Hourly Wind and Solar Generation Profiles (1980-2021)

PREPARED FOR:
ELECTRIC RELIABILITY COUNCIL OF TEXAS (ERCOT)

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DOCUMENT HISTORY

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1. EXECUTIVE SUMMARY

UL Services Group, LLC.[1.1] was retained by the Electric Reliability Council of Texas ("ERCOT" or the "Client") to generate hourly power profiles for 38.0 gigawatts (GW) of operational and planned wind, 22.2 GW of operational and planned utility-scale solar, and 7.45 GW of hypothetical utility-scale solar for the period of January 1, 1980 through December 31, 2021. The purpose of this work is to support ERCOT's various modeling and analysis efforts. The current study was predated by similar works, most recently UL (2021).[1.2]

Historical meteorological conditions were simulated on a 9-kilometer grid over the state of Texas using the Weather Research and Forecasting (WRF) model to obtain the variables necessary for power conversion. Model data were adjusted with surface measurements to ensure the annual, seasonal, and diurnal mean wind speed and irradiance patterns (including ramping characteristics) are accurately represented. Results show that the adjusted model time series capture the dynamic behavior of annual, monthly, and diurnal wind speeds and solar irradiance. Other meteorological variables such as temperature, air density, relative humidity, precipitation, and turbulence intensity also served as inputs to the power conversion software.

Wind and solar plant specifications were compiled from data provided by ERCOT, along with numerous other sources. The plant layouts and other static details of operational plants were used to model each plant as accurately as possible. Measured generation data were supplied for wind and solar plants, as well as the plant's estimate of potential generation (without curtailment). Substantially more observed generation was incorporated into this year's work. The data were filtered and periods of high-quality, uncurtailed generation data were used to validate and adjust the modeled time series at operational wind and solar plants.

Hourly wind power profiles were generated at 213 operational and planned sites with Openwind, UL's plant design and optimization software used for energy production estimates. The adjusted WRF time series and plant characteristics were used to simulate hourly net wind power generation for two scenarios: generation with standard availability losses and generation with adjusted availability losses that included only planned maintenance (thus omitting unplanned or random outages). Operational and planned plants were modeled collectively, to include the effect of additional, upstream wake losses anticipated from nearby plants. Of the 213 wind time series modeled, 58 represent new plants or unit codes not modeled in the previous work. No hypothetical wind plants were simulated in 2022.

The modeled wind generation at operational plants was adjusted to account for non-standard and site-specific plant losses, such as turbine availability or site-specific power curve derating behavior, that were not explicitly modeled in Openwind. At each operational plant, an adjustment was developed using concurrent observed and modeled generation data. For operational or planned plants with an insufficient data record, a composite adjustment was developed and applied. The plant-specific adjustments were developed using the standard availability modeled generation data and applied to both the standard availability and the adjusted availability time series.

The final wind power generation results were evaluated for reasonableness and compared to historical wind generation. The net capacity factor (NCF) of the modeled generation time series with standard availability range from 20.5% to 53.7% for the operational plants. The final dataset has a bias of less than 1% and an hourly coefficient of determination (R^2) of 0.91 for the aggregate

[1.1] Formerly known as AWS Truepower (AWST).

[1.2] Rojowsky, K, Gothandaraman, A. 2021. Hourly Wind and Solar Generation Profiles. Prepared for the Electric Reliability Council of Texas. Technical Report prepared for ERCOT by UL. Reference number 21-03-36658 generation. The modeled wind generation time series are shown to well capture the seasonal and diurnal cycle of observed generation, as well as the ramping behavior.

The hourly averaged irradiance was converted to solar generation using UL's latest power conversion software at 164 operational and 149 hypothetical (single- and dual-axis) utility-scale plants. Of these, 10 hypothetical plants and 103 operational plants (or unit codes) were new to the 2022 analysis. For the hypothetical sites, the future technology and scenario assumptions were retained from UL (2021). No distributed generation solar PV profiles were modeled in 2022.

Results show that the overall PV generation values align well with expectations on a monthly, diurnal, and annual basis, and that ramping statistics appear to reasonably depict fluctuations in power generation. The operational plants have mean NCFs ranging from 22.2% to 31.4% with an aggregate bias of 0.02% on generation and an hourly coefficient of determination (R^2) of 0.95.

2. INTRODUCTION AND BACKGROUND

UL has collaborated with ERCOT since 2012 to simulate hourly generation profiles across its service territory. Modeling wind and solar generation fleets is a challenging task that seeks to balance the required model inputs with an efficient process to reproduce plant behavior that aligns with historic weather patterns. This requires the use of state-of-the-art modeling techniques that are updated continuously as industry knowledge expands and rapidly evolves. Over the past decade, new methods have been applied in the development of ERCOT's hourly generation profiles including updated or new atmospheric models, initialization data, resource assessment methods, power conversion software tools, and adjustment processes. Understanding the similarities and differences between methods used to create each version of profiles is important to its application, and therefore references to previous work are provided throughout this report.

The first series of power profiles simulated wind generation for the period of 1997 – 2011. This dataset was updated through 2014 using consistent power conversion methods and composite power curves. In 2015, UL began using an updated source of modeled atmospheric data, the Weather Research and Forecast Model (WRF), and the previous wind profiles were recreated (1997-2014) using the variables from WRF as input to UL's power conversion method. All other wind resource assessment and power conversion processes and specifications remained static. This dataset was updated through 2017 using the same methods and input parameters by appending new model data and converting it to power. In 2018, hourly wind profiles were simulated for an extended historical record (1980-2017) using the 2017 fleet configuration. 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. Modeled plants were adjusted to historical data to capture the effect of plant-on-plant wakes without modeling them explicitly. In 2020, two significant methodology advancements were made. First, a new dataset provided the model initialization and boundary conditions i.e., ERA5 — the fifth-generation reanalysis dataset provided by the European Center for Medium Range Weather Forecasting. Second, wind profiles were now generated using Openwind, UL's plant design and optimization software used for high-fidelity energy production estimates. Profiles were modeled for two scenarios. The first scenario included only operational plants. The second scenario included both operational and hypothetical wind farms, so that hypothetical profiles include the effect of additional wake losses from nearby operational wind plants. The wind profiles were modeled in this manner (with additional plants added to the fleet annually) until the current work, in which hypothetical plants have been omitted from modeling.

In 2017, UL began simulating solar PV generation across the ERCOT territory. A site screening was performed for both utility-scale solar photovoltaic (PV) plants and distributed solar PV resources (DPV) across the state of Texas, and hourly solar generation profiles were developed for 1997-2015. This work was updated in 2019 and spanned the years 1980-2018 to provide concurrent solar and wind generation data sets. The fleet of operational and planned utility-scale plants modeled increased substantially, and additional hypothetical plants were identified from the previous site screening. Updated technology assumptions were used for modeling the hypothetical utility-scale PV and DPV profiles, and the adjustment to historical data was improved as more historical data became available. In 2020, the fleet was updated to include the newest planned and operational utility-scale PV plants. UL also developed a new method to estimate rural distributed rooftop capacity and simulated its hourly generation for each of ERCOT's six Capacity, Demand, and Reserves (CDR) zones. The same fleet configuration was simulated in 2021, again with updates to include the newest utility PV additions as well as method updates to better reflect hour-ending averaged irradiance.

Current methods were applied to convert the meteorological conditions into hourly power for 38.0 GW of operational wind; 22.2 GW of operational and planned solar; and 7.45 GW of hypothetical utility-scale solar for the period of January 1, 1980, through December 31, 2021. DPV profiles were not included in the current work. This report summarizes the methods and results and is divided into the following sections:

Section 3 describes the methods used to develop the modeled atmospheric time series using a state-of-the-art Numerical Weather Prediction model for each operational and hypothetical location. Resource validation and adjustment are described, as well as new initialization data and the application of a microscale model for wind.

Section 4 describes the wind power conversion process using Openwind, a state-of-the-art wind resource assessment and optimization software, including the plant specifications used as input for operation plants, operational data available for validation, and the results.

Section 5 describes the specifications used for utility-scale operational and hypothetical (single and dual-axis tracking) solar PV plants, the composite technology applied, and the operational data available for validation.

Section 6 summarizes the validation and results for the utility-scale operational and hypothetical utility-scale solar PV plants.

Section 7 provides end-users with a summary of assumptions and potential sources of bias in the hourly profiles to help guide their future use and application.

3. ATMOSPHERIC MODELING, VALIDATION, AND ADJUSTMENT

3.1 Mesoscale Modeling

Historical meteorological conditions were simulated over the state of Texas using the Weather Research and Forecasting (WRF) model, a leading open-source numerical weather prediction (NWP) model.[3.3] The WRF model was initialized with ERA5, the fifth-generation reanalysis dataset provided by the European Center for Medium Range Weather Forecasting.[3.4]

WRF simulations were carried out to model the atmospheric circulation for the 1980 to 2021 study period to obtain the variables necessary for estimating wind and solar power production at each site. WRF was set up to run two nested grids simultaneously over the project area with horizontal grid spacings of 27 and 9 kilometers (km). Further details of the WRF model setup can be found in UL (2020).[3.5] The final model simulation includes both the ERCOT service area and nearby adjacent land areas to provide a complete dataset for the period of January 1, 1980 to December 31, 2021. Simulated meteorological values required for solar PV and wind power production models were retained on an hourly basis.

3.2 Resource Validation and Adjustment

Before converting the modeled meteorological time series to plant production, it is first necessary to correct for biases to ensure accuracy of the modeled wind and solar resource. This was done by scaling the WRF meteorological variables to match 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 to tune the modeled variables to observed values.

The resource adjustment process followed the methods outlined in UL (2020). The atmospheric variables for wind were adjusted using wind speed data from 39 tall towers. For solar, the model irradiance was adjusted using solar irradiance measurements from 13 reference locations.

The 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 capture the dynamic behavior of annual, monthly, and diurnal wind speeds, with an average bias of -0.6%.[3.6] The root-mean-squared error (RMSE) after adjustment is 4.2% for wind speed.[3.7] The adjusted WRF wind speed and other meteorological variables such as temperature, air density, relative humidity, precipitation, and turbulence intensity served as inputs to the Openwind software used to create the power profiles.

High-quality solar irradiance measurements (both GHI and components, when available) were used to validate and adjust the modeled irradiance time series.[3.8] Data from 13 reference stations were compiled and used to adjust the modeled irradiance resource. The frequency distribution of the

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[3.3] 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.

[3.4] Available at: https://www.ecmwf.int/en/forecasts/datasets/reanalysid-datasets/era5

[3.5] Rojowsky, K, Gothandaraman, A , Beaucage, P. 2020. Hourly Wind and Solar Generation Profiles. Prepared for the Electric Reliability Council of Texas. Technical Report prepared for ERCOT by UL. Reference number 19-08-027944

[3.6] The percentage bias is the sum of the differences between the simulated and observed values divided by the sum of the observed values, multiplied by 100. A negative percentage bias indicates that the model underestimates simulated values on average, whereas a positive value indicates overestimation of the simulated values.

[3.7] Root mean squared error (RMSE) is the square root of the average of all the squared errors (differences between observed and simulated values). RMSE is a good predictor of dataset accuracy and is sensitive to large errors. The RMSE has been normalized (divided by) the average observed resource for context.

[3.8] GHI is defined as the total solar radiation received on a surface horizontal to the ground. It is comprised of direct beam radiation and diffuse radiation scattered by atmospheric constituents.

modeled irradiance time series was adjusted to better reflect the distribution of observed values. This process adjusts both the means and the extremes of modeled irradiance data and results in a more accurate representation of clear, partly cloudy, and cloudy days. The adjustment reduced the annual irradiance bias at all thirteen validation stations to well within reasonable limits (and measurement uncertainty), resulting in an average bias of -2.0% for GHI.[3.6] The root-mean-squared error (RMSE) after adjustment is 3.8% for GHI.[3.7]

3.3 Mesoscale-Microscale Wind Modeling

The accurate prediction of a wind plant’s energy production is dependent upon a detailed understanding of the spatial distribution of the wind resource across the project area. UL independently pioneered a method to couple a mesoscale model and a microscale model to characterize the wind resource at spatial resolutions on the order of 10 to 100 meters.[3.9] UL's modeling system, known as SiteWind, relies on a mesoscale model to properly simulate the atmospheric flow up to the meso-gamma scales (~1 km). The mean wind flow modeled by the mesoscale model is downscaled to a 200-m grid spacing using a diagnostic mass-conserving model called WindMap. The WindMap model is a mass conserving model that ingests mesoscale NWP model outputs and computes the three-dimensional wind field. WindMap attempts to retain as much information as possible from the mesoscale NWP model while accounting for the high-resolution terrain elevation and land cover data. The WindMap model outputs are stored in binary wind resource grid (WRB) files, which are later used by the Openwind software to extrapolate the adjusted WRF meteorological time series to the turbine sites and estimate wind power generation.

4. WIND GENERATION PROFILES

4.1 Operational and Planned Wind Plants

A total of 213 operational and planned wind plant profiles were modeled in this study. The static plant details for previously modeled sites were re-used from UL (2021), except for plants at which repowering activity was identified. For repowered plants, the turbine coordinates and power curves were updated as necessary. The new wind plants added in 2022 are represented by site numbers 5000 through 5057. These new plants achieved commercial operation between 2020 and 2021. Details for these plants were compiled and processed as described in UL (2020). The counties represented by the operational and planned units are highlighted in Figure 4.1 (the counties which contain new plants are shaded dark red). For each new wind plant, the layouts were compared to static plant details and aerial imagery, when possible. Plant capacity assumptions were compared to historical generation data and outside sources of information, e.g., ERCOT Seasonal Assessment of Resource Adequacy (SARA) reports and data queried from ERCOT’s Resource Integration and Ongoing Operations (RIOO) system.

Each plant’s turbine model and the manufacturer's power curve were used to simulate the operational unit at the installed hub heights. Although plant-specific power curves were not available, wind turbine and power curve details were updated to align with regional expectations given UL’s extensive industry knowledge. For some units, the RIOO turbine megawatt (MW) ratings did not exactly match the manufacturer’s standard power curve ratings (representing a particular power mode variant). For these unit codes, generic performance settings were developed to best approximate the expected behavior of the variant or a site-specific power curve. UL identified plants at which to enable a turbine

[3.9] Brower, M.C. (1999). Validation of the WindMap Program and Development of MesoMap. Proceedings from AWEA's WindPower conference. Washington, DC, USA.

model-specific high temperature threshold by evaluating the observed generation at each plant or unit code.

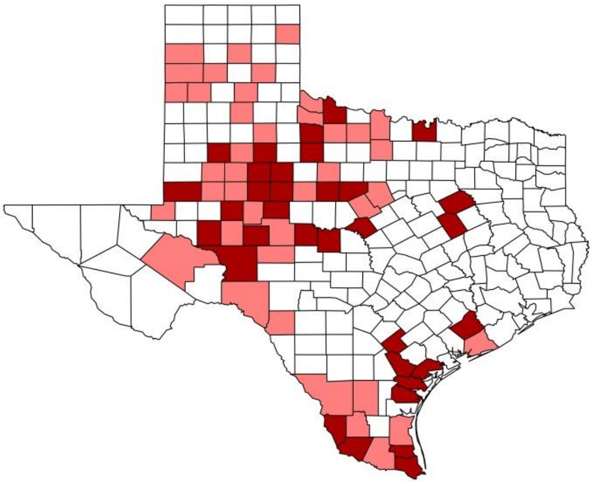

Figure 4.1: Counties with Operational & Planned Wind Plants Modeled

4.1.1 Operational Data Review

Operational wind plant production data were reviewed to determine the period of valid data for each individual plant that was subsequently used for modeled time series adjustment. The valid period is defined as the period of generation following each plant's "break-in" period, once it has achieved its "fully-waked" condition. UL assumes a typical break-in period of four months (minimum) before plants are running at peak efficiency. All observed generation data available from each plant for the period of January 1, 2016 through December 31, 2021 were evaluated, and substantially more measurements were incorporated into this year's work.

Historical hourly generation data from operational plants were used to adjust the modeled plant profiles to account for turbine and plant underperformance, plant availability, power curve variants, generator heating or cooling packages, and other plant-specific losses that were not explicitly modeled. The historical generation data includes the actual, measured power generation (including 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 expected, uncurtailed power generation at actual plant availability. UL used the greater of the observed power and the HSL to help define the valid "historical" period to be used in the adjustment process.

The historical plant data were screened, filtered, and truncated as necessary before being used in the modeling process. The plant's break-in period was filtered out of the historical period, and the remaining data from each plant was quality controlled via UL's latest methods.[4.10] The dataset was then truncated to include only the period of data after which all upstream wind farms were built and operational (the "fully waked period"). 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". The remaining

[4.10] The current process of screening observed generation data builds upon the methods described in UL (2020), but also considers additional criteria such as a step test (excludes observations where the step between sequential observations is found to fall outside of a given range) and power curve test (excludes observations where the difference between actual and potential production is found to fall outside of a given range).

data available for each plant was considered the "valid" period for use in adjustment and validation processes. Only plants with at least one year of operational data past the break-in period were adjusted and validated using their plant-specific generation data; the remainders were adjusted with a composite adjustment described in Section 4.3. Of the 213 operational and planned plants, 187 wind plants were considered by UL as being past their break-in period.

4.2 Wind Power Generation

Hourly wind power profiles were generated at 213 operational and planned sites. The adjusted WRF time series (Section 3.2) served as input to Openwind, UL's plant design and optimization software used for energy production estimates.[4.11] Site-specific plant characteristics were used to simulate hourly wind power generation across all sites. The following section describes the Openwind setup and configuration used to simulate gross and net energy production, as well as plant losses.

4.2.1 Openwind Configuration

The Openwind model simulations were set up according to UL (2020). The spatial distribution of the wind resource was obtained from binary wind resource grids (WRBs), generated by UL's Windmap (the coupled mesoscale-microscale modeling system described in Section 3.3). Terrain elevation and surface roughness maps were imported from the WindMap simulations. Adjusted WRF meteorological time series (Section 3.2) from each wind plant were also imported into Openwind as "virtual meteorological masts" to adjust the resource grid and provide hourly time series, extrapolating the wind resource and ancillary variables to each turbine location. Turbine characteristic files were created (or obtained from the previous study) for each of the operational and next-generation turbines; these files include parameters for the hub height and rotor diameter, power and thrust curves, cut-in, cut-out, and cut-back-in wind speeds, and extreme temperature shutdown.

The Openwind time series energy capture module runs the meteorological time series at each turbine through the respective power curve and estimates gross wind power generation, adjusting for the effects of turbulence intensity and air density on the power curve. Data from adjacent heights are used within Openwind for extrapolating to any turbine-specific hub heights that are between these mesoscale model levels. Details of the energy loss calculations to estimate net power are given in the following section.

The time series energy capture module was run for two scenarios. Both scenarios included the operational and planned wind farms. The first scenario was simulated using standard availability losses, and the second scenario was simulated using adjusted availability losses in which unplanned maintenance or forced outages were removed (described in the following section).

4.2.2 Plant Losses and Availability

The net energy production is derived by subtracting all the wind plant losses from the gross energy and represents the total power at the electrical connection point of the wind farm to the grid (typically a substation). UL estimated gross and net energy production, including losses for the following categories: wake, availability, environmental, and electrical. Losses not included in this simulation were: blade degradation, curtailment, and turbine performance. Blade degradation is minimal and difficult to estimate accurately, therefore it was omitted. All profiles were modeled with no grid curtailment losses. UL did not have a clear indication of turbine performance issues in the ERCOT territory or specific turbine de-rating behavior, and therefore assumed that the power generation of all turbines followed their advertised power curve or a known variant. However, the final, adjusted model profiles at operational plants account for plant-specific turbine performance losses because of their

[4.11] Openwind version 4545

adjustment to historical HSL data (which reflects the real-time, expected and uncurtailed power generation). No force majeure was considered.

UL uses the Deep Array Wake Model (DAWM) inside Openwind to calculate wake losses.[4.12] The DAWM is comprised of two separate wake models operating independently: (1) the Eddy Viscosity model (based on the Navier-Stokes equations rate of wake dissipation) [4.13] and (2) a model designed to better capture wake losses in deep (multi-row) arrays of wind turbines.[4.14] In combining the two models, the DAWM implicitly defines "shallow" and "deep" zones within a turbine array. In the shallow zone, the direct wake effects of individual turbines dominate, and the unmodified Eddy Viscosity (EV) model is used to calculate wake deficits; in the deep zone, the deep-array effect is more prominent, and a surface roughness-based model is employed.

In addition to wake effects from turbines within the same wind farm (i.e., internal wakes), the turbine-induced wakes from neighboring wind farms located upstream can impact the energy production at any particular plant. Openwind captures these plant-on-plant wake losses (i.e., the "wind farm shadowing effect").

Time-varying wind plant availability was modeled in the Openwind software using a Markov chain method.[4.15] The availability model simulates the change in the number of turbines that are available to generate power from one time step to the next. Availability losses occur when some turbines in a project, or the entire project, are unavailable for some reason when they could be generating power. This can occur due to turbine faults or a failure of one or more turbine components. It can also be caused by a failure or shutdown of the power grid or substation. Plant start-up problems, repair delays, fleet-wide turbine retrofits, or systemic operational issues can cause extended periods of downtime that reduce the long-term average availability. An average availability loss of 2-10% is typically encountered in operations, and can vary widely amongst plants. [4.16]

The main component of the Markov chain is a transition matrix, which indicates the probability of transitioning from any given current state to any other state in the next time step. In Openwind, for a given availability state, specific turbines are selected at random to be switched off. This allows the effect of availability on wake losses, for example, to be correctly modeled. From one time step to the next, only the minimum number of turbines that need to be switched on or off to arrive at the next availability state is selected in order to model the persistence of turbine downtime patterns. To prevent wind turbines from going on and off constantly in an unrealistic way, once a turbine is shut down due to maintenance or an outage, the model keeps it down until the availability rises enough that it must be turned back on.

Various environmental losses are calculated in Openwind using the WRB-adjusted resource time series at each turbine location. These losses include low and high-temperature shutdowns, and high wind hysteresis. Openwind models the low- and high-temperature shutdown or power curve derating behavior for each turbine type using several wind turbine control set points such as the minimum and maximum threshold, if available and applicable. High wind hysteresis is accounted for using the

[4.12] Brower, M. C. and N. M. Robinson, (2012) The Openwind Deep Array Wake Model – Development and Validation, Technical report from AWS Truepower, Albany (NY), USA. 16 pp.

[4.13] "Openwind Theoretical Basis and Validation. Technical report from AWS Truepower. Albany (NY), USA. 26 pp.

[4.14] Loosely based on Frandsen, S.T. (2007). "Turbulence and Turbulence-Generated Structural Loading in Wind Turbine Clusters". Technical report from the DTU Wind Energy (Risø-R-1188), Roskilde, Denmark. 130 pp.

[4.15] Plant availability includes planned and unplanned turbine outages, grid or substation shutdowns, and any repair or restart times.

[4.16] Brower, M.C. et al. (2012). "Wind Resource Assessment: A Practical Guide to Developing a Wind Project". Wiley, 296 pp.

waked wind speeds and the appropriate cut-in and cut-out speeds, as well as power curve derating, for each turbine type.

Electrical losses are experienced by all electrical components of a wind farm, including those from the padmount and substation transformers, electrical collection system, as well as turbine power consumption, including any hot or cold weather packages. The electrical efficiency of a wind farm is primarily driven by losses associated with the transformers and the collector system. The Openwind software includes an electrical efficiency model derived from operational data that simulates this behavior. Turbine power consumption consists of electricity used to run equipment such as yaw mechanisms, blade-pitch controls, aircraft warning lights, oil heaters, pumps, etc. The sum of these sources of turbine power consumption is typically much less than 1%.[4.17] The Openwind software includes a turbine consumption model derived from operational data to account for these losses.

Two sets of profiles were provided for the modeled wind plants. One set includes UL's standard availability assumptions (planned & unplanned outages). The other set is the "adjusted-availability" profiles, which only include planned availability losses (i.e., no unplanned maintenance or forced outages). In modeling these profiles, the unplanned availability loss is randomized and planned outages or maintenance follows a schedule (varying on a per-turbine basis). Thus, the wind profiles are modeled with partial plant outages. The availability rates and maintenance schedule are gleaned from UL's experience across North America.

4.3 Adjustment and Validation

The model generation time series were adjusted using the valid historical generation data from operational plants to more accurately reflect real power generation patterns. The main purpose of this adjustment is to account for non-standard and site-specific plant losses, such as turbine availability or power curve derating behavior that were not explicitly modeled in Openwind. For the adjustment process, correction matrices were developed based on concurrent historical and modeled power generation at each plant. The modeled data with standard availability was used for this purpose. The plant-specific matrices were used to adjust the power generation time series at each operational plant with at least one year of valid data. For the operational or planned plants with an insufficient data record (see Section 4.1.1), a composite adjustment was developed from data at the other plants.

The plant-specific (or composite) adjustments described above were applied to both sets of modeled time series, i.e., the standard availability profiles and the adjusted availability profiles. The final generation profiles were examined for reasonableness by plant and as an aggregate for the operational plants with at least one year of historical generation available (i.e., 187 plants of 213 modeled, or 31.2 GW of 38.0 GW total wind capacity modeled). Figure 4.2 and Figure 4.3 provide a comparison of observed data and the profiles modeled with standard availability. The modeled generation time series capture the diurnal cycle and ramp distribution of observed generation reasonably well. The final dataset has a bias of less than 1% and an hourly coefficient of determination (R^2) of 0.91 for the aggregate generation. Figure 4.3 includes the histogram and the frequency duration curve of concurrent, modeled and observed power generation data for the operational wind plants with at least one year of validation data. As shown, the wind profiles capture the dynamic behavior of generation at the operational wind plants.

[4.17] UL identified plants at which to enable a turbine model-specific high temperature threshold by evaluating the observed generation at each plant or unit code.

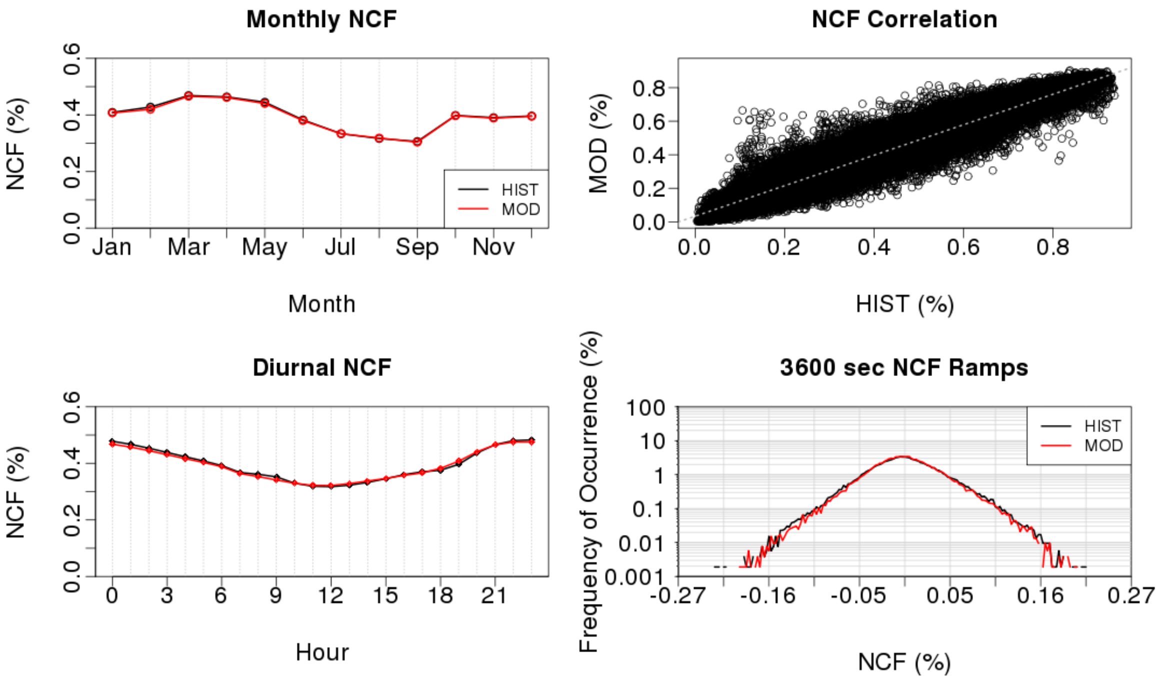

Figure 4.2: Monthly, Hourly (local standard time), Correlation, and 1-Hour Ramp Distribution of Aggregated Net Capacity Factor for Concurrent Observed Generation (black) and Profiles Modeled with Standard Availability (red).

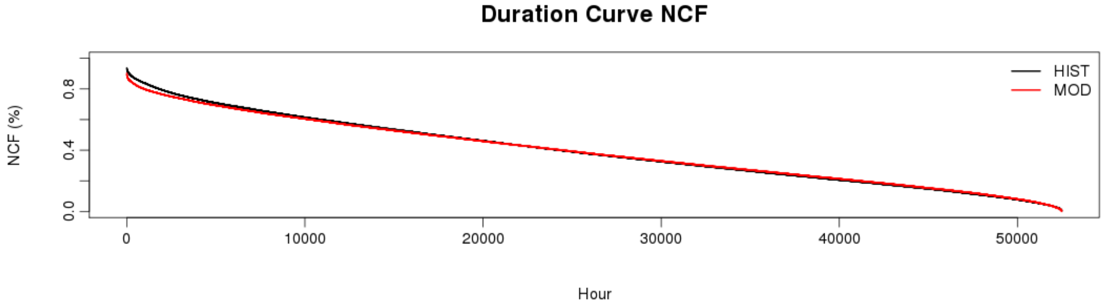

Figure 4.3: Frequency Duration Curve for Operational Wind Plants with Standard Availability

4.4 Wind Power Generation Results

Hourly net generation profiles were simulated for the period 1980-2021 across 213 operational and planned plants within the ERCOT domain (Figure 4.4). The Capacity, Demand, and Reserves (CDR) zones are also shown in this figure. The net capacity factor (NCF) values range from 20.5% to 53.7 (20.8% to 55.5%) for the standard (adjusted) availability profiles. The average net capacity factor across the region increases from 39.0% to 40.4% when removing forced outages (i.e., for the adjusted availability profiles).

The power generation across the ERCOT domain shows a peak in the 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 4.5). An in-depth discussion of weather conditions in the ERCOT territory was provided in UL (2020).

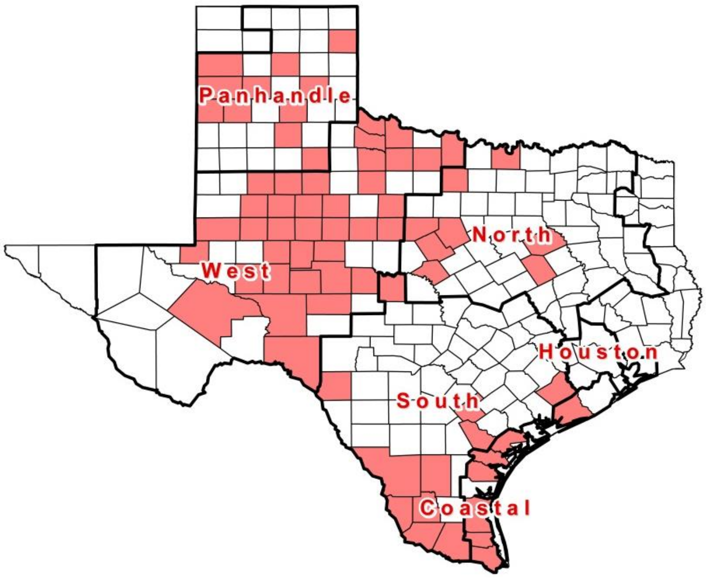

Figure 4.4: Counties Intersecting Operational Wind Plants with CDR Zones Outlined

Table 4.1: Generation Summary by CDR Zone for Operational Wind Plants

Zone	Cap (GW)	Standard Availability		Adjusted Availability	
		Avg NCF	Range NCF	Avg NCF	Range NCF
Coastal	5.4	34.0%	28.3% - 43.1%	35.3%	29.6% - 44.6%
North	2.8	40.4%	28.0% - 49.2%	41.9%	28.7% - 51.0%
Panhandle	4.4	45.0%	37.7% - 53.7%	46.6%	39.3% - 55.5%
South	3.8	38.9%	30.6% - 47.1%	40.2%	31.7% - 48.4%
West	21.6	38.9%	20.5% - 53.0%	40.3%	20.8% - 54.9%
Total	38.0	39.0%	20.5% - 53.7%	40.4%	20.8% - 55.5%

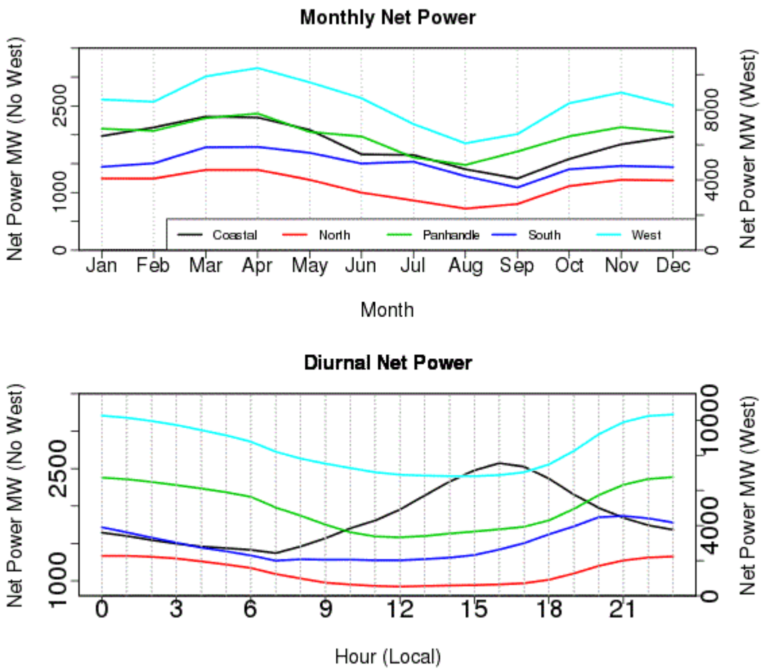

Figure 4.5: Monthly & Diurnal Modeled Net Power (Standard Availability) for Operational and Planned Wind Plants by CDR Zone (local standard time). Y-axis on the right is for the West CDR zone.

5. UTILITY-SCALE SOLAR PLANTS

5.1 Operational and Planned Solar PV Plants

5.1.1 Plant Characteristics

Static plant details for all operational and planned solar PV plants were provided by ERCOT. For most previously modeled sites, the specifications were retained from previous studies (UL 2020 and UL 2021). However, some previously modeled sites were found to have erroneous specifications. Any such discrepancies between the assumed and as-built static plant details have been corrected to the best of UL's knowledge. The static plant details for newly operational and planned plants provided by ERCOT were confirmed with other public and proprietary sources. The plants were classified as operational or planned (non-operational) based on the availability of their generation data and client-provided development status. In 2022, each RIOO unit code was modeled individually,[5.18] as opposed to prior works in which unit codes of the same plant were combined. A total of 164 utility-scale PV time series were modeled representing all the RIOO unit codes provided by ERCOT. This information was reviewed for consistency and compared to information from public sources, as applicable.

5.1.2 Operational Plant Data

Observed generation data concurrent with the modeling period was received from ERCOT and subsequently screened for reasonableness. Data from individual plants provided by ERCOT was not truncated for a break-in period, unless substantial deviation from nameplate capacity was apparent.

[5.18] Exceptions to this are the Horizon Unit 1 & 2 unit codes, which were modeled as one because a distinction between the plant setup for these two could not be made.

The historical generation data for all plants consisted of the hourly high sustainable limit HSL In essence, the HSL reflects the expected, uncurtailed power generation at actual plant availability.

All observed generation data from January 1, 2018 to December 31, 2021 were evaluated for use in this study. The same quality control procedures outlined in UL (2020) were applied. Of the 164 utility-scale plants modeled, 40 plants had greater than 1 year of valid data. The remaining 124 plants had less than 1 year of valid data or no data at all. The utility-scale plants modeled were categorized as follows based on their operational status, the availability of generation data, and knowledge of static plant details:

- operational plants with generation data sufficient for adjustment tuning to operational data; and
- operational or planned plants with less than 1 year of valid generation data meeting QC requirements receiving a composite adjustment.

Plants with bifacial modules were modeled with monofacial technology and adjusted to plant-specific observed generation data, as available. For the bifacial plants with no observed generation, a composite adjustment derived from operational plants with bifacial modules was applied. In this way, the increase in diurnal generation due to bifacial modules is captured by adjusting to historical generation.

5.2 Hypothetical Solar PV Plants

A total of 149 hypothetical, utility-scale PV sites were modeled in the present work (summing to 7.45 GW). This consisted of 139 hypothetical sites from prior studies and 10 sites new to the present study. As previously, the new hypothetical sites were identified based on their resource potential, proximity to key operational or planned utility-scale solar PV plants, and distance to transmission. The counties with hypothetical sites are shown in Figure 5.1, along with the locations of operational and planned PV plants. The same technology specifications were used as in UL (2020), and hypothetical plants were modeled as both single-axis and dual-axis. For an in-depth discussion of how these composite specifications were made, and for the module specifications, see UL (2020).

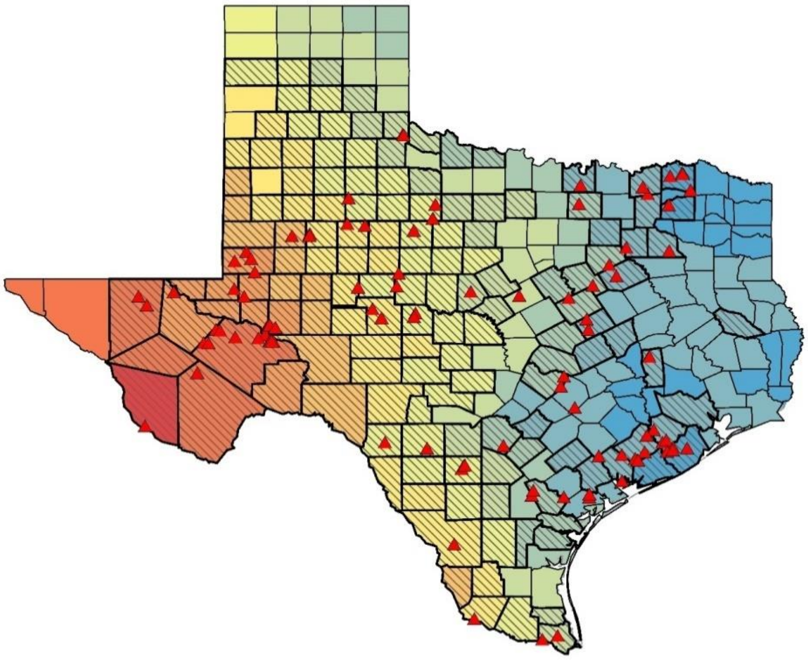

Figure 5.1: Counties with Hypothetical PV Plants (shaded) and Operational or Planned PV Plants (triangles), with GHI Resource as Background (Red = High Irradiance, Blue = Low Irradiance).

6. SOLAR GENERATION PROFILES

6.1 Solar Power Generation

UL simulated hourly generation at the utility-scale sites using the adjusted WRF modeled time series. Atmospheric variables that impact module performance and power conversion were extracted from the WRF numerical data output. The instantaneous WRF modeled irradiance was converted to hourly averaged irradiance using the interval-averaging method from UL (2021). UL's power conversion software, TS2Solar Version 5.3 was to convert the hourly averaged modeled irradiance to solar PV output. Operational sites were modeled with plant-specific parameters provided by ERCOT and verified by UL. The static plant details from UL (2021) were used to model the previously modeled and newly added hypothetical sites.

The power conversion process follows the methodology in AWST (2017)[6.19] and UL (2020). The static loss assumptions used for power conversion can be found in UL (2020).

6.2 Adjustment and Validation

The modeled solar generation data were adjusted using quality-controlled, hourly-ending historical generation data to more accurately reflect real-world power generation patterns. The main purpose of this adjustment is to account for discrepancies in static plant details (e.g., layout, equipment, tilt, tracking characteristics), loss assumptions, and any other deficiencies in the modeling process. All valid data was used from each plant. Periods of underperformance during the mature operational period were retained (aside from pronounced outages or obvious step downs). This allowed the modeled solar generation data to reflect the actual performance of plants in the ERCOT territory. The

[6.19] Rojowsky, K. (2017). Solar Site Screening and Hourly Generation Profiles. Technical report prepared for ERCOT by AWS Truepower. Reference number: 03-16-014484 final adjustment process applied a correction based on the concurrent observed and modeled power generation.

6.2.1 Utility-Scale Solar PV

Historical generation data from operational, utility-scale plants were used to adjust the modeled profiles at all utility-scale PV plants (operational or planned, and hypothetical). All site-specific adjustment matrices were (re)calculated for the present study to include all of the valid generation data available from January 1, 2018 to December 31, 2021. A composite adjustment was applied to the profiles of the operational or planned utility-scale solar plants with less than 1 year of valid data, and to the hypothetical plant profiles.[6.20] Operational plants with bifacial modules received a site-specific adjustment if valid observed generation data were available. For operational or planned bifacial plants with no observed generation, a composite adjustment was calculated from the operational bifacial plants. This adjustment accounts for the increased generation expected due to modules able to convert radiation reflected to the back-side of the module to power.

After adjustment to monthly and diurnal expected values, the overall generation time series were scaled to the observed maximum value at each plant. Therefore, modeled generation will reach 100% of the nameplate MW_{AC} capacity at the operational sites if the generation reaches 100% capacity. For hypothetical sites, the modeled generation reaches 100% of the 50 MW_{AC} capacity.

The final generation profiles were examined for reasonableness at the plant level and as an aggregate for the operational plants with at least one year of historical generation data available. The adjusted modeled generation time series match the observed monthly and diurnal patterns and also capture the observed hourly ramp frequency distribution well (Figure 6.1). The final dataset has a bias of 0.02% on generation and an hourly coefficient of determination (R^2) of 0.95. Depicted in Figure 6.2 is the frequency duration curve for all concurrent hourly historical and adjusted model data for plants that had at least one year of historical generation data (i.e., 40 unit codes of 164 modeled, or 4.0 GW of 22.2 GW total solar capacity modeled). This analysis shows that the final dataset accurately captures the dynamic behavior of utility-scale solar plants.

[6.20] The use of operational data to adjust the hypothetical profiles assumes that the hypothetical sites will operate like the existing operational sites, including availability issues inherent in the observed generation data. Also, deficiencies in the static plant details of operational plants and subsequent modeling process will be reflected in this adjustment. Therefore, the adjusted profiles may represent a conservative lower bound for the generation at future hypothetical sites given historical availability patterns and the static assumptions provided for the operational sites. High-quality operational plant metadata (static data) may benefit future work when adjusting to operational data.

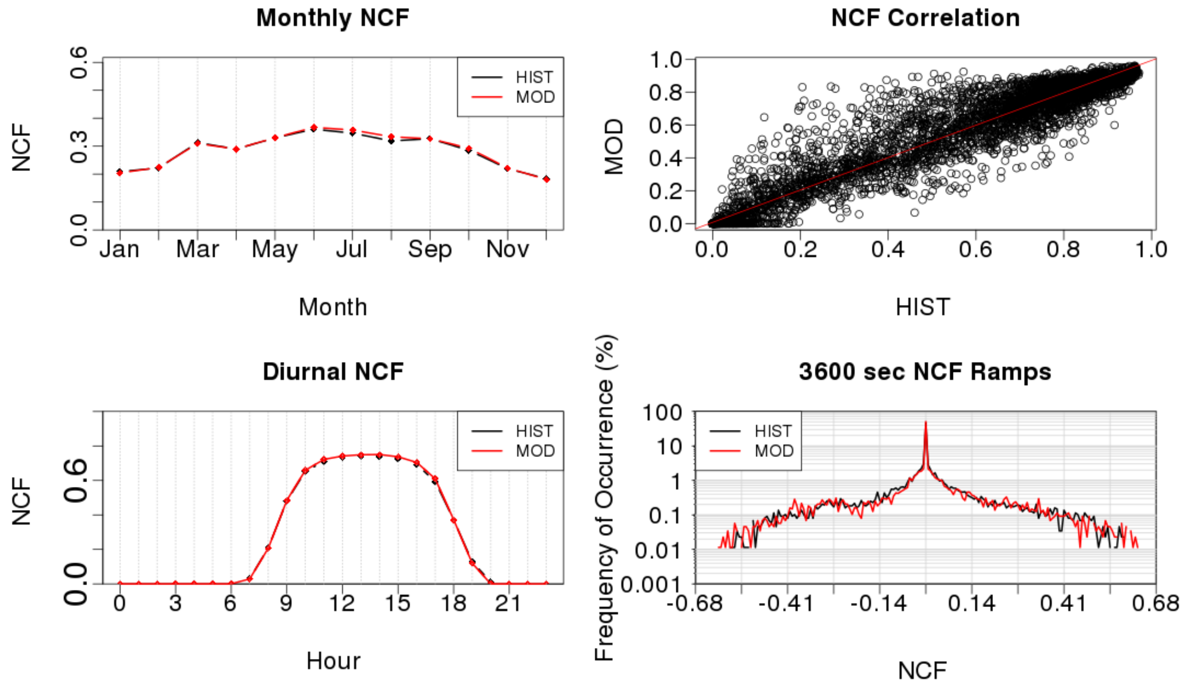

Figure 6.1: Monthly, Hourly, Correlation, and 1-Hour Ramp Distribution of Aggregated Operational Solar Plant Time Series for Concurrent Observed (black) and Modeled (red) Net Capacity Factor with Correlation Plot (local standard time).

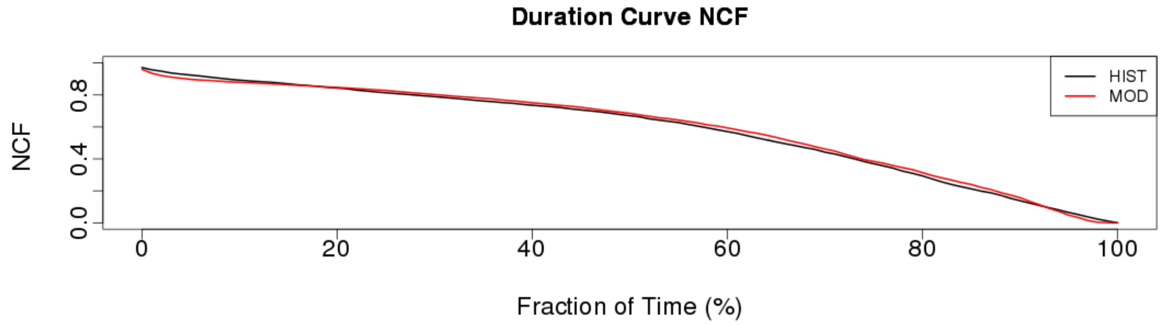

Figure 6.2: Frequency Duration Curve for Operational Solar Plants with Historical Data

6.3 Solar Power Generation Results

Hour-ending time series of PV generation profiles were developed for 149 hypothetical utility-scale sites and 164 operational or planned utility-scale plants for the years 1980-2021.

The range of net capacity factor (NCF) values for each type of site can be found in Table 6.1. The operational plants have mean NCF values of 22.2% to 31.4%.[6.21] The hypothetical plant profiles have mean NCF values of 22.6 to 31.3% (for single-axis tracking) and 23.3 to 31.3% (for dual-axis

6.21 It was noted that some sites, namely a subset of the single-axis tracking sites with less than 1 year of valid observed data, had lower than anticipated generation at the end of days (e.g., at hour 20 or 08:00pm local time). Their short record of valid data required they be treated as planned sites and receive a composite adjustment from the operational tuning. The subset of sites used for adjustment included some operational plants with low generation during the late day. These operational plants were not removed from the adjustment process because their data were deemed valid, albeit low (despite only using data from their period of mature operations after break-in).

tracking). The use of operational data to adjust the hypothetical profiles assumes that the hypothetical sites would operate like the existing operational sites (i.e., with equivalent availability and performance).

The monthly and diurnal mean net power at a sample hypothetical site modeled is shown in Figure 6.3. As expected, the dual-axis profiles exhibit higher power than the single-axis counterparts during midday and in the winter, when dual-axis trackers are better able to maximize production during the sun's low wintertime altitude compared to the single-axis trackers, which are flat midday.[6.22] This difference is more pronounced with increasing latitude (not shown).

Table 6.1: Range of Net Capacity Factors (NCFs) for Modeled Solar PV Time Series

PV Generator Type	Range NCF (%)
Operational and Planned Utility-Scale	22.2 – 31.4
Utility-Scale Hypothetical (Single-Axis)	22.6 – 31.3
Utility-Scale Hypothetical (Dual-Axis)	23.3 – 31.3

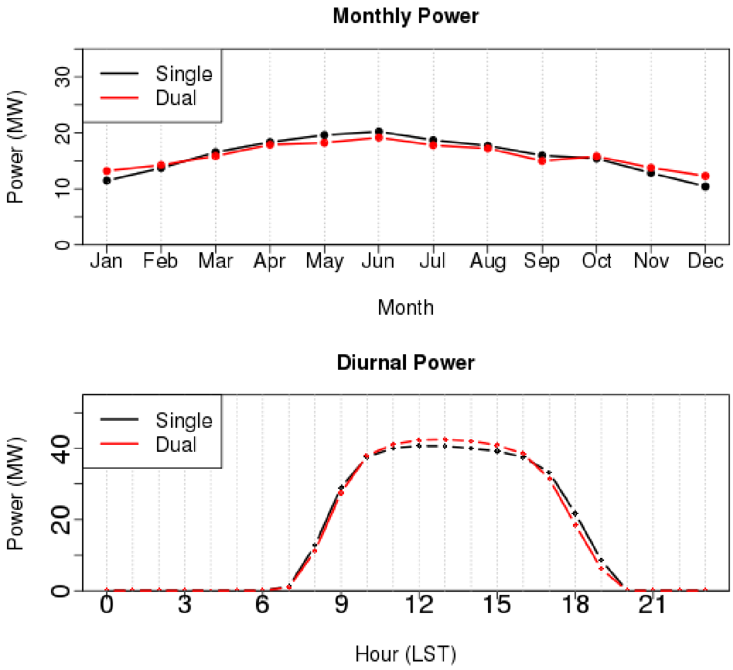

Figure 6.3: Monthly and Diurnal Mean Net Power at a Sample Hypothetical Site Modeled as Single-axis (black) and Dual-axis (red) Tracking (local standard time)

7. DATASET USAGE

The goal of this work was to provide high fidelity power generation profiles for operational and hypothetical wind and solar plants to support regional planning studies. Therefore, it is important to understand the modeling assumptions and methods applied to guide their future use and application.

UL simulated ERCOT's wind power profiles using Openwind, a state-of-the-art resource assessment and power optimization modeling tool used across the wind industry during all phases of project

[6.22] The final generation profiles for the dual-axis trackers exhibit slightly lower NCF during the summertime than their single-axis counterparts, primarily due to the adjustment to historical generation data where this is observed.

development. Openwind calculates plant-level and turbine level losses at each time step including wake, availability, environmental, turbine performance, and electrical losses. Plant-specific characteristics such as plant layout, turbine model, and power curve heavily influence the power generation and wind plant losses on various time scales.

UL adapted the Openwind software allowing for fleet-wide modeling with a high degree of success across large project areas where plant specifications are well documented. These characteristics were defined for ERCOT's wind plants to the best of UL's ability through public and proprietary sources of information. However, in the absence of measured plant-specific losses for this work, UL applied assumptions in the Openwind model based on UL's methods derived from operational plants across North America. These wind profiles reflect a significant change in the methods used to simulate wind power profiles in ERCOT prior to 2020, and therefore a record-to-record comparison with earlier works may not be appropriate.

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

- All plants were modeled for the period 1980-2021 using the most recent (2022) configurations, regardless of the actual commissioning date or any change in plant specifications over time. Information regarding changes in plant configuration or the repowering of operational wind plants (i.e., layout or turbine make/model) were incorporated when possible. No plant-specific information about the software configuration or operational settings was available.
- Plant details did not always align with expectations based on data review. UL and ERCOT discussed deviations and assumptions employed to mimic unknown static details at these plants (e.g., DC/AC ratio for operational solar plants). Some plants may not reach full generation capacity.
- The final wind and solar profiles from previously modeled sites with >1 year of operational data relied on post-processing adjustment using operational data. Substantially more observed generation was incorporated into this year's work. Wind and solar plants with <1 year of operational data were adjusted using a composite adjustment developed from those sites with sufficient data, and therefore would not align with the individual plant operations (as these vary from site to site). It is highly recommended that these sites be re-adjusted when a year or more of actual plant generation data is available.
- The modeled wind data were adjusted to historical generation to account for site-specific losses not captured in the model output. The need for adjustment indicates that input data for the plants may be lacking (e.g., a derating of power curves), or that atmospheric variables contain a bias that affects the Openwind simulation of time-varying losses.
- 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 curtailment that may have been experienced at a wind or solar plant, as is present in the actual generation measurements.
- UL did not have an hourly historical record of the actual turbine availability indicating downtime due to events such as preventive or unscheduled maintenance, and plant or grid outages. Instead, the turbine availability was modeled in Openwind with a Markov Chain to best represent the statistical behavior of turbine availability based on a large number of operational plants in the US. Because plant or turbine-level availability was not explicitly given for any plant, it is possible that the modeled availability does not align with the actual availability at each operational plant.
- Standard methods were applied for cold temperature conditions at wind plants, which seek to optimize related losses (e.g. icing, accretion, melting) over the long-term, not for a specific

event or duration. An advanced icing model is available for wind plants that may more accurately capture these time-varying losses.

The hypothetical PV sites modeled in this study were identified via a high-level identification of allowable land remaining after exclusions and additional assumptions were applied. A detailed analysis below 200-m resolution was not performed, and therefore some sites may not be commercially viable. Factors such as the total area of contiguous land available to build, construct, and operate a solar PV plant with a reasonable cost of energy have not been considered, neither have policy or regulatory constraints.

The wind and solar resource were modeled at a 9-km horizontal resolution. While this resolution captures much of the spatial variability in wind and solar resource across the state of Texas, assumptions need to be made about details in the weather patterns. For example, a mesoscale model such as WRF with grid spacing coarser than 4 or 5 km cannot explicitly resolve cumulus clouds, and thus it must rely on convective parameterization scheme. Rather than physically simulating the lifecycle of individual cloud elements, these parameterizations characterize the bulk effects of various cloud types and their lifecycles based on the environmental conditions present at the grid cell level. Because of this parameterization, the 9-km resolution is generally considered sufficient for hourly solar generation studies by striking a balance between computational time and the need to resolve localized terrain and roughness effects. For both wind and solar power generation studies, accurate environmental resource characterization is fundamental to replicating real-world power generation. UL incorporated observed wind speed and solar radiation data to ground-truth these specific parameters. However, a bias in any ancillary variables such as temperature, turbulence intensity, relative humidity, or precipitation can adversely affect the modeled wind or solar generation.

This dataset was developed specifically for use in modeling and analysis efforts related to the high penetration of wind and solar and its long-term variability. It has been shown that the final modeled dataset accurately represents the historical generation patterns at individual plants and on an aggregate basis. Additional bias correction for atmospheric variables and updated plant specifications may improve the alignment with the operational data, reducing the need for post-processing adjustment in the future. Finally, it should be noted that modeled data provided by this study is not a replacement for onsite measurements.