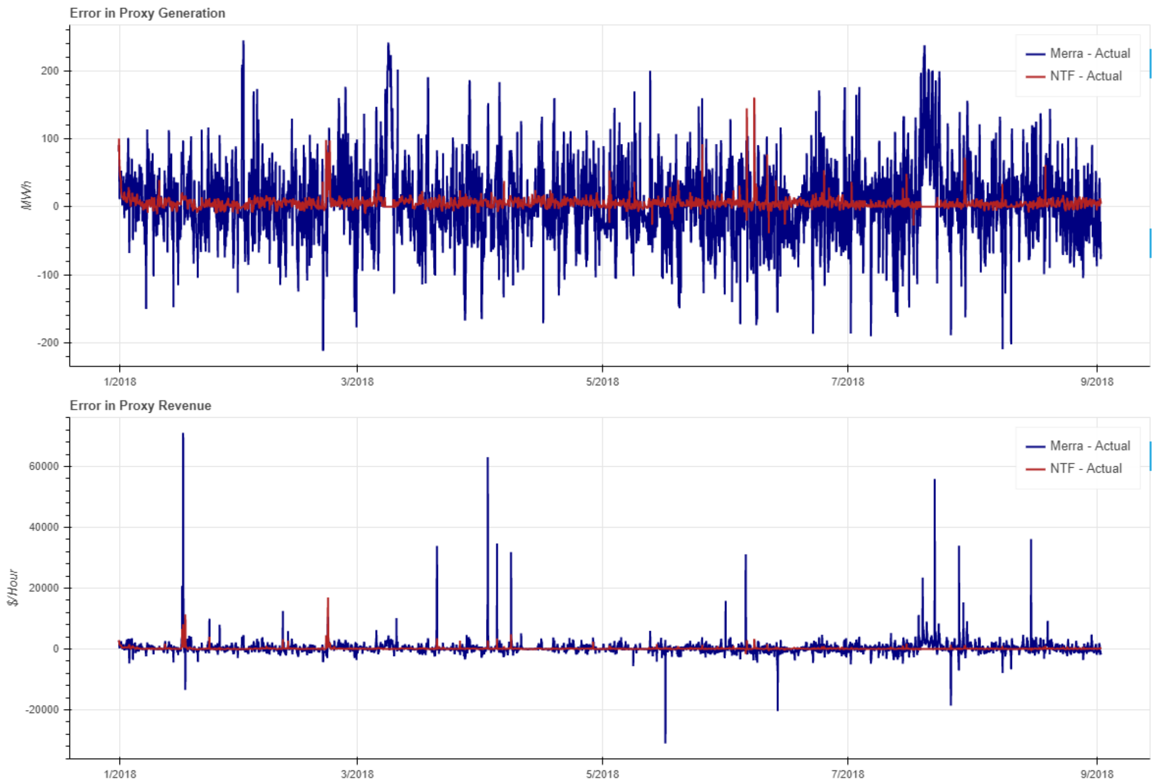


Figure 17: Proxy – Actual Generation and Revenue Timeseries

These two histograms in Figure 18**Error! Reference source not found.** show again the difference in the spread of error for the two methods, with the range in MERRA-2 error much larger than that of the NTF method.

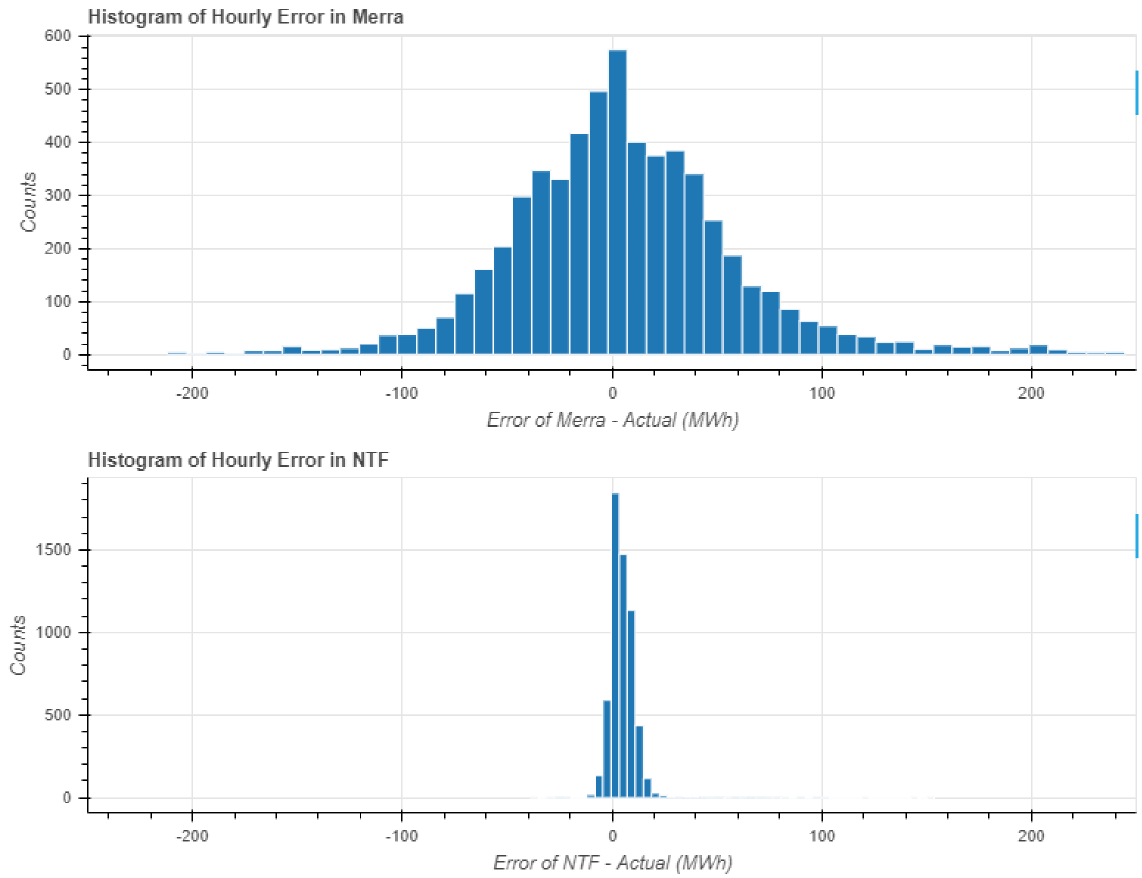


Figure 18: Error in PG Histogram

Table 8 below provides summary statistics. The NTF method here has not yet accounted for the operational efficiency losses, so the mean error of 5.15 MWh is not yet representative, and the true value is slightly lower. Although the MERRA-2 mean error is only slightly higher than that of the NTF method, it is clear from both the histograms and corresponding standard deviations that the NTF method has significantly less error.

Table 8: Summary Statics for Error in PG

	MERRA-2 Error	NTF Error
Mean (MWh)	5.69	5.15
Standard Dev. (MWh)	54.85	7.96
90th Percentile (MWh)	69.37	11.52

Table 9: Summary Statics for Error in PR

	MERRA-2 Error	NTF Error
Mean ($)	$ 341.09	$ 134.67
Standard Dev. ($)	$ 2,441.13	$ 422.93
90th Percentile ($)	$ 1,787.42	$ 259.83
Min ($)	$ (31,002.96)	$ (1,631.46)
Max ($)	$ 71,034.53	$16,934.84

Table 10 below shows the annualized generation and revenue of the two methods compared to the actual values. The MERRA method has a mean error of only 5% in the proxy generation, but the proxy revenue shows that the error in proxy generation was ill-timed with price of energy, since the method overpredicts the project revenue by 7%. In contrast, the NTF method prediction decreases from generation to revenue, and the method underpredicts the project revenue by only 3%.

Table 10: PG and Actual Generation and Revenue Comparison

	MERRA-2	Actual	NTF
% Error	-5%	N/A	-5%
Annualized, Loss corrected[1] MWh	983,785	1,031,196	979,452
Total MWh	723,437	690,054	720,250
% Error	7%	N/A	-3%
Annualized, Loss corrected[1] $	$18,561,262.37	$17,409,032.59	$16,915,721.85
Total $	$13,649,219.73	$11,649,743.04	$12,439,154.18

From the annualized results, the percent error in PG for MERRA appears within the same range as those given by the NTF method. However, smaller time scales must be investigated for the impacts of a price excursion, which is discussed further in the following section.

6.2 Time duration analysis

The error in these methods is likely to have more impact if their duration is significant. If the model overpredicts, and then underpredicts, but evens out to zero error over the course of one hour, it does not have an impact on the settlement calculation. If the model takes multiple hours or days to “even out” the error, a price excursion event could occur and impact the results. Therefore, we examined the timescale on which the error was likely to even out.

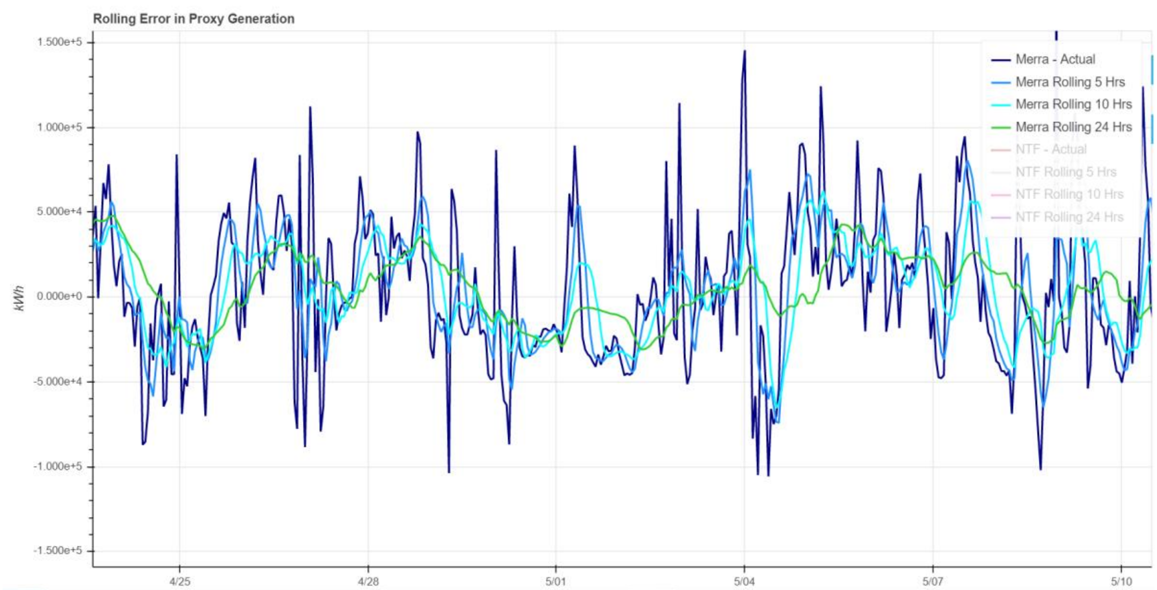


Figure 19: MERRA-2 Rolling Avg Error Generation

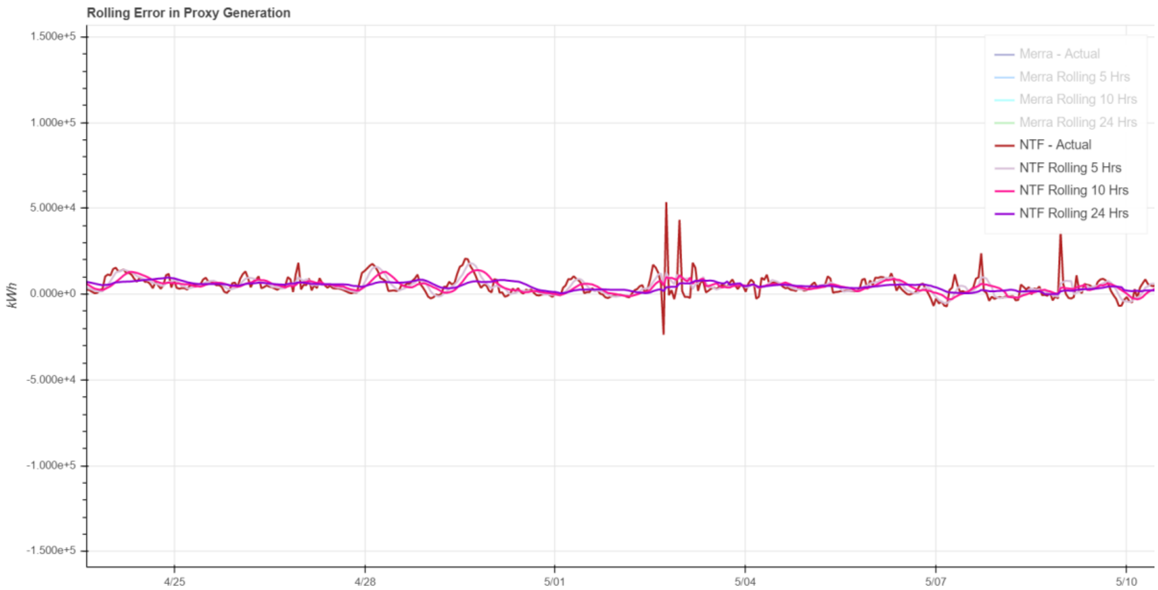


Figure 20: NTF Rolling Average Error Generation

Figure 21: NTF vs MERRA Rolling Average Error in Generation

Figure 19 and Figure 20 above show the MERRA-2 and NTF error in generation, on a 1, 5, 10, and 24 hour rolling average. Rolling error evens out the NTF method significantly. MERRA-2 still has a large magnitude of error even on the 24 hour rolling average.

Figure 21 shows the MERRA-2 rolling average 24 hours compared to NTF hourly and rolling average 24 hours. The difference in magnitude of error of the two methods is significant. If, for example, the large green spike that occurs in the MERRA-2 result at 01 February were to have occurred during 10-12 February 2021 in Texas when the price of energy was $9000 MWh, a wind farm using the reanalysis method for their settlement would have to pay a much larger settlement than one using the NTF method. This type of price excursion corresponding with large error in energy estimates is the ultimate focus of this work. It is clear that the NTF method provides less price risk in proxy generation calculations than the MERRA-2 reanalysis method.

Further analysis in the MERRA-2 method to characterize the error can be seen below in Figure 22 and Figure 23, which show the rolling average error in wind speed and proxy generation. The error in MERRA-2 wind speed compared to onsite measurements is much worse on an hourly time scale (see section 5.2) but when examining the rolling average error up to 24 hours it improves significantly. This is unsurprising, as MERRA-2 is known to be less accurate at finer temporal scales. However, when examining the rolling average error for MERRA-2 proxy generation, the same trends are not present. Figure 23 shows the rolling error in PG at various longer time scales up to one month, and the range and distribution of error in MERRA-2 results is still worse than that of the NTF method. This indicates that the power matrix is a large source of error for the reanalysis data method.

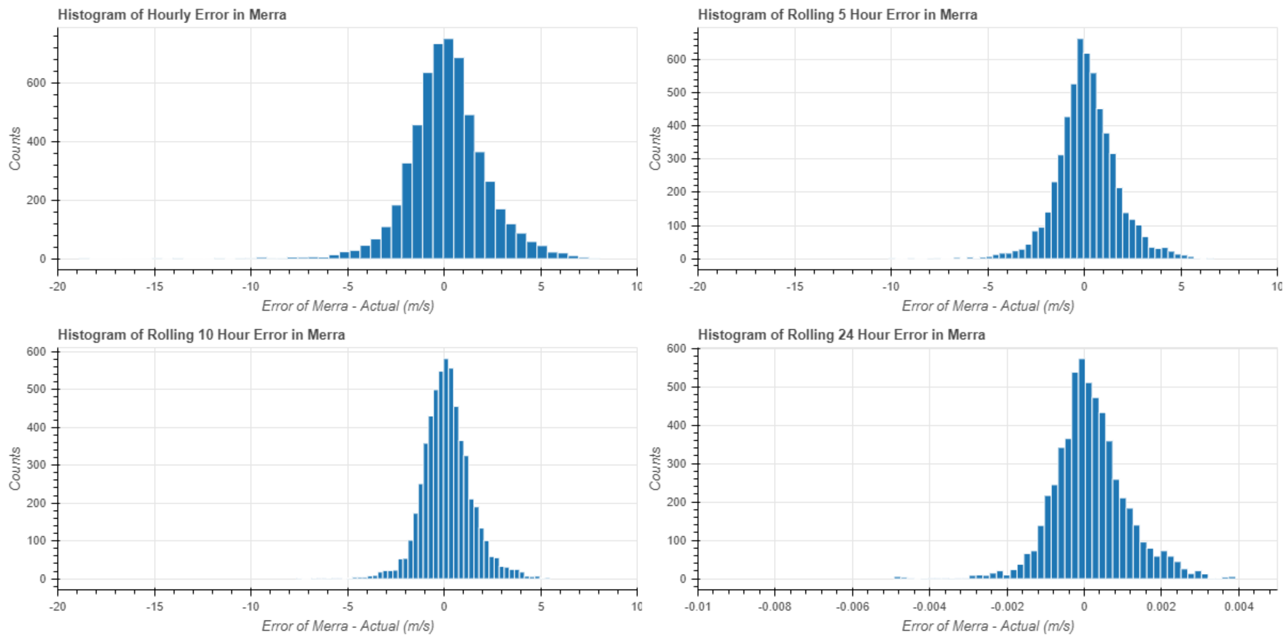


Figure 22: MERRA-2 Wind Speed Rolling Average Histograms

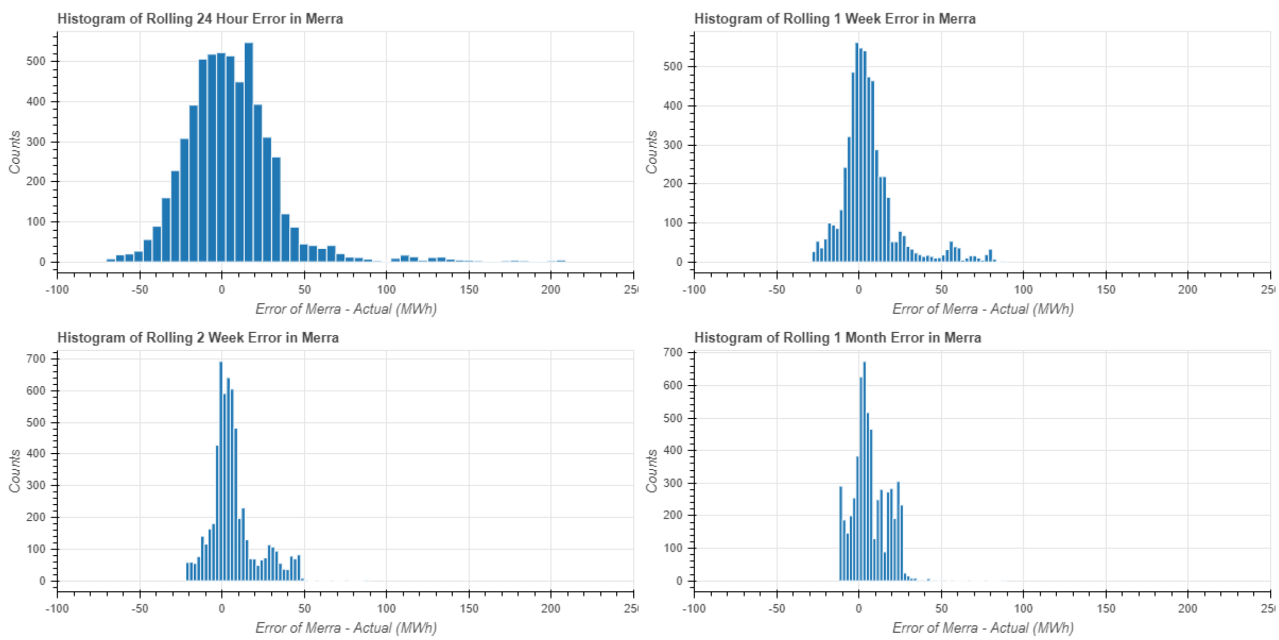


Figure 23: MERRA-2 PG Rolling Average Histograms

Figure 24 below shows an error matrix for MERRA-2. This analysis was to determine if there were any sections of the power matrix primarily responsible for the error in MERRA-2. Instead, locations with large error were all clustered at where the most data points were. In addition to this, cells with significant over and underestimates were all located next to each other. This seems to indicate that the error is fairly random, and this is an area for future work (discussed further in Section 7.2.1).

Sum of m WD WS	0	10	20	30	40	50	60	70	80	90	100	110
1								466.22				
1.5				613.2		215.43			239.72	-2592		
2				-640.6	-11546	-6900		542.88	214.09	-1430		-13345
2.5		1116.5	471.41	-20257	-19277	-52155	-24008	-55152	-1E+05	-14543	-2E+05	-28249
3		-23580	-14536	-13213	-3572	9545.7	14172	-47754	2830.2	-26391	-2E+05	-17472
3.5		30736	117822	15081	22186	-435.5	29592	11145	46637	55287	97357	107487
4		-80439	28127	223304	76210	162664	76923	-40431	143729	118620	130835	197069
4.5		-76482	110802	90385	24635	136035	71727	152118	114376	38599	148855	27124
5		20963	26727	-2759	70445	118298	23648	-99377	29470	68104	-3E+05	-47393
5.5		-36287	139508	-1E+05	30851	104679	100948	100390	130431	2493.2	56842	-3E+05
6	31018	301771	-69074	242005	143541	-76191	-1E+05	13967	26498	29377	63296	166447
6.5		-46046	41888		97764	127987	27689	122442	626074	-5E+05	475870	479266
7	116074	503555	-98972	162132	60677	147583		178926	10089	-2E+05	211761	391520
7.5	6070.7	320858	49741	584157	142851	65726	138733	-42222	76297	-19852	176936	853.44
8		74314	411486	561466	146143	89676	203148	-3E+05	-2E+05	-19733	68301	199157
8.5	100167	371.84	314491	349179	321472	78225	-33954	-21653	-47382	102577	166012	58904
9	-11860	276767	-3E+05	133942	149403	-23298	67174	-1E+05	83802	40940	148625	319900
9.5	125766	-3E+05	-2E+05	-4E+05	-2E+05	238701	109676	-84870	-2416	-73875	-2E+05	29637
10	-70075	-2E+05	-6E+05	-3E+05	29942	-10569	159974	-58247	-32585	56265		251893
10.5	-32160	-2E+05	-1E+05	-3E+05	66827					85681	88151	27441
11		-728.8	29723	-1E+05					-1E+05			
11.5		-23750	-73077	-29232								
12	-4417	-6241	-33996	-13670								
12.5		-20237	-27422						2004.4			
13	536.66	172681	8375.4					-8838				
13.5		-5334										
14			5448.7									

WS	120	130	140	150	160	170	180	190	200	210	220	230
1	563.11	531.31					-1034		-1815			
1.5	-5363	568	640.82	-22532		-20434	167.21	237.35	477.92			
2	-1E+05	-69696	-4159	-30501	-82479	534.17	-1E+05	-66844		266.54	335.62	
2.5	-9257	-5100	-36096	-1014	-16385	-50590	-2E+05	-62797	-80181	-1E+05	-1E+05	
3	-65662	-2E+05	-1E+05	10389	8685.5	-94421	-54060	-2E+05	-1E+05	-38007	-1E+05	-1E+05
3.5	92163	137650	69346	35450	76898	-94356	74683	44072	-2E+05	121158	-2E+05	5865.8
4	41838	28349	92562	33619	-11790	182116	137909	429916	229845	135262	113646	-2E+05
4.5	171766	126354	135695	161727	160417	178863	51266	39046	179097	242371	29955	91604
5	298552	125105	206876	333191	323923	41963	49094	325260	138585	205634	-2E+05	13338
5.5	280290	365034	188341	135063	122688	197027	-2E+05	159726	162909	554874	-2E+05	-1E+05
6	312010	172879	225849	264848	428998	244441	-2E+05	-11002	-45801	184549	257496	-8E+05
6.5	-54151	179126	38826	-2E+05	302316	54404	-20099	-36478	131205	334487	395460	-2E+05
7	504040	-1E+05	86458	222661	401388	352294	321309	-3E+05	436314	282890	380675	48928
7.5	75532	254960	69992	291219	303274	440861	-5E+05	-1E+05	403881	178752	191081	784677
8	-6E+05	212054	80331	-4E+05	-90790	362929	205279	-5E+05	-34529	13857	-20717	463695
8.5	-38895	-61441	373792	114543	-5E+05	490192	-5E+05	636023	-4E+05	373140	274439	1110
9	181390	170640	126326	572594	-1E+05	456323	-10643	435820	-6E+05	58797	629024	654905
9.5	14718	178006	71386	284108	-5E+05	-2E+05	185209	148275	-29990	1E+06	735852	169295
10	-94522	443816	629424	229387	561234	52660	234367	206852	465062	146698	457743	517352
10.5			37547	288910	124527	-2E+05	-99545	50511	-3E+05	24203	226884	-12171
11		-37404	189039	72073	84814	-2E+05	234445	476161	-3E+05	336592	273897	-1715
11.5	-24280		-74690	-75235	-2E+05	-2E+05	117563	53925	68821	358193	224817	29207
12		-31838	114197	-5862	42462	-2E+05	409447	-96248	-13883	236185	-21241	47091
12.5			136738		-7358	-1214	-23609	-20823	36972	-16638	243993	
13					-1264	1708.5	48746	3926.4	-5756	-7122	50036	4798.8
13.5							-253	3730.7	-8565	-31481	-49498	-2750
14									3289	-5240		

WS	240	250	260	270	280	290	300	310	320	330	340	350	360
1	-787.4	281.65	-2985										
1.5	318.51	-29460	-66849		762.76	357.93		930.11			581.87		
2	-31358	-211.5	-38.33	-1E+05	-2E+05	-116.4		-1819	896.58	491.08		427.85	
2.5	-39065		-863	223.2	658.37	858.09	-25712	426.59	-16477	-759	-3330	-8014	
3	-1E+05		-66719	422.36	-12421		-62544	1730.9	-9522	-49127	-3508	2446.2	
3.5	36159	8006.6		123524		10358	37882	16796	39841	152527	142143	-6260	
4	12008	44335		185514	86023	36848	-3E+05	88127	59234	37760	86988	79182	
4.5	37645	94706	13948	32969		22927	-91436		62559	43280	78828	83020	30599
5	81046	-1E+05	111044	-2E+05	100380	-44223	24699		-19324		37749	162630	
5.5	-61856	-3E+05	152147	45396	21197	-44503	4111.4		10083	87585	27166	114461	
6	78411	-13977	111082	2201.8	40645	13851		61840	-29628		117776	370073	
6.5	-2E+05	-95005	-85951		34320	-97853	92528	-67870		75678	119325	254094	40065
7	296020	141471	-24407		21858	-68789	311873	100471	56369	305348	-2E+05	146027	129092
7.5	-4E+05	129608	-25763	77167		47148	49792	98930	-28451	-1E+05	390409	11810	
8	230186	116750	109304		171355	55218	-1E+05	116490	29338	-25641	-28927	-36621	
8.5	355155	324087	-38961	-3E+05	27080	43425	-2E+05		-3E+05	-1570	56309	-2E+05	
9	83732	192028	45681	6353.9		60027	-46995	-1E+05	-1E+05		38963	-1E+05	
9.5	135504	131783			-76227	79147	151498		7097.4	-80871	-65602	-1E+05	
10	-29683	3540	-2E+05	-1E+05	-15317	48114	94290	35035	-50131	-73545	29291	-97334	
10.5	-1E+05	-3E+05	-1E+05		324737	-86144	-15357		-73712	35819	10647	-93708	
11	-46345	-1E+05	-1E+05	89145	134141	1536.5	27132		-12812	22767	249007	-4619	-18884
11.5		-21090	-1E+05	83185	-28425	-4990	-13437	-81062		28190	25304	5250.4	-15069
12		-15591	5709.5		-19908			-9066	19179	52283			-20068
12.5	507.71		-14538	-26012	-510.6			20127		10741	2284.3	-15994	
13	913.04	-10963	4899.3		2999.5	20431				15021	-14465		
13.5					7561.8					20100	34494	-688.6	
14					6519.7					-20107		-74713	

Figure 24: MERRA-2 Error Matrix

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Concluding Remarks

The NTF method results are shown to vary depending on the mast/turbine pair configuration at the site, which ultimately has an impact on the project proxy revenue. The number of met mast and mast/turbine pairs at the site is one of the risk factors in the NTF method. Using met masts and a site specific NTF also greatly increase the accuracy of both wind turbine power prediction and proxy revenue, compared to using just the nacelle wind speed with the OEM corrected NTF. The reanalysis data method attempts to estimate the site wide proxy generation using one wind direction and wind speed, and the results from this case study show that it is a poor method of estimation.

Overall, there is serious benefit in using onsite wind condition measurements in turbine power prediction. The NTF method handles risk of a price excursion much better than MERRA-2. The original motivation for this project was in part due to the problematic correlation of wind and price. The events in Texas in February 2021 were an extreme case demonstrating a potential scenario in which different power prediction methods could have a drastic effect on the financial settlement for a wind plant [20] .

If turbine SCADA or other onsite measurements are unavailable, the financial settlement may be calculated using proxy generation results from MERRA-2 data. Comparing results from the NTF method and MERRA-2 show the financial implications of that choice. If a large price event coincides with a financial settlement calculated with MERRA-2 , the wind farm may suffer significant financial implications.

7.2 Future Work

7.2.1 Reanalysis data method alternatives

Future work includes alternative methods to develop the power matrix for the Reanalysis Data method. For this analysis, only a power matrix developed through empirical data was used, and the power matrix was shown to be a large source of error and uncertainty in this method. It would be possible to use a CFD modeling software to predict power production and create a power matrix, and it would be interesting to compare the results to our empirical method results.

Another area of investigation for the reanalysis data method would be to use a different reanalysis data set. MERRA-2 was used for this analysis comparison as it is the current industry standard for financial agreements, however ERA5 has emerged as the new standard for wind resource analysis, and other applications of wind power modeling [19]. It would be interesting to use ERA5 and compare to the results derived from MERRA-2.

7.2.2 Additional projects

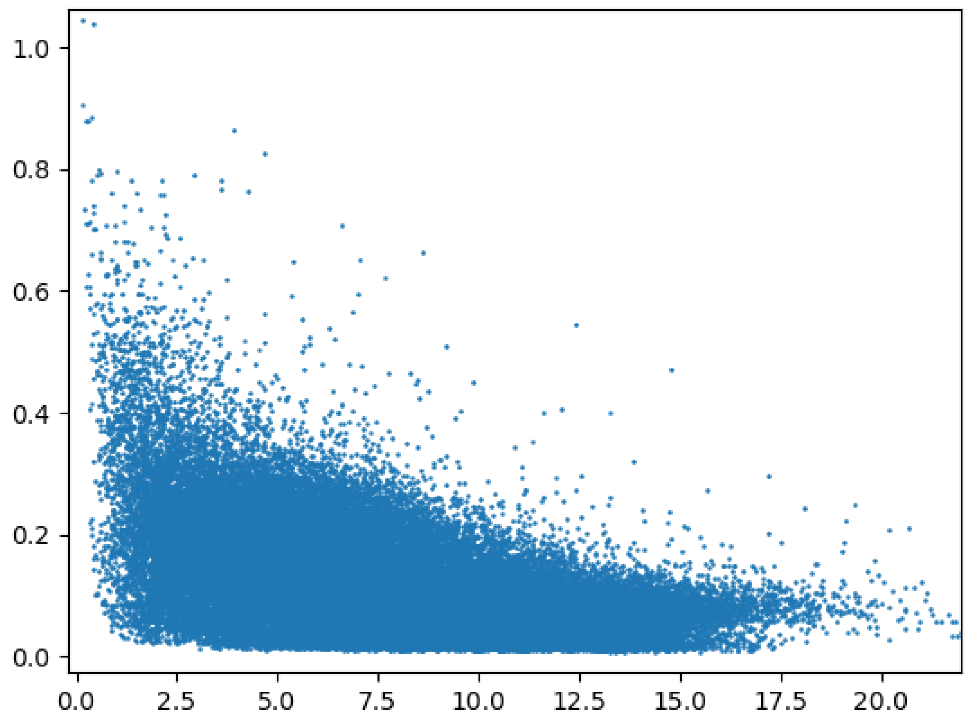
This case study was performed on a wind site in north Texas, with relatively simple terrain. This analysis should be performed on data from other wind projects, as well as those in more complex terrain. Financial settlements using the PG values from both NTF and reanalysis data method are already in place without an understanding of the financial implication of either method. Better understanding of the impacts of each method across varied terrain should be explored.

7.2.3 Applications in other agreements

The development of two different models to predict site wide power production have other applications besides financial agreements of wind farms. The methods derived here can now be applied to settlement and curtailment agreements, as well as contractual guarantees.

APPENDIX A

Turbulence Intensity (TI) plot. Used to help determine correct power curve for site.



APPENDIX B

Data Filtering

Valid Sectors:

Table 4-1 Nominated turbines and IEC valid sectors

Turbine	Valid sector start (degrees true north)	Valid sector end (degrees true north)
WTG 2	313	55
WTG 3	304	52
WTG 85	128	244
WTG 86	126	239
WTG 97	124	236
WTG 98	123	236

QC Filtering:

Signal QC filter	Value < Min or Value > Max	OR	Value = Standard deviation
	Min	**Max**	**Standard deviation**
Wind speed [m/s]	0	30	0
Wind direction [degrees]	0	360	≤ 0.1
Temperature [°C]	-15	40	N/A
Pressure [hPa]	700	1100	N/A
Relative humidity [%]	0	100	N/A
Power [kW]	-625	3125	0

APPENDIX C

NTF ratios for each turbine/mast pair as well as site-wide.

Turbine 1

ws	mast	nws
2.5	2.734372	2.511097
3	3.112904	3.022191
3.5	3.468608	3.503105
4	3.998144	3.997784
4.5	4.225415	4.492045
5	4.72474	5.000425
5.5	5.194625	5.511516
6	5.748798	6.00955
6.5	6.207016	6.503831
7	6.675636	6.999001
7.5	7.076087	7.495316
8	7.549469	8.004309
8.5	7.884521	8.496406
9	8.323643	9.003724
9.5	8.905595	9.498925
10	9.441888	9.99424
10.5	9.959815	10.51925
11	10.33419	11.00368
11.5	11.00765	11.49566
12	11.30769	11.97696
12.5	11.78219	12.48866
13	12.27879	12.99184
13.5	12.92724	13.51216
14	13.26564	13.99357
14.5	13.84047	14.51056
15	13.83776	14.98107
15.5	14.34303	15.4966
16	14.61064	15.99157

Turbine 2

ws	mast	nws
2.5	2.868944	2.534234
3	3.209425	3.016887
3.5	3.490864	3.495402
4	4.018945	3.996298
4.5	4.365038	4.498613
5	4.873364	5.001578
5.5	5.328132	5.516625
6	5.902885	5.993734
6.5	6.285366	6.50755
7	6.85219	6.999439
7.5	7.233408	7.498147
8	7.69785	7.997359
8.5	8.160507	8.483963
9	8.696649	9.007513
9.5	9.153162	9.50005
10	9.640314	9.99249
10.5	10.04944	10.48479
11	10.77758	11.00071
11.5	11.27745	11.49341
12	11.60429	11.97888
12.5	12.21214	12.48931
13	12.62186	12.97503
13.5	13.18263	13.50783
14	13.49667	13.96235
14.5	13.92263	14.50482
15	14.23298	15.00762
15.5	14.94042	15.49002
16	15.05004	15.97255

Turbine 3

ws	mast	nws
2.5	2.15486	2.503817
3	2.730862	3.00914
3.5	3.285519	3.498864
4	3.770012	4.005846
4.5	4.390045	4.505879
5	4.841252	5.006643
5.5	5.362283	5.503782
6	5.892164	6.001534
6.5	6.382297	6.504989
7	6.890624	6.998134
7.5	7.378637	7.503731
8	7.821582	8.006218
8.5	8.263374	8.495782
9	8.778781	9.011133
9.5	9.230263	9.504229
10	9.743025	9.997285
10.5	10.25006	10.49674
11	10.8239	10.9973
11.5	11.38561	11.49283
12	11.93308	11.98389
12.5	12.40193	12.49124
13	12.91042	12.98995
13.5	13.33201	13.4928
14	13.8284	13.98588
14.5	14.23277	14.50603
15	14.7069	14.98907
15.5	15.22959	15.48406
16	15.66459	15.96844

Turbine 4

ws	mast	nws
2.5	2.151579	2.512723
3	2.719961	3.015583
3.5	3.236851	3.503783
4	3.775165	4.000388
4.5	4.333821	4.500922
5	4.853491	5.007935
5.5	5.339453	5.505569
6	5.89574	6.001644
6.5	6.486348	6.501511
7	6.982092	6.995369
7.5	7.422984	7.511915
8	7.890243	7.997533
8.5	8.385812	8.503948
9	8.892681	9.006596
9.5	9.384689	9.507173
10	9.877827	9.999272
10.5	10.41296	10.50144
11	10.94754	10.98597
11.5	11.46784	11.48831
12	12.00834	11.99161
12.5	12.49773	12.48944
13	12.95932	12.98652
13.5	13.46059	13.48645
14	13.95219	13.99016
14.5	14.36222	14.48094
15	14.81473	14.98508
15.5	15.3862	15.46984
16	15.86213	15.97161

Turbine 5

ws	mast	nws
2.5	2.744918	2.521359
3	3.226585	3.00903
3.5	3.587041	3.499455
4	4.085807	3.997534
4.5	4.611294	4.505747
5	4.997325	5.006424
5.5	5.514093	5.503958
6	5.90056	6.002641
6.5	6.424521	6.506822
7	6.862234	7.006464
7.5	7.308433	7.505089
8	7.721312	8.001328
8.5	8.274645	8.50515
9	8.647402	8.999011
9.5	9.037746	9.499698
10	9.543142	9.998342
10.5	9.973287	10.50162
11	10.42141	10.99215
11.5	10.99579	11.49343
12	11.52715	11.98449
12.5	11.97078	12.47701
13	12.38153	12.98673
13.5	12.9352	13.50148
14	13.33723	13.99293
14.5	13.59783	14.47512
15	13.99964	14.98746
15.5	14.03031	15.47915
16	14.65907	15.99645

Turbine 6

ws	mast	nws
2.5	2.662413	2.51882
3	3.227837	3.023911
3.5	3.643696	3.499979
4	4.090188	3.998429
4.5	4.660008	4.500986
5	5.065069	5.003161
5.5	5.606358	5.505466
6	6.006784	6.002406
6.5	6.707894	6.502547
7	7.060513	7.008969
7.5	7.359588	7.500648
8	7.829581	7.996845
8.5	8.288891	8.497565
9	8.624357	9.006411
9.5	9.062601	9.50072
10	9.470047	9.997046
10.5	9.95129	10.49853
11	10.37754	10.99636
11.5	10.85842	11.4832
12	11.41742	11.99076
12.5	11.91248	12.48485
13	12.44217	12.98186
13.5	12.89024	13.4768
14	13.27733	14.00339
14.5	13.53468	14.50887
15	13.93396	14.99824
15.5	14.01203	15.44702
16	14.48181	15.98173

Site Wide

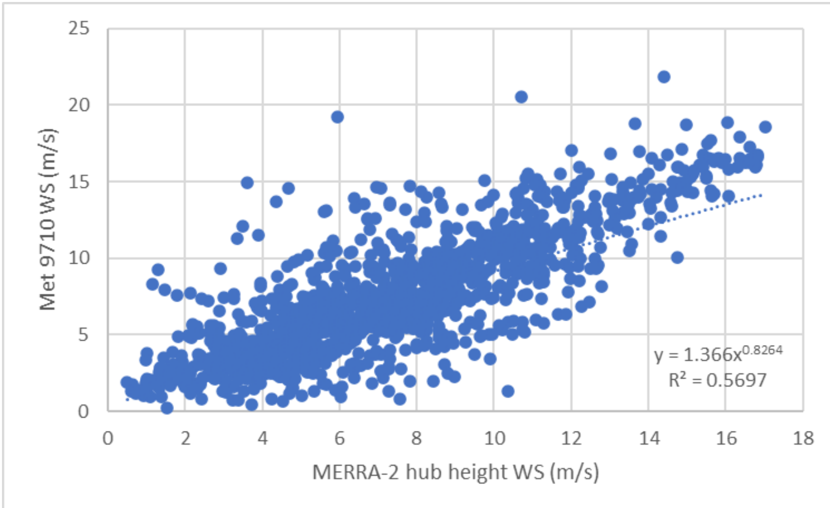
ws	mast	nws
2.5	2.523316	2.516344
3	3.035813	3.015645
3.5	3.453866	3.500163
4	3.954164	3.999593
4.5	4.457547	4.501556
5	4.914763	5.004933
5.5	5.422371	5.506604
6	5.904972	6.00192
6.5	6.454071	6.50426
7	6.913271	7.001993
7.5	7.325641	7.503592
8	7.785669	8.000408
8.5	8.264244	8.499221
9	8.700353	9.005436
9.5	9.160702	9.502531
10	9.647811	9.997509
10.5	10.13734	10.49984
11	10.63807	10.99399
11.5	11.1799	11.49003
12	11.69612	11.98647
12.5	12.18475	12.48648
13	12.65417	12.98608
13.5	13.15809	13.49329
14	13.59311	13.98981
14.5	13.95487	14.49613
15	14.32979	14.99094
15.5	14.73555	15.47809
16	15.09868	15.9797

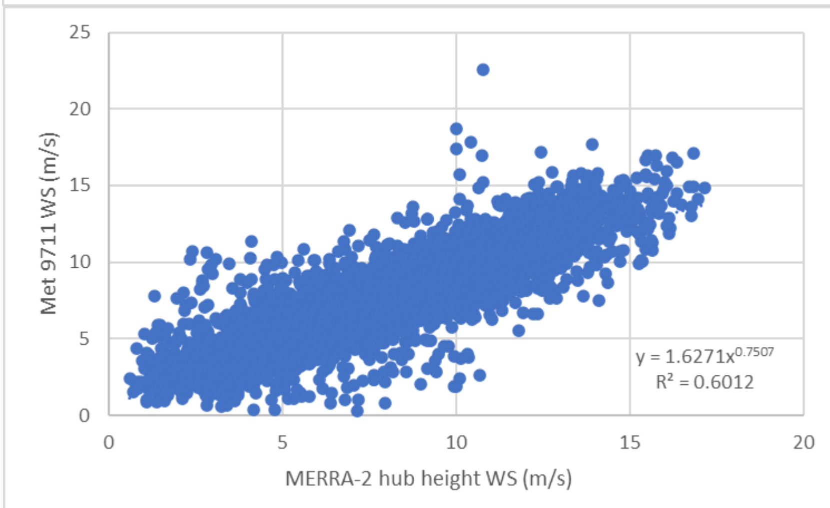
APPENDIX D

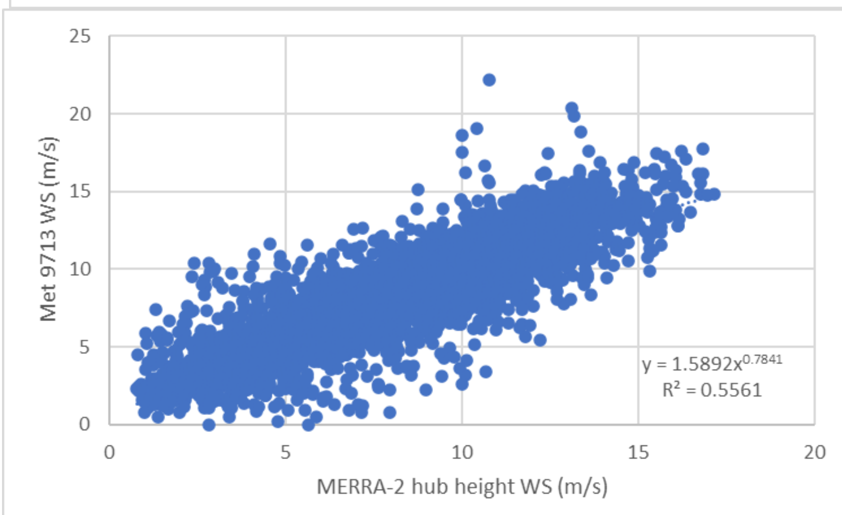
power_matrix.csv

APPENDIX E

MERRA-2 vs each Met Mast







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