Hourly Wind Generation Profiles for Operational Plants (1980-2017)

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AWS Truepower, LLC
463 New Karner Road | Albany, NY 12205 | United States
www.ul.com/renewables

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AUTHOR(S)	REVIEWER(S)	APPROVED BY
Rojowsky, K. Beaucage, P. Johanson, C.	Frank, J.	Shakarjian, M.

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1. EXECUTIVE SUMMARY

UL, formerly AWS Truepower (AWST), was retained by the Electric Reliability Council of Texas ("ERCOT" or the "Client") to generate hourly wind power generation profiles for almost 22 GW of installed capacity across their service area for the period of 1980–2017. The purpose of this work was to support ERCOT's various modeling and analysis efforts related to the high penetration of wind and long-term reliability. The final deliverable of hourly profiles simulate the current configuration of the 2017 ERCOT fleet as applied to an extended historical weather record (1980-2017).

Wind plant details were compiled from public, private, and proprietary data sources in order to best ensure completeness and accuracy of the ERCOT fleet to be modeled. The plant layout and other static details were gathered from numerous publicly and privately available datasets. This information was used to model each plant as close to reality as possible.

UL simulated the atmospheric variables necessary to convert meteorological information to power using Weather Research and Forecast Model (WRF) for the study period of 1980-2017. WRF model data were adjusted using on-site measurements to ensure annual, seasonal, and diurnal mean wind patterns as well as ramping characteristics were accurately represented. The final observed dataset used in the adjustment process consisted of 10-minute data from 40 towers, for a total of over 200 years of data. Results show that the adjusted model time series captures the dynamic behavior of annual, monthly, and diurnal wind speeds exhibit an overall annual bias of -0.18 m/s. The adjusted WRF wind speed and other meteorological variables served as input to UL's power conversion software to synthesize wind generation profiles.

Power generation modeling differed for the operational and queued (non-operational) wind generation plants. Each plant was classified as operational or non-operational based primarily on the availability of historical generation data. A total of 137 out of the 140 wind plants were commissioned within the ERCOT service area. Generation data from commissioned plants were reviewed to determine the valid period of data considered outside the break-in period and if the plants were mature enough to meaningful actual power generation for the modeling process. Four plants were not mature enough to exceed this threshold and provide meaningful actual power generation for the modeling process, while still other had less than a full year of observed data after filtering for the break-in period, wind farm shadowing (fully-waked conditions), and other factors. Without sufficient operational data for the four new operational plants and no historical data for the three queued (non-operational) plants, UL treated these plants differently. A modified adjustment process was also applied to sites with less than one year of data.

Power conversion proceeded using the grid-scale wind power method, along with the hourly wind speed and other meteorological inputs from mesoscale weather model. The resulting hourly profiles were adjusted to account for non-standard, site-specific characteristics using an adjustment to historical generation. The final hourly profiles represent uncurtailed generation, current plant-on-plant wake conditions (where applicable), and operational plant losses as derived from historical generation data. Therefore, it is important to note that the actual power profile at a plant for a given time period may not entirely agree with the simulated profiles.

The final power generation results were evaluated for reasonableness and compared to historical wind generation. Results show that the overall generation values align well with expectations on a monthly, diurnal, and overall annual basis, and ramping statistics appear to reasonably depict fluctuations in power generation.

2. INTRODUCTION

Beginning in 2012, UL, working as AWST, simulated hourly wind generation for both operational and hypothetical wind capacity across the ERCOT region using standard tools for fleet generation profiles. The first series of profiles simulated historical wind power generation for the period of 1997 – 2012, with annual updates provided through 2016, using consistent power conversion methods and composite power curves.

In 2015, UL used the Weather Research and Forecast Model (WRF) to simulate the hourly atmospheric variables, and all previous profiles were recreated (1997-2014) using the adjusted resource variables from WRF as input to UL's standard power conversion methods. All other wind resource assessment and power conversion processes and specifications remained static. This dataset was updated annually until 2017 using the same methods and input parameters, but with additional data from the WRF model (i.e., consistent modeled time series spanning 1997-2016).

In 2018, ERCOT contracted with UL to provide a new set of hourly profiles for its operational fleet of almost 22 gigawatts (GW) of installed wind capacity. This effort is a major update to previous modeling efforts, as well as a significant increase in the length of the simulation period. The purpose of this effort was to provide a long-term time series of high fidelity, hourly production profiles based on current wind fleet characteristics to support ERCOT's various planning and reliability modeling efforts.. As such, the hourly generation profiles assume the current configuration of the 2017 ERCOT fleet as applied to an extended historical weather record (1980-2017). The profiles were developed to represent the historical plant availability and 2017 losses without curtailment. Therefore, it is important to note that as a result of using the 2017 fleet configuration, historical generation at a given plant or for a given time period may not entirely agree with the simulated profiles; especially at sites where plant-on-plant wake losses have been introduced over time.

Measured data and plant characteristics were incorporated to reflect the potential long-term generation at operational and queued plants. As such, the plant layout and turbine models were obtained for all plants and historical power generation data for all operational plants in the ERCOT fleet were compiled (133 plants out of 140 plants modeled). Improvements were also made to the power conversion process to account for wind farm shadowing and to remove the historical curtailment present in the generation data that was used for validation and model adjustment.

The extended long-term time series have been simulated using UL's method for grid-scale wind power studies. This report summarizes the methods and results for 140 operational or queued wind plants in the ERCOT region.

3. WIND PLANT SPECIFICATIONS

3.1 Wind Plant Characteristics

Wind plant details were compiled from public, private, and proprietary data sources in order to best ensure completeness and accuracy of the ERCOT fleet to be modeled. ERCOT provided RARF[3.1] data comprised of 190 individual wind unit codes, their installed capacity, and centroids of the units to be modeled. This information was reviewed and compared to other plant information derived from outside sources as follows.

[3.1] The RARF (Resource Asset Registration Form) database contains static details for power plants as provided to ERCOT from the developer, plant owner, or operator.

The turbine layouts of individual plants were compiled from a number of sources. As-built information from the Client was used, where available. For each RARF unit code, an associated plant layout was extracted from the American Wind Energy Association (AWEA) WindIQ Wind Turbine database.[3.2] The AWEA plant layout data included several turbine specific data fields such as hub height, capacity factor, and power curve information. Turbine coordinates from the FAA's Obstruction Evaluation - Airport Airspace Analysis (OE-AAA) database,[3.3] the USGS's Wind Turbine database,[3.4] and the Energy Velocity[3.5] database were also used to cross check the AWEA coordinates and to help reconcile differences between RARF unit codes and plant names. Plant details from theWindpower.net,[3.6] Global Data,[3.7] ERCOT interconnection agreements,[3.8] and UL's internal wind farm and turbine inventory were used as supplemental verification to confirm capacity estimates and identify potential data gaps among the various sources (e.g., turbine type or hub height). Each plant was classified as operational or queued (non-operational) based on availability of generation data, client-provided information, as well as information from outside data sources mentioned previously.

The plant layouts were verified based on static plant details and aerial imagery, when possible. Turbine locations were visually inspected using satellite imagery to identify mismatches between expected coordinates and the as-built locations. Visual inspection was not possible for queued plants (under construction) or for several existing plants in areas where aerial imagery is not current. Adjustments were made to align turbine coordinates with imagery, remove turbines reported as decommissioned, and remove any meteorological towers or other structures misidentified as turbines from the layout data. The centroid locations of the wind plants to be modeled were delivered to ERCOT for review.[3.9] The counties which contain turbines that were modeled are highlighted in Figure 3.1.

Once the turbine layouts were confirmed, the estimated installed capacity for each plant was calculated from the respective number of turbines and the turbine rated capacity values. UL's estimated capacity was compared to the RARF installed capacity for each unit code to ensure that all turbines had been accounted for. The RARF installed capacity was also verified against the maximum historical power generation data from ERCOT for the years 2011-2017. UL's expected installed capacities were equivalent to the RARF installed capacities at the vast majority of sites. Wherever small discrepancies did arise, UL worked with the ERCOT to finalize the sites for modeling.

RARF unit codes were aggregated under various scenarios as follows: (1) where the unit code for the same plant did not add additional capacity to the plant to be modeled (these generally represented a second point of interconnection; (2) if individual turbines could not be geographically assigned to one unit code for a project with multiple phases and therefore multiple RARF codes; or (3) if a plant had more than one turbine model in a multiple-phased plant. Following the review and consolidation process, a total of 140 plants were modeled, representing all 190 RARF unit codes provided by ERCOT. Once the final plant configurations were assigned, the modeled plant profiles were validated and adjusted using the highest granularity of historical generation possible.

[3.2] http://windiq.awea.org

[3.3] https://oeaaa.faa.gov/oeaaa/external/portal.jsp

[3.4] https://eerscmap.usgs.gov/windfarm

[3.5] https://new.abb.com/enterprise-software/energy-portfolio-management/market-intelligence-services/velocity-suite

[3.6] https://www.thewindpower.net

[3.7] https://energy.globaldata.com

[3.8] http://interchange.puc.texas.gov/WebApp/Interchange/application/dbapps/filings/pgControl.asp?TXT_CNTRL_NO=35077

[3.9] UL provided a kml file in March of 2018.

The static details of the 140 plants are given in Appendix A. These tables contain the following information for each plant profile: public name and UL site number, county which encompasses the site centroid, plant capacity, and hub height(s) modeled. A total of 10 hub heights were modeled, and the actual turbine models and manufacturer power curves were assumed. The turbine hub heights were rounded to the nearest 5 meters, and Table 3.1 lists the unique heights for turbines modeled in this project, along with the height at which they were modeled.

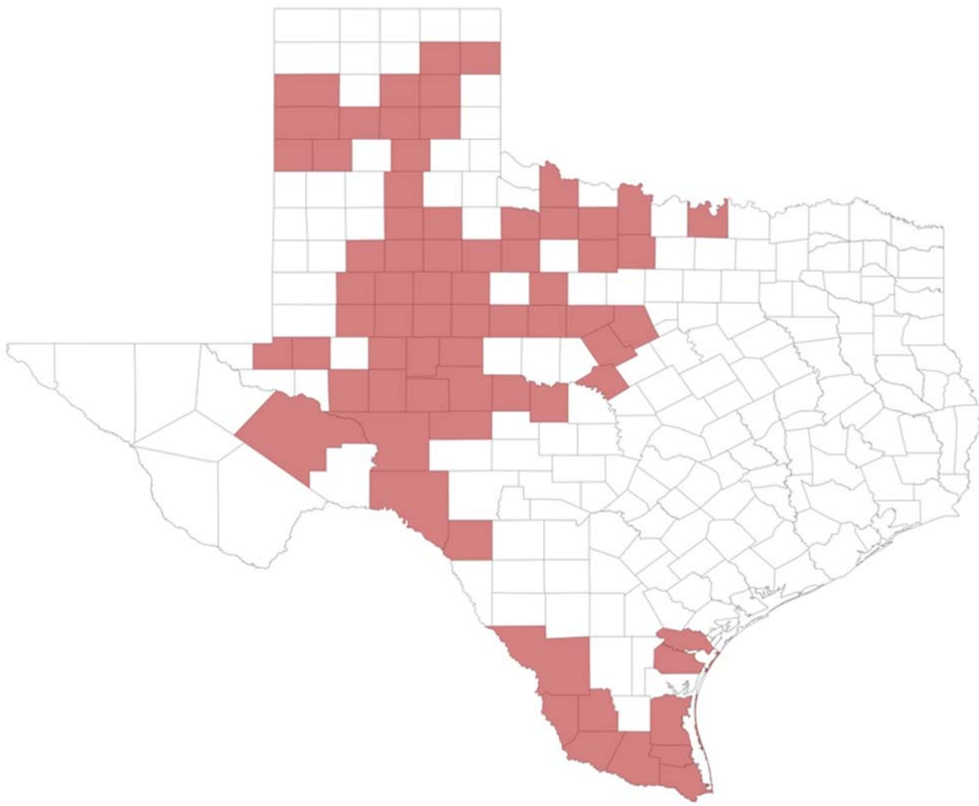

Figure 3.1: Counties with Wind Turbines Modeled

Table 3.1: Hub Heights Modeled

Hub Height Modeled (m)	Turbine Hub Heights (m)
50	50
60	60
65	65
70	69
80	78, 79, 80
85	85, 87, 87.5
90	90, 91.5, 92
95	94, 95
100	98.1, 100
105	105

3.2 Operational and Non-operational Plants Data Collection and Screening

Power generation modeling differed for the existing and queued (non-operational) wind generation plants. A total of 137 out of the 140 wind plants were operational within the ERCOT service area. All data from commissioned plants were reviewed to determine the valid data, considered outside the break-in period. UL assumes a typical break-in period of four months (minimum) before turbines are running at peak efficiency. In total, 133 wind plants were initially considered by UL as being past their break-in period.

Four plants were not mature enough to exceed this threshold and provide meaningful actual power generation for the modeling process. The four operational wind farms within their break-in period were: Magic Valley (#4), Santa Rita (#53), Bearkat (#88) and Willow Springs Wind Farm (#108). In addition, three queued, or non-operational, wind farms were also modeled without historical data: Cactus Flats (#25), Flat Top (#42) and Rattlesnake Wind (#106). Without sufficient operational data for the four new operational plants and no historical data for the queued (non-operational) plants, UL treated these plants differently for the purposes of modeling with limited information. The variation in modeling approach for these seven plants as it deviates from the other 133 plants is described throughout.

Historical, hourly generation data from operational plants was used to adjust the modeled plant profiles to account for wake effects from upstream farms, turbine underperformance, plant availability, and other plant-specific losses. The historical generation data includes the actual, measured power generation (which includes plant losses and curtailment), and the high sustainable limit (HSL) for each hourly record. The HSL refers to the limit established by the plant owner/operator (qualified scheduling entities) that describes the maximum sustained energy production capability of the plant at that time. In essence, the HSL reflects the theoretical, uncurtailed power generation at actual plant availability. UL used the greater of the observed power and the HSL as “historical” data for validation and model adjustment.

The “break-in” period was also filtered out of the historical generation data. The initial period of running the wind turbines typically involves fine tuning of the wind turbine/plant operation and usually shows lower availability than normal. By default, the first four months of generation data after the commercial operation data were flagged as the “break-in” period and discarded. A visual inspection of the generation data was carried out for each plant to determine if the break-in period extended beyond the first four months. At some plants, up to six months of initial generation data were discarded because of data discontinuity with the remainder of the record; e.g., no data, low data recovery, or unusual fluctuations in power generation.

The remaining historical generation time series at each plant was quality controlled as follows. Historical power generation in excess of the plant capacity range was discarded. It was assumed that the historical generation contained periods of erroneous values if the generation was stuck on a constant value, including 0 MW, for a period of 24 consecutive hours or more. These data were discarded. In UL's experience, power generation data that is stuck on a constant value, even 0, is often times indicative of data transmission issues. A potential drawback to the automated QC procedure is that it may have artificially increased the net capacity factor since it discards periods of what may be valid plant outages. It should be noted that most periods of no generation for a full 24-hour cycle (i.e., 0 MW for the whole plant) was seen during the "break-in" period.

Another important consideration was if plants were considered "waked" by upstream wind farms and when the upstream wind farms were built. Wind farms are known to modulate the wind flow well downstream of their positions. ERCOT has several regions where multiple wind farms have been constructed in close proximity over time; therefore, it is important to understand if a plant was subject to increased waking with time, which may therefore be present in the historical generation. Since historical generation data are used to adjust modeled output at these wind farms to account for effects of upstream wind farms, it is important to only consider only the period of data after which upstream wind farms were built (the "fully waked period"). The fully waked period was determined as follows: (1) the wind rose at hub height was obtained for each plant from UL's windNavigator;[3.10] (2) any plants within 20 kilometers (km) upstream of the prevailing wind direction(s) were noted;[3.11] and (3) each upstream plant's installation or latest recorded commissioning date, as found in the RARF or other databases, was determined and recorded. The date of the most recently installed upstream wind farm was used as the start of the fully-waked period for plants that were identified as "waked".

An evaluation of the potential for upstream wake effects from neighboring farms proceeded for the four plants considered within their respective break-in periods, as well as the three queued (non-operational) plants. Further assumptions made in the adjustment process for these plants (and others) are discussed in the relevant report sections.

4. ATMOSPHERIC MODELING, VALIDATION AND ADJUSTMENT

4.1 Mesoscale Modeling

Historical meteorological conditions were simulated over the state of Texas and adjacent areas using the Weather Research and Forecasting (WRF) model,[4.12] a leading open-source numerical weather prediction (NWP) model that simulates the fundamental physics of the atmosphere. WRF solves the fully compressible, non-hydrostatic Navier-Stokes equations (i.e., conservation of mass, momentum and energy) and utilizes a complete suite of physics parameterization schemes. These include radiation, land surface-atmosphere interactions, planetary boundary layer turbulence, microphysics, and cloud convection. WRF contains 11 boundary layer schemes, 18 microphysics schemes, and 10 convective parameterization schemes, as well as a three-dimensional grid to simulate atmospheric processes. The vertical levels of this grid extend far into the stratosphere (roughly equivalent to 20.5

[3.10] https://dashboards.awstruepower.com/wsa

[3.11] UL assumed a typical distance of 20 km for the wind speed downstream of turbine arrays to recover to the free stream wind speed.

[4.12] Skamarock, W. C., Klemp J.B., Dudhia J., Gill D.O., Barker D.M., Duda M.G., Huang X-Y., Wang W. and Powers J.G. A Description of the Advanced Research WRF Version 3. Boulder: NCAR Technical Note NCAR/TN-475+STR, 2008.

km in altitude), so as to capture the jet stream. Input into the WRF model includes a variety of online, global geophysical and meteorological databases. ERA-Interim,[4.13] a historic global weather archive provided by the European Center for Medium Range Weather Forecasting, supplied the model initialization and boundary conditions. These data provide a snapshot of atmospheric conditions around the world at all levels of the atmosphere in intervals of six hours. High-resolution terrain, soil, and vegetation data were also used as input where available. The WRF model was then set to run to determine the evolution of atmospheric conditions within the region based on interactions amongst different elements in the atmosphere and between the atmosphere and the surface.

WRF simulations were carried out to model the atmospheric circulation during the 1980 to 2017 historical period, with a strong focus on meteorological variables such as wind speed, turbulence kinetic energy, temperature, and precipitation in order to estimate wind power production at each plant location.[4.14] WRF was set up to run two nested grids simultaneously with a horizontal grid spacing of 27 and 9 km (see Figure 4.1). In essence, different scales of motion are resolved by grids with different resolutions. A ratio of 3 between the parent and child grid resolution (i.e., 27 vs. 9-km) ensures a proper energy cascade from the large scales to the small scales, which is mainly due to the non-linear interactions. The two grids at 27-km (shown in red) and 9-km (shown in green), respectively, resolve successively finer scales across the whole region. The 27-km grid passes the boundary conditions to the innermost 9-km grid, which modifies the atmospheric circulations in response to a consistent set of surface forcings from the terrain elevation, land cover, soil temperature and moisture, etc. In other words, the met data is passed from one grid to the next in a way that allows the model to develop the finest scales in a consistent way. The final model simulation includes both the ERCOT service area and nearby adjacent land areas to provide a complete dataset for the period of 1 January 1980 to 31 December 2017. Simulated meteorological values were retained on an hourly basis. The model configuration used in this study is summarized in Table 4.1.

[4.13] Dee, D. P. et al. "The ERA-Interim reanalysis: configuration and performance of the data assimilation system." Q.J.R. Meteorol. Soc., 2011: 137: 553–597.

[4.14] UL utilized previous WRF runs available in-house for the period of 1/1/1996 – 12/31/2016. This dataset was extended for 1/1/1980-12/31/2015 and 1/1/2017-12/31/2017, to support this project.

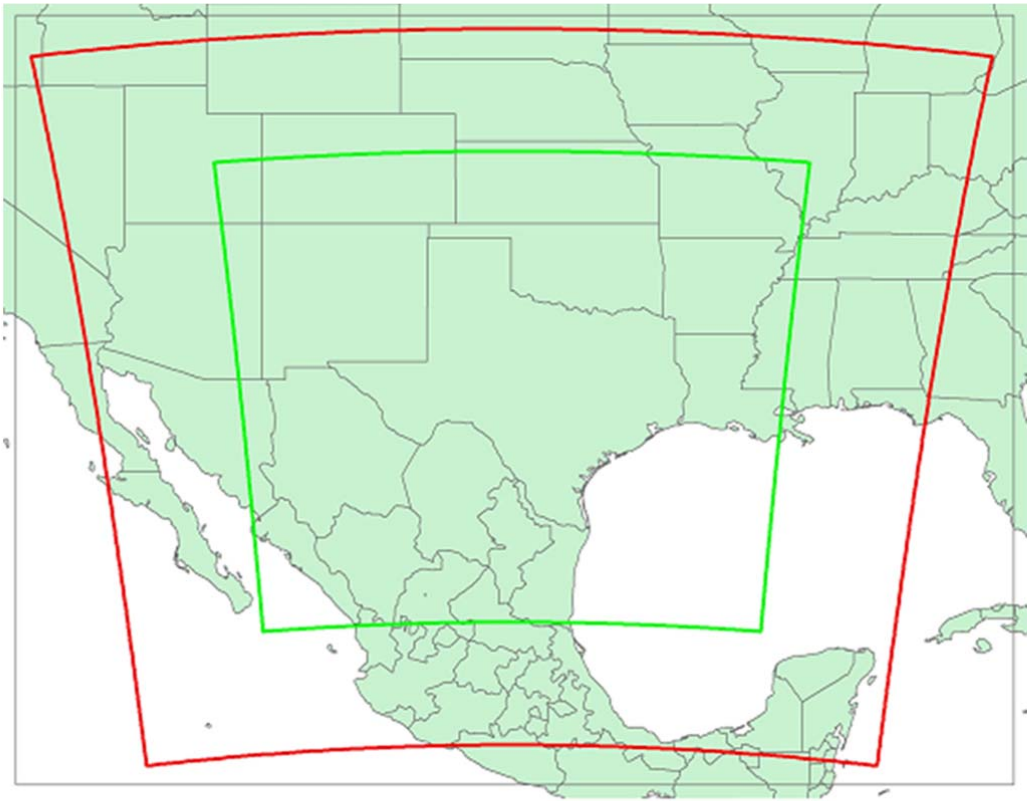

Figure 4.1: WRF Nested Grids for the Study Domain

Table 4.1: Model Configuration for WRF Runs

Model	**WRF v3.5.1**
Initialization Data Source	ERA-Interim
Data Assimilation	Spectral Nudging
PBL Scheme	Mellor-Yamada-Janjic Scheme
Frequency of Data Sampling	1 Hour
Spatial Resolution (Innermost Grid)	9 km

4.2 Resource Adjustment and Validation

Before converting the modeled meteorological time series to plant production, it is first necessary to correct for biases to ensure that the modeled wind resource used in the conversion to power is accurate. This is done by scaling the WRF meteorological variables to match a best estimate of the expected resource average and resource variability at each site. The adjustment and validation of model data requires a sufficiently large sample of observed data. For this project, data from public and private tall tower data sources from within the modeling domain were used to adjust the WRF-derived wind speeds (Figure 4.2).

The measured data were quality-controlled, including, but not limited to: ensuring data were not suspiciously below or above the expected wind speed thresholds, comparing measurements at redundant sensors, and performing analyses to examine suspect trends. Datasets were discarded if they did not pass the quality-control tests, have a sufficient period of record (at least one year), or provide meaningful values for validation and adjustment. Some datasets were truncated to a period that was considered valid. These data were then used to validate and adjust the final atmospheric dataset used in the power production models.

The final observed dataset used in the adjustment process consisted of 10-minute data from 40 towers, for a total of over 200 years of data. This is significantly more observed data than used in previous studies,[4.15] which increases confidence in the accuracy of resource characterization at the sites being modeled. Most towers (36 of 40) are located in Texas. Four towers from neighboring areas of New Mexico and Oklahoma were also included. These tall tower data were used to adjust diurnal mean patterns in the modeled hub-height wind speed time series. Results show that the adjusted model time series captures the dynamic behavior of annual, monthly, and diurnal wind speeds (Figure 4.3 and Figure 4.4) exhibit an overall annual bias of -0.18 m/s. The adjusted WRF wind speed and other meteorological variables served as input to UL's power conversion software to synthesize wind generation profiles.

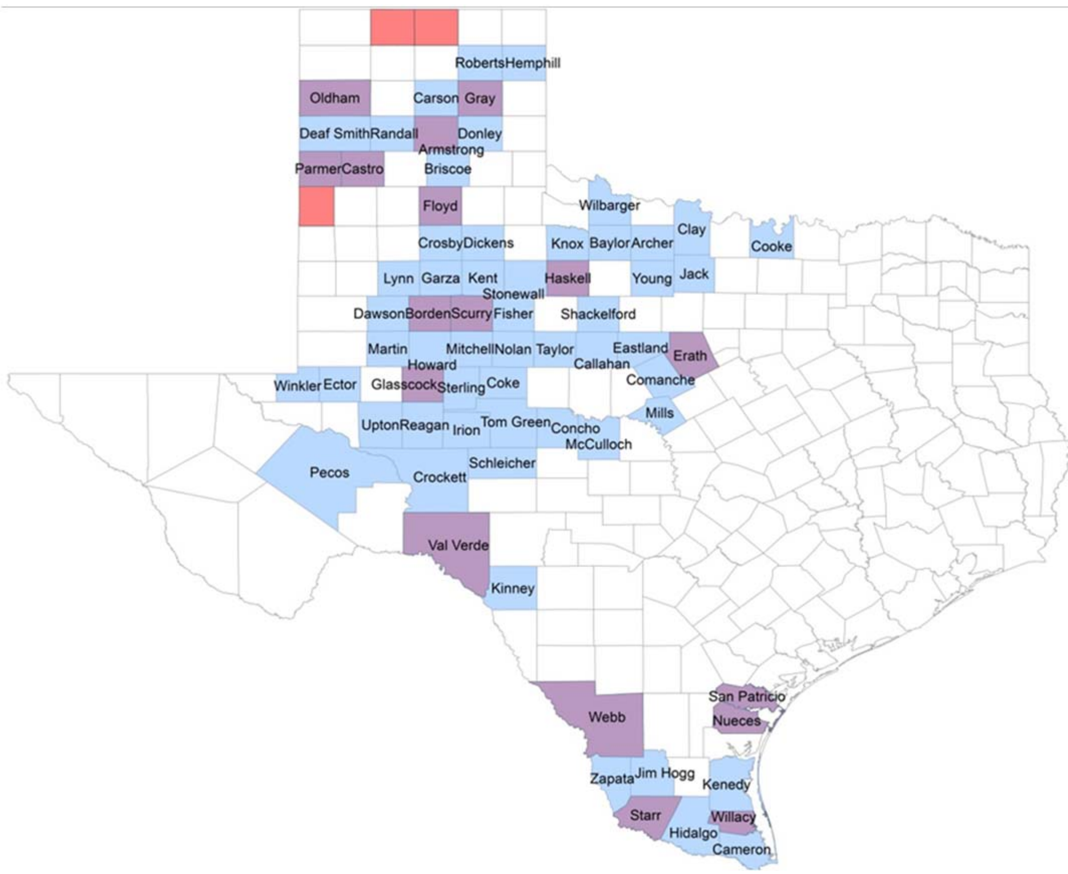

Figure 4.2: Counties with Tall Towers (red) and Wind Turbines (blue)

4.15 Previous wind generation studies conducted by AWST utilized observed data from 7 tall towers within the modeling domain.

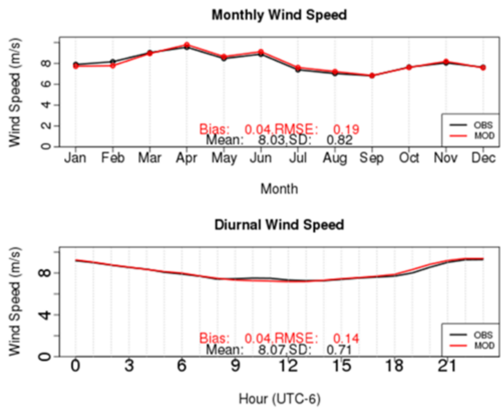

Figure 4.3: Observed and Modeled Wind Speeds at an Inland Tall Tower (local time)

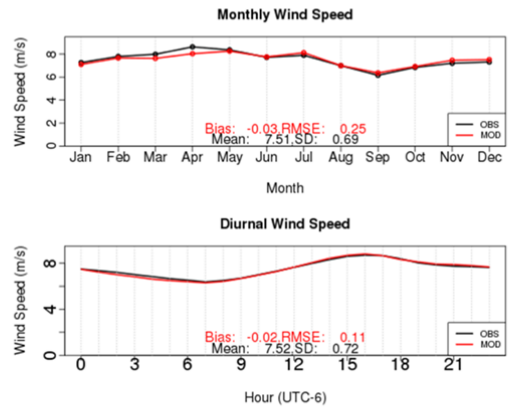

Figure 4.4: Observed and Modeled Wind Speeds at a Coastal Tall Tower (local time)

5. POWER CONVERSION

5.1 Wind Power Generation

Hourly time series from the adjusted WRF meteorological dataset were extracted for each site. Using the plant layouts described in Section 3.1, UL identified the WRF grid cells within the footprint of each wind farm and extracted hourly time series of the following variables:

- wind speed, wind direction, and turbulence kinetic energy (TKE) at hub height,
- air temperature at 2 m above the ground and at hub height,
- air pressure at the ground surface.

For each model point, the estimated mean speed at hub height, the mesoscale grid cell elevation, and the actual site elevation were obtained.

UL's wind power conversion software was used to convert the adjusted WRF meteorological time series to net wind plant generation. The wind speed time series were converted to power using the plant layout and manufacturer's power curve (Appendix A - Details for Plants Modeled). The power conversion process adjusts the curves based on the air density computed from the modeled temperature and pressure, corrected for the difference between the mesoscale model and turbine hub-height elevation above sea level

The next step consists of applying individual plant losses. UL considered the following categories of plant losses to derive net power: wakes, availability, high wind hysteresis, and electrical losses, as described below. The net power represents the total power at the electrical connection point of the wind farm to the grid, typically a substation.

The modeled speeds for each site were adjusted for wake effects in a manner dependent on the simulated wind direction, θ, relative to the prevailing (most frequent) direction, θ_0. The loss is given by:

$$\omega = (\omega_{max}-\omega_{min})\sin^2(\theta-\theta_0)$$

where ω_{min} is the minimum deficit, which occurs when the wind (θ) is aligned with or opposite to the prevailing direction (θ_0), and ω_{max} is the maximum deficit, which occurs when the wind is perpendicular to the prevailing direction. This formula reflects the fact that turbines are typically spaced farther apart in the prevailing wind direction in order to minimize the total wake loss and more closely together in the transverse direction in order to maximize the plant rated capacity. In addition, the formula accounts for other losses such as blade soiling and pitting that affect the efficiency of power conversion over all directions.

High wind hysteresis is accounted for using the waked wind speeds and the appropriate cut-in and cut-out speeds from the site-specific turbine power curve.

A time-varying power loss was applied to account for turbine and plant availability. Based on data obtained by UL for operating wind projects, the availability was assumed to follow a normal distribution with a mean of 94.8% and a standard deviation of 2.3%; the distribution is truncated at 100%. An additional loss of 3% is subtracted from the output prior to the point of interconnect to represent electrical losses.

In order to simulate fluctuations in time more accurately, the wind speeds were further adjusted by adding a random factor (from -1 to +1) multiplied by the predicted TKE. This adjustment reflects the impact of gusts and lulls on the speeds experienced by the turbines in the wind project. The frequency and intensity of such simulated gusts depends to a degree on time of day, as TKE is generally higher in the day when the planetary boundary layer is thermally unstable or neutral than at night when it is thermally stable.

The plant-specific losses were further refined using an adjustment to historical generation data (further described below). The final, adjusted model profiles account for the following additional plant-specific loss factors on generation: wind farm shadowing,[5.16] environmental,[5.17] and turbine performance. Curtailment was not included in the historical generation data used for adjustment, and therefore is not reflected in the final, adjusted model profiles.

5.2 Modeled Time Series Adjustment

The model generation data were adjusted using the filtered, historical generation data from operational plants[5.18] to more accurately reflect real power generation patterns. The main purpose for this adjustment is to account for non-standard and site-specific plant losses that are not directly estimated by UL's wind power conversion software, and secondarily, to tune the standard losses assumed in UL's wind power conversion software. The final adjustment process created a correction matrix specific for each plant based on concurrent historical and modeled power generation. The correction matrix is a two-dimensional scaling table as a function of plant generation bins by month. Once the correction matrices were created, the modeled generation time series at each plant was adjusted based on the plant generation bin and month for each record.

Although many operational plants had a sufficiently long record of historical generation data, 25 of the 140 plants modeled had less than a full calendar year of historical power generation (the minimum necessary to build the correction matrices). The lack of historical generation data at these other plants required additional consideration. For plants with some historical generation data, although less than a full calendar year, the months in the correction matrix with missing values were filled with an average value per power bin computed from the valid values in the other months. For the three non-operational and four operational plants within the break-in period, a correction matrix from a nearby plant considered likely to be closely correlated or "representative" was used. The representativeness of nearby plants was evaluated based on the following criteria of surrogate plants: sufficient data

[5.16] Wake effects from neighboring wind farms

[5.17] Environmental losses typically include low and high temperature shutdowns and icing.

[5.18] The historical generation data is described in Section 3.2

recovery, distance between reference and target site, and similarity of wind speed and direction distribution.

The final generation profiles were examined for reasonableness at the plant level and as an aggregate of all 115 operational plants (totaling 17.6 GW) with at least one year of historical generation data (see Figure 5.1 and Figure 5.2). Although not shown, the raw (unadjusted) modeled wind power time series already captured the diurnal cycle and ramp distribution well. Figure 5.1 shows that the mean diurnal patterns and ramp distribution also agree with the historical generation after adjustment. The monthly historical and adjusted model mean generation also fit very well for the aggregate, as expected with an adjustment based on power bins and month. The final dataset has a bias of about 1% and an hourly coefficient of determination (R^2) of 0.86. Figure 5.2 includes the histogram and the frequency duration curve for all concurrent, hourly historical and adjusted model data for the 115 plants. This analysis shows that final dataset is able to accurately capture the dynamic behavior of wind plants.

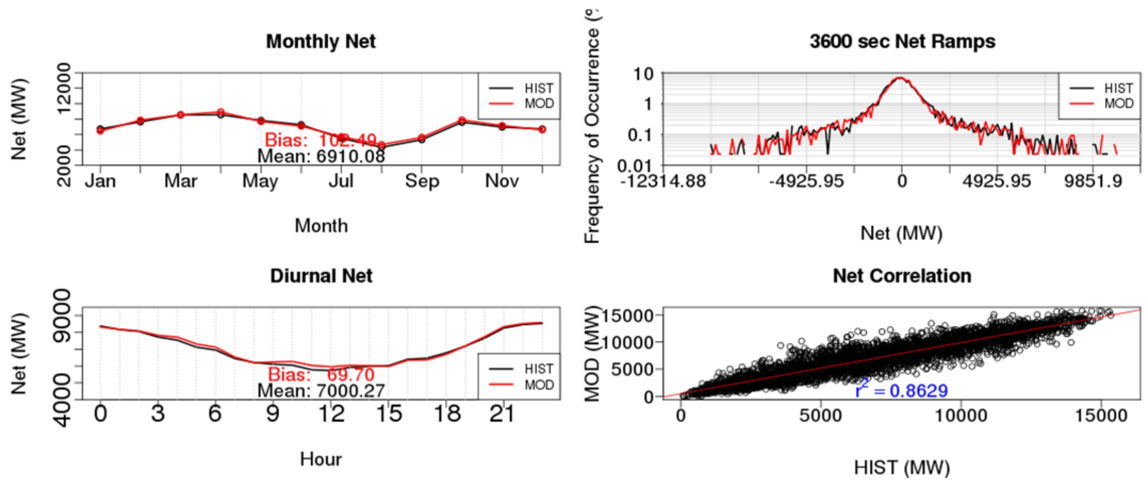

Figure 5.1: Net Power for Concurrent, Hourly Historical (black) and Adjusted Model (red) data from an Aggregate of 115 Plants. Net power is shown by month (upper left) and by hour of day in local time (lower left). The correlation of these values appears in the lower right. The frequency distribution of 1-hour ramps is in the upper right.

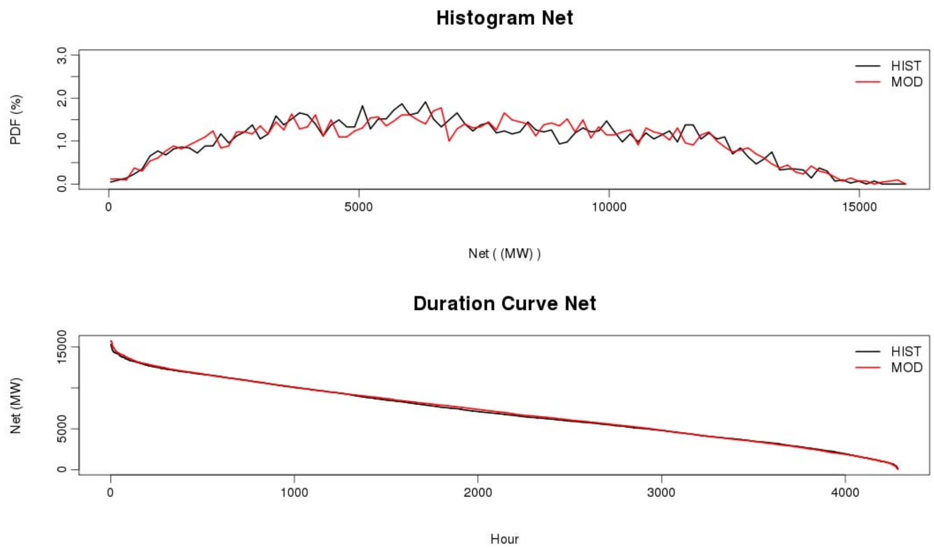

Figure 5.2: Probability Distribution Function (top) and the Duration Curve (bottom) of Hourly Concurrent Historical (black) and Adjusted Model (red) Net Wind Power Generation for an Aggregate of 115 Plants

6. RESULTS

Hourly net generation profiles were simulated for the period 1980-2017 across 140 plants within the ERCOT domain. The net capacity factor of the adjusted model generation time series from these plants range from 22.3% to 53.3% (Appendix A - Details for Plants Modeled). These values compare well with historical generation data. The total plant losses average about 27%, which is high but reasonable for plants in North America.[6.19] Many plants in the domain are affected by wake from adjacent wind farms, particularly in western and far western Texas.

Aggregate generation statistics for all sites modeled is shown in Figure 6.1. The inter-annual variation in generation amongst the modeled plants is approximately 5%. Overall, the upper magnitude of hourly ramps is limited to about 25% of total capacity. The monthly and diurnal mean generation patterns reflect regional expectations.

The power generation across the ERCOT domain shows a peak in overall generation during the spring months and a lull in late summer; the diurnal pattern exhibits a peak in the generation during the overnight hours (Figure 6.1). However, this pattern does not describe the typical generation at all sites within the domain. The power generation at a typical inland and coastal wind plants are shown in Figure 6.2 andFigure 6.3, respectively. As seen, the generation of the inland site more closely resembles the domain-wide generation. About 18 GW of the 22 GWs of installed capacity is sited well away from the coast, and hence dominates the overall generation pattern. Generation is dominated by increased wind speeds during the springtime in part due to relatively high baroclinicity (temperature gradients), which manifests as windy springtime cold fronts. This baroclinicity is diminished as the warm season progresses. Another phenomenon develops at inland location during the spring and summer as well: the nocturnal low-level jet. Much of the production in the summer in Texas comes

[6.19] Brower, M.C. et al. (2012). “Wind Resource Assessment, a practical guide to developing a wind project ”. Wiley, 280 pp.

from the nocturnal low-level jet, a phenomena during which nighttime cooling produces a shallow stable layer of air and winds just above the surface speed up because of reduced frictional effects. Because of the jet, wind generation peaks in the overnight and early morning hours, with a typical down ramp during the morning load ramp up. Along the coast, a sea breeze circulation is driven by the temperature difference between the land and sea. This circulation drives winds ashore during the daytime heating of the land surface. Hence, winds at hub height near the coast peak during the late afternoon.

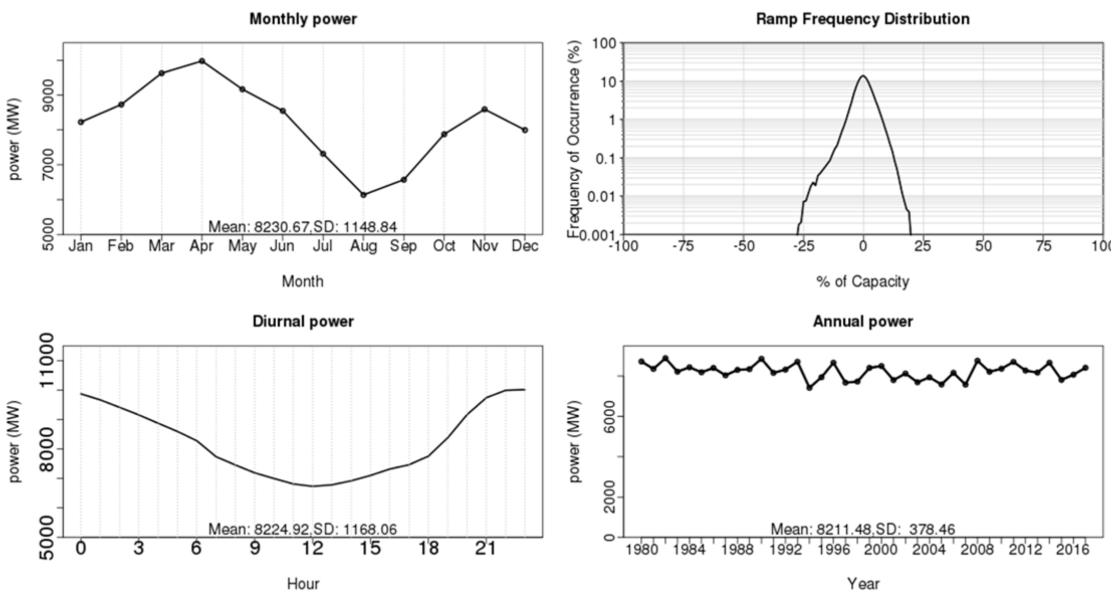

Figure 6.1: Aggregated Annual, Monthly and Hourly Net Power and 1-Hour Ramp Distribution

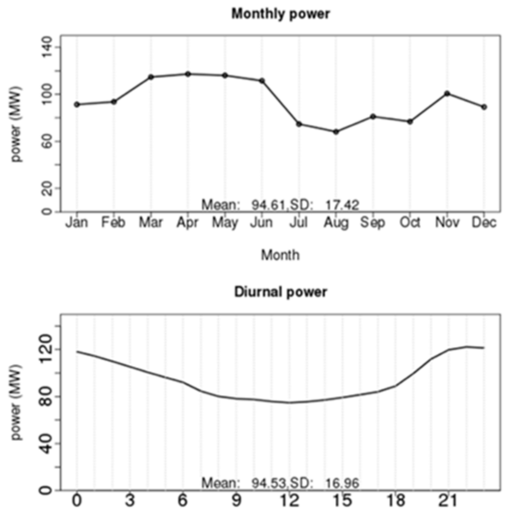

Figure 6.2: Monthly and Diurnal Adjusted Model Wind Generation for a Site near the Inland Tower Depicted in Figure 4.3 (local time)

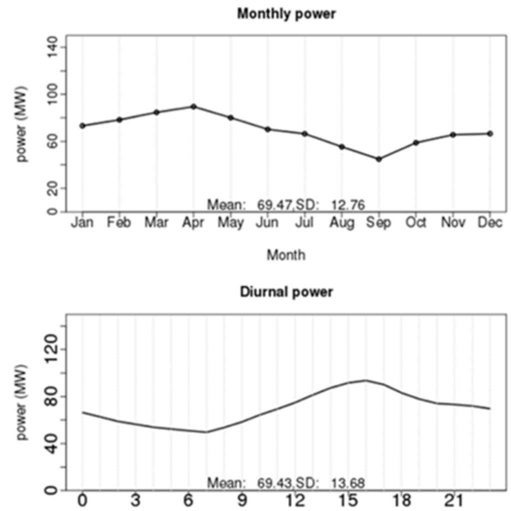

Figure 6.3: Monthly and Diurnal Adjusted Model Wind Generation for a Site near the Coastal Tower Depicted in Figure 4.4 (local time)

Analysis of generation values shows that the counties with highest annual energy production (AEP) are those in west Texas and the Panhandle area: Nolan, Floyd, Carson, and Scurry (Figure 6.4 and Appendix B - County Statistics). Many sites in west Texas exhibit relatively modest net capacity factors (at or below about 35%), compared to 45% in the Panhandle. The high AEP in west Texas is due to the relatively high capacity installed in the area (Figure 6.5), even though the wind resource is not as favorable as across parts of the Texas Panhandle.

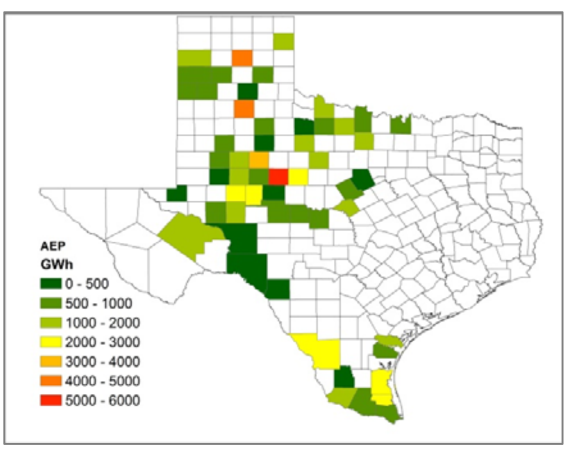

Figure 6.4: Summed Annual Energy Production by County as Determined by Site Centroids

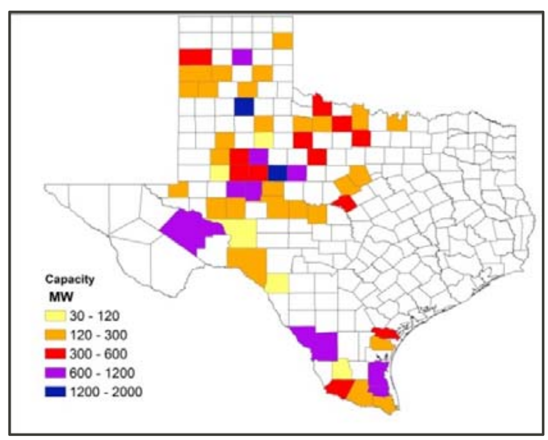

Figure 6.5: MW Capacity by County as Determined by Site Centroids

The adjusted model profiles were further validated against the monthly energy production reported by the US Energy Information Administration (EIA).[6.20] UL retrieved monthly energy production data from the EIA database for 89 plants with a period of record of 12 months or more.[6.21] Overall, the monthly energy production of the adjusted model profiles matches the EIA very well as shown in Figure 6.6. Note, the monthly patterns are similar to the ones seen previously in Figure 5.1 with a peak in spring, a low in late summer and a secondary peak in fall. The adjusted model monthly energy production matches the EIA production better in the summer than in the spring which is most likely due to seasonal curtailment, which tends to occur in the winter and spring season, if at all. Another potential source of discrepancy between the adjusted model and EIA monthly energy production is that the adjusted model time series have 100% data recovery, whereas the EIA monthly production is based on hourly, actual power generation with a data recovery between 80% and 100%, thereby reducing the data present in the EIA monthly energy, i.e. sum of power for the month.

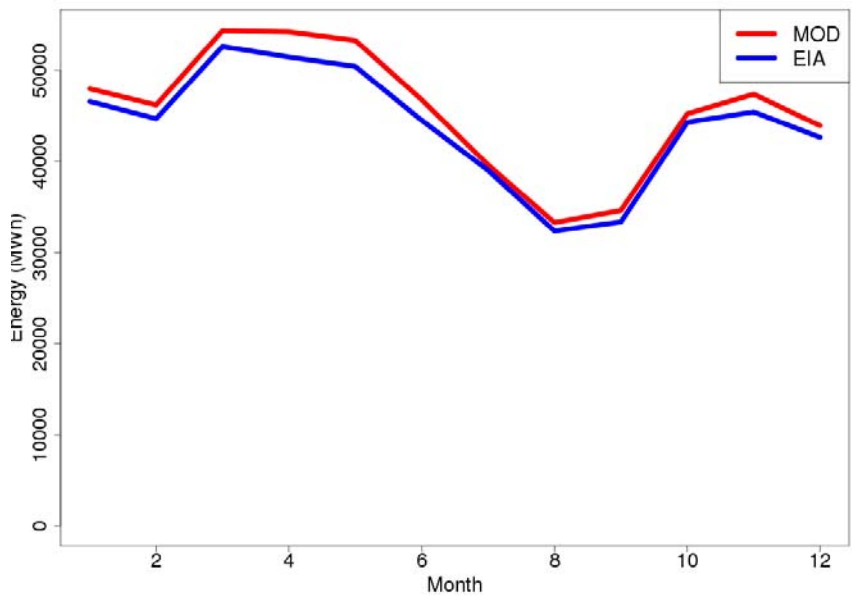

Figure 6.6: Net Power by Month for Concurrent Adjusted Model (red) and EIA (blue) Data for an Aggregate of 89 Plants

7. SUMMARY AND DATASET USAGE

UL was retained by ERCOT to simulate hourly wind generation for the period 1980-2017 across its fleet of almost 22 GWs of installed wind capacity. The goal of this work was to provide high-fidelity power profiles for the operational plants without modeling individual losses using SCADA. The final hourly profiles represent uncurtailed generation, current plant-on-plant wake conditions (where applicable), and operational plant losses as derived from historical generation data.

[6.20] https://www.eia.gov/opendata/qb.php?category=902974

[6.21] UL discarded one plant from this analysis: Grandview. The EIA energy production at Grandview was nearly 50% of the HSL, indicating a large difference in plant capacity and how the four phases of Grandview were aggregated.

This dataset reflects a significant enhancement to methods previously used to simulate operational wind power profiles in ERCOT, and therefore, a direct comparison to previous work may not be appropriate. Significant updates include incorporating more tall tower wind speed data across the service area to enhance wind resource fidelity, incorporating individual plant layouts and power curves, and adjusting power profiles using site-specific historical generation. Furthermore, previous power profiles represented net generation at the point of interconnection, whereas these profiles represent net power at the plant.

It is important to note that simulated profiles may not match historical generation at a given plant for a particular time for a number of reasons:

- All plants were modeled for the period 1980-2017 using the 2017 fleet configuration, regardless of the actual commissioning dates or changes in plant configuration over time.
- The modeled data were scaled to historical generation in order to account for site-specific losses not typically assumed as a part of UL's standard modeling for grid integration studies. Only the "fully waked" period was used in the adjustment to account for wind farm shadowing. Therefore, wind farm shadowing is likely overestimated in the period before upstream wind farms were installed at a particular location.
- An attempt was made to remove the effects of grid curtailment from the historical generation data by using the HSL data for the model adjustment. Therefore, the modeled data are not reflective of actual curtailment that may have been experienced at the wind farms.
- Finally, nearly 20% of the plants modeled for this effort did not have one year of valid data for the final adjustment process. Therefore, proxy plants were chosen and alternative methods for model adjustment were developed that may not reflect plant performance at these locations. It is highly recommended that these sites be re-adjusted once a year of more of actual plant generation data is available.

This dataset was developed specifically for use in modeling and analysis efforts related to the high penetration of wind and its long term variability. It has been shown that the adjusted model data accurately represent historical generation patterns at individual wind farms and on an aggregate basis.

APPENDIX A - DETAILS FOR PLANTS MODELED

Table A.1: Details for Sites Named Am - Ca

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
Amazon Wind Farm Texas	32	Scurry	253	80	43.6%
Anacacho	1	Kinney	99.825	80	39.3%
Baffin	3	Kenedy	202	90	33.4%
Barton Chapel	13	Jack	120	80	30.8%
Bearkat	88	Glasscock	196.6	85	39.3%
Big Spring	2112	Howard	34.32	80, 65	22.3%
Blue Cloud	2006	Wilbarger	135.4	80, 80	39.6%
Bobcat Bluff	5	Archer	150	80	32.7%
Brazos Wind Ranch	10	Scurry	99	70	25.5%
Brazos Wind Ranch	11	Borden	61	70	33.9%
Briscoe	12	Briscoe	149.85	80	37.7%
Buckthorn	2014	Erath	100.6	85, 90	33.5%
Buffalo Gap	15	Taylor	120.6	80	34.4%
Buffalo Gap	16	Nolan	232.5	80	33.2%
Buffalo Gap	17	Nolan	170.2	80	32.2%
Bull Creek	18	Borden	180	70	24.8%
Cactus Flats	25	Concho	148.35	85	44.9%
Callahan Divide	19	Taylor	114	80	38.4%
Cameron	20	Cameron	165	85	35.5%
Camp Springs I	30	Scurry	130.5	80	37.4%
Camp Springs II	31	Scurry	120	80	37.7%
Capricorn Ridge	21	Sterling	214.5	80	36.7%
Capricorn Ridge	23	Sterling	298.5	80	33.2%

Table A.2: Details for Sites Named Ca - Ha

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
Capricorn Ridge Expansion	22	Sterling	149.5	80	28.2%
Cedro Hill	24	Webb	150	80	39.2%
Chapman Ranch	110	Nueces	249	85	37.3%
Cotton Plains Wind	27	Floyd	50.4	80	44.4%
Desert Sky	60	Pecos	170.25	65	30.5%
Elbow Creek Wind Farm	34	Howard	121.9	80	34.3%
Electra Wind	33	Wilbarger	230	80	43.9%
Falvez Astra	2	Randall	163.2	80	45.4%
Flat Top	42	Mills	200	95	48.6%
Fluvanna	41	Scurry	155.4	80	42.8%
Forest Creek	80	Sterling	124.2	80	36.6%
Goat Mountain Wind Ranch	43	Coke	69.6	80	34.2%
Goat Mountain Wind Ranch	44	Coke	80	70	29.9%
Golden Spread Panhandle Wind Ranch	99	Carson	218.3	80	42.4%
Golden Spread Panhandle Wind Ranch	100	Carson	190.79	80	49.7%
Goldthwaite	2049	Mills	155.16	85, 80	39.3%
Grandview	46	Carson	200.48	80	50.3%
Grandview	47	Carson	211.2	80	49.3%
Green Pastures	45	Baylor	150	90	39.1%
Green Pastures	136	Knox	150	90	37.5%
Gulf Wind	130	Kenedy	283.2	80	30.6%
Gunsight	48	Howard	119.93	80	46.0%
Hackberry	58	Shackelford	165.6	80	35.2%

Table A.3: Details for Sites Named He - Lo

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
Hereford	56	Deaf Smith	99.9	80	38.9%
Hereford	57	Deaf Smith	100	95	47.0%
Hidalgo	84	Hidalgo	150	80	40.1%
Hidalgo	85	Hidalgo	100	80	38.9%
Horse Creek Wind	54	Haskell	230	80	41.1%
Horse Hollow	50	Taylor	213	80	36.8%
Horse Hollow II	51	Taylor	299	80	33.3%
Horse Hollow III	52	Nolan	223.5	80	33.9%
Indian Mesa	92	Pecos	82.5	50	28.9%
Javelina	7	Webb	19.69	80	36.5%
Javelina	8	Webb	230	80	46.2%
Javelina	2009	Webb	200	95, 80	45.4%
Jumbo Road	55	Castro	299.7	80	37.1%
Keechi	61	Jack	110	95	44.6%
King Mountain	64	Upton	79.3	60	22.4%
King Mountain	65	Upton	158.6	60	25.1%
King Mountain	66	Upton	40.3	60	22.5%
Langford	67	Tom Green	155	80	39.2%
Logans Gap Wind	68	Comanche	210.11	80	38.5%
Lone Star	71	Shackelford	200	80	34.1%
Lone Star I	2070	Shackelford	200	80, 80	31.9%
Longhorn	69	Floyd	200	80	43.1%
Loraine	73	Mitchell	49.5	80	35.0%

Table A.4: Details for Sites Named Lo - Ra

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
Loraine I	72	Mitchell	100.5	80	32.9%
Los Vientos I	74	Willacy	200.1	100	36.0%
Los Vientos I	76	Starr	200	95	40.5%
Los Vientos II	75	Willacy	201.6	90	32.6%
Los Vientos IV	77	Starr	200	95	41.8%
Los Vientos V	78	Starr	110	95	39.7%
Magic Valley	4	Willacy	228	80	33.3%
Magic Valley	103	Willacy	203.29	80	37.8%
Mariah East	79	Parmer	230.4	80	43.6%
McAdoo	87	Dickens	150	80	43.7%
Mesquite Creek	82	Dawson	211.22	80	39.2%
Miami	83	Hemphill	288.6	80	44.1%
Mozart	86	Kent	30	80	34.1%
Notrees	90	Winkler	60	80	36.3%
Notrees	2089	Winkler	92.61	80, 80	31.8%
Old Settler Wind	28	Floyd	151.2	80	43.0%
Panther Creek	94	Glasscock	142.5	80	38.2%
Panther Creek	95	Glasscock	115.5	80	38.2%
Panther Creek	96	Sterling	199.5	80	36.7%
Papalote Creek I	93	San Patricio	179.85	80	34.7%
Papalote Creek II	29	San Patricio	200.1	80	34.7%
Penascal	97	Kenedy	403.2	80	32.3%
Rattlesnake	2105	Glasscock	207.25	80, 80	45.9%

Table A.5: Details for Sites Named Ra - So

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
Rattlesnake Wind	106	McCulloch	160	90	42.7%
Red Canyon	102	Borden	84	80	40.7%
Rocksprings	38	Val Verde	121.9	80	36.4%
Rocksprings	39	Val Verde	27.44	80	43.3%
Roscoe	26	Nolan	126.5	80	35.2%
Roscoe	59	Nolan	197	70	32.0%
Roscoe	101	Scurry	249	80	35.2%
Roscoe	131	Mitchell	209	70	30.2%
Route 66	104	Carson	150	80	53.3%
Salt Fork	107	Donley	174	80	46.8%
San Roman	109	Cameron	95.4	85	37.3%
Sand Bluff	81	Glasscock	90	80	31.0%
Santa Rita	53	Reagan	300	90	45.0%
Senate	111	Jack	150	100	39.6%
Sendero	36	Jim Hogg	78	80	47.7%
Shannon	114	Clay	204.1	80	36.8%
Sherbino I	62	Pecos	150	80	32.3%
Sherbino I	91	Howard	58.8	80	29.9%
Sherbino II	63	Pecos	145	80	33.4%
Silver Star I	40	Erath	60	80	34.9%
Snyder Wind Energy Project	35	Scurry	63	105	28.2%
South Plains	115	Floyd	200	80	46.9%
South Plains	116	Floyd	300.3	90	40.9%

Table A.6: Details for Sites Named So - Wo

Wind Plant	SITE #	County	Capacity (MW)	Hub Height (m)	NCF (%)
South Trent Mesa	121	Nolan	101.2	80	37.0%
Southwest Mesa	122	Crockett	80.25	50	22.9%
Spinning Spur 2	120	Oldham	160.95	80	43.4%
Spinning Spur 3	119	Oldham	194	80	49.2%
Stanton Wind	123	Martin	120	80	36.5%
Stephens Ranch	117	Lynn	164.68	80	40.1%
Stephens Ranch	118	Borden	211.22	80	41.2%
Sweetwater	124	Nolan	98.8	80	37.0%
Sweetwater	125	Nolan	135	70	32.6%
Sweetwater	126	Nolan	135	80	34.0%
Sweetwater	127	Nolan	105.8	80	32.9%
Sweetwater	128	Nolan	80.5	80	33.2%
Sweetwater 1	129	Nolan	37.5	80	37.0%
Trent Mesa	132	Nolan	150	65	33.8%
Trinity Hills	133	Archer	225	80	30.8%
Turkey Track	134	Nolan	169.5	80	33.4%
Tyler Bluff	135	Cooke	125.6	80	36.3%
Wake	137	Floyd	257.26	80	50.3%
Whirlwind Energy Center	138	Floyd	59.8	80	39.9%
Whitetail	37	Webb	92.34	80	32.4%
Willow Springs Wind Farm	108	Haskell	250	80	38.5%
Windthorst-2	140	Archer	67.62	80	38.4%
Wolf Ridge Wind	139	Cooke	112.5	80	35.5%
Woodward Mountain I	142	Pecos	82.5	50	26.4%
Woodward Mountain II	141	Pecos	77.22	50	26.6%

APPENDIX B - COUNTY STATISTICS

Table B.1: Annual Energy Production by Country of Plant Centroid

County	AEP (GWh)	Rank
Archer	1265.5	20
Baylor	513.9	44
Borden	1636.1	15
Briscoe	495.4	45
Cameron	825.6	29
Carson	4139.6	3
Castro	975.1	26
Clay	658.8	36
Coke	418.5	50
Comanche	709.8	35
Concho	583.7	39
Cooke	750.2	32
Crockett	161.1	54
Dawson	725.3	33
Deaf Smith	752.2	31
Dickens	574.7	42
Donley	714.0	34
Erath	479.4	48
Floyd	4763.1	2
Glasscock	2618.7	6
Haskell	1673.3	13
Hemphill	1116.9	23
Hidalgo	867.9	28
Howard	1071.0	24
Jack	1274.6	19
Jim Hogg	326.1	53
Kenedy	2495.2	9
Kent	89.6	55
Kinney	343.7	52
Knox	492.8	47
Lynn	579.0	41
Martin	384.1	51
McCulloch	598.5	38
Mills	1386.5	17
Mitchell	995.0	25
Nolan	5802.5	1
Nueces	815.1	30
Oldham	1450.1	16
Parmer	880.5	27
Pecos	1884.3	11
Randall	649.5	37
Reagan	1183.1	21
San Patricio	1155.1	22
Scurry	3520.8	4
Shackelford	1667.8	14
Starr	1826.2	12
Sterling	2968.5	5
Taylor	2306.8	10
Tom Green	533.1	43
Upton	583.5	40
Val Verde	493.5	46
Webb	2569.5	7
Wilbarger	1355.6	18
Willacy	2545.7	8
Winkler	449.2	49