# Utility-Scale Solar and Distributed Rooftop Generation Profiles for Select Urban Areas

PREPARED FOR:
**Electric Reliability Council of Texas (ERCOT)**

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HOURLY SOLAR GENERATION
(1980-2018)
Texas, USA

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# 1. INTRODUCTION

On behalf of the Electric Reliability Council of Texas (ERCOT), AWS Truepower (AWST), a UL Company (UL), developed hourly solar generation profiles for operational and hypothetical utility-scale plants across Texas, and distributed generation profiles based on four land use classes in the major urban areas of Austin, Dallas, Houston, and San Antonio. The generation period modeled includes 1980–2018 to provide concurrent solar and wind generation data sets.[1.1] This work is predated by the 2017 study, which provided hourly solar generation profiles for utility-scale and distributed generation profiles for the years 1997-2015.[1.2]

In 2017, UL performed a site screening for both utility-scale solar photovoltaic (PV) plants across Texas, as well as distributed rooftop solar PV (DGPV) in major urban areas. Six operational PV plants were modeled with their plant-specific parameters. Future technology assumptions were applied for the hypothetical and rooftop generation, which represented a 4% increase in module efficiency over then present-day 2016 technology.

In 2019, ERCOT commissioned UL to perform an update to the 2017 work. Hourly solar generation was simulated for operational and planned utility-scale plants using revised plant specifications. Generation was also simulated for hypothetical utility-scale plants and distributed generation using near-current technology. Many new operational and hypothetical utility-scale plants are now included. ERCOT has almost 2 gigawatts (GW) of utility-scale solar plants within its service area. Many of these plants became operational after 2016 and therefore are not represented in previous work. Leveraging the site screening results from 2017, additional hypothetical plants have been modeled in counties with planned or proposed plants.[1.3]

Hourly power generation profiles were modeled for the period of January 1, 1980, through December 31, 2018, at 23 operational and planned plants, 139 hypothetical utility-scale sites, and 12 DGPV aggregate sites. In addition to providing a longer record, many updates have been incorporated including additional solar reference station data, modifications to technology assumptions, improvements to the power conversion modeling process, and incorporating more operational data for tuning.

This report describes the methods, results, and validation for the operational and hypothetical hourly power profile development.

# 2. SOLAR PLANT SPECIFICATIONS

Utility-scale and distributed solar PV sites across the ERCOT service area were designated for solar generation modeling. These sites reflect current operational or planned utility-scale PV plants, hypothetical utility-scale PV plants in areas favorable for solar plant development, and potential distributed generation within four metro areas of Texas.

The utility-scale plants modeled were categorized based on their operational status, the availability of generation data, and knowledge of static plant details. This information facilitated the hypothetical site

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[1.1] Rojowsky, K., P. Beaucage and C. Johanson (2018). Hourly Wind Generation Profiles for Operational Plants (1980-2017). Technical report prepared for ERCOT by UL. Reference number: 17-12-019252.

[1.2] Rojowsky, K. (2017). Solar Site Screening and Hourly Generation Profiles. Technical report prepared for ERCOT by AWS Truepower. Reference number: 03-16-014484.

[1.3] ERCOT. Monthly Generator Interconnection Status Report. Available at http://www.ercot.com/gridinfo/resource selection process to ensure adequate geographic representation of anticipated future development and enabled the adjustment of modeled data using observed generation. Three types of utility-scale PV plants were modeled:

- Operational: centroid coordinate specified, PV module(s) and inverter(s) known; tuning to operational data
- Planned: centroid coordinate specified, PV module(s) and inverter(s) known; composite adjustment from operational tuning
- Hypothetical: site locations of screen sites chosen by ERCOT; utility composite specifications (50 $MW_{AC}$ capacity); composite adjustment from operational tuning

UL used a Geographical Information System (GIS) based approach to identify development constraints and build out potential sites for utility-scale PV and distributed PV generation across the ERCOT territory. The methods used to identify hypothetical sites in the present study leverage results from the preceding work. A review of these methods follows below, while complete reporting can be found in AWST (2017).[1.2]

## 2.1 Operational & Planned Utility-Scale PV Plants

Solar 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 centroid coordinates and static plant details including location, installed MW capacity (AC and DC), county, tracking type, and the make and models of the inverter and modules at each plant based on Resource Asset Registration Form (RARF) information. Their locations were reviewed via satellite imagery and adjusted, as appropriate. Visual inspection was not possible for planned plants (under construction) or for several existing plants in areas where aerial imagery is not current. The static plant details were verified using various resources to cross-check the plant details and to help reconcile differences between RARF unit code information and ERCOT interconnection agreements. The tracking system types for operational and planned units were verified via public sources of data available online. Additionally, the tracking system type for operational units was verified by reviewing hourly plant generation data, as well as aerial imagery.

Once the layouts were confirmed, the estimated installed DC/AC capacity for each plant was calculated from the respective number of modules and inverters. UL’s estimated capacity was compared to the RARF installed capacity for each unit code. The RARF installed AC capacity was also verified against the maximum historical power generation data from ERCOT. UL’s expected installed capacities were equivalent to the RARF installed capacities at the majority of sites. Wherever small discrepancies did arise, UL worked with ERCOT to finalize the sites for modeling.[2.4]

A total of 25 individual generating units, as designated by their RARF unit code name, were modeled. Each plant was classified as operational or planned (non-operational) based on the availability of generation data and client-provided information. RARF unit codes were aggregated for multi-phase projects if the phases were geographically aligned such that no obvious distinction could be made between their layouts. Following the review and consolidation process, a total of 23 plants were modeled, representing all 25 RARF unit codes provided by ERCOT. Once the final plant configurations were assigned, the modeled plant profiles were validated and adjusted using available historical generation.

[2.4] At some sites, the $MW_{AC}$ capacity provided by ERCOT and used for modeling does not match that which UL would expect given the number of inverters specified and nominal inverter capacity. It is suspected that the $MW_{AC}$ capacity at some plants was not listed based on the inverter capacity at standard test conditions (STC). The $MW_{AC}$ capacity provided by the Client was used at all sites, even if this resulted in a decimal number of inverters.

### 2.1.1 Operational Data Collection and Screening

One year of observed generation data concurrent with the modeling period was received from ERCOT and subsequently screened for reasonableness. Data from individual plants start on the date that ERCOT approved commercial operations, and therefore did not require truncating for a break-in period. The historical generation data for most plants consisted of the hourly high sustainable limit (HSL) for each record. The HSL refers to the limit established by the plant owner/operator (i.e., 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 which is monitored in real-time and also available historically for each plant registered with ERCOT as a Generation Resource.[2.5]

The remaining historical generation at each plant was quality controlled as follows. Historical power generation was verified not to exceed the plant capacity. The record-to-record variability was analyzed, verifying that concurrent records of generation were not identical.[2.6] Fluctuations in generation were evaluated to assess any unaccounted for change in capacity or temporal reporting convention (i.e. verifying all generation time series are reported in UTC or local standard time, not a mix of multiple time conventions). Datasets were discarded if they did not pass these quality-control tests, have sufficient period of record, or provide meaningful values for validation and adjustment. Of the 20 plants modeled for which historical generation data were available, data for 14 plants spanned all of 2018; four plants had data for at least 6 months in 2018; and two plants had under one month of data. Additional generation data from outside the modeling period (January-June 2019) were incorporated into the adjustment of modeled data from these two plants.

## 2.2 Hypothetical Utility-Scale Plants

### 2.2.1 Hypothetical Plants Site Selection

UL performed a solar site screening for ERCOT in 2017, which included many sites that were not previously modeled.[1.2] Using these results, UL and ERCOT worked to identify many new hypothetical utility-scale PV plants for the present study to expand the geographic distribution of the sites. In total, 139 hypothetical utility-scale sites were modeled, with a single site in each county represented as outlined below.

The hypothetical utility-scale PV plants were identified by first distilling the list of sites modeled in AWST 2017. Of these sites, only those with the highest solar resource were retained for each county (e.g., in the high resource counties of western Texas for which two sites were modeled, the site with lower irradiance was discarded). The remaining sites were retained if they were within counties in the ERCOT service territory.[2.7] The sites were then classified according to their distance to transmission[2.8] and the operational plants being modeled in the present study (Table 2.1). Through this process, 107 out of 125 sites from the previous study were retained.

[2.5] The HSL data is not available for one operating plant; as a Settlement Only Generator (SOG) it is not required to provide HSL data to ERCOT. Historical power generation data, including any plant losses and curtailment, was provided.

[2.6] In UL's experience, power generation data that is stuck on a constant value is often indicative of data transmission issues.

[2.7] The sites for Dallam, El Paso, Hartley, Hudspeth, and Moore counties were discarded because these counties lie outside of ERCOT territory.

[2.8] The thresholds applied assume line voltages required to support maximum plant sizes and represent conservative values applicable to a high-level analysis. The power which an individual transmission line can carry varies depending on a number of parameters, including line characteristics and environmental conditions. The interconnection feasibility of individual projects was not evaluated in this screening.

Additional hypothetical PV plant profiles were sought to represent geographic the areas in which recently proposed or planned plants are located. Counties with anticipated future development were identified. This review yielded 32 additional counties for which hypothetical PV plant profiles were modeled, primarily in the lower irradiance resource counties of northern, central, and coastal Texas. The locations of all sites selected to be modeled as hypothetical utility-scale plants are indicated on the map in Figure 2.1. In this figure, the global horizontal irradiance (GHI) is depicted in the background.[2.9]

**Table 2.1: Selection of Hypothetical Utility-Scale PV Plants**

| Type | 50 MW Utility-Scale Hypothetical Plant Description | # of Profiles |
|---|---|---|
| 1 | 2019 new hypothetical sites (representative of additional counties with operational, planned, or queued as per ERCOT GIS report) | 32 |
| 2 | 2016 hypothetical sites within 3 km of transmission | 48 |
| 3 | 2016 hypothetical sites more than 3 km from transmission but within 25-30 km of operational plants | 3 |
| 4 | 2016 hypothetical sites not near transmission nor operational plants | 56 |

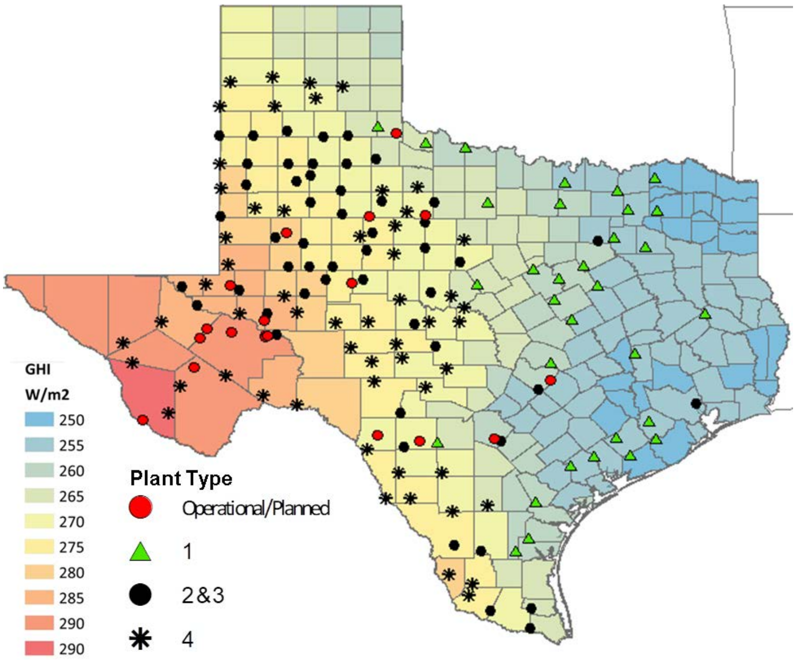


**Figure 2.1: Locations of utility-scale solar PV plants modeled and GHI resource**

## 2.3 Distributed Rooftop Generation for Greater Metro Areas

In 2017, UL evaluated four metro regions for potential DGPV generation (Austin, Dallas, Houston, and San Antonio). A total of 12 DGPV aggregate sites were identified within these four metro regions, defined according to their intensity of development (high, medium, or low). The energy density per unit land area was then approximated using aerial imagery and reasonable development assumptions

[2.9] GHI is defined as the total solar radiation received on a surface horizontal to the ground. GHI is the sum of direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). The DNI component is the radiation received perpendicular to the sun's rays. The DHI component is radiation that is received indirectly from the sun via scattering by the atmosphere.

for each land class. The resulting energy density assumptions were applied to the available land area to obtain the maximum potential DGPV capacity for each metro region (Table 2.2). These capacities were used to model the DGPV profiles for the 12 aggregate sites in this study.

**Table 2.2: Capacity ($MW_{AC}$) by Metro Region and Intensity of Development**

| Metro Region | Low | Medium | High |
|---|---|---|---|
| Austin | 262 | 310 | 927 |
| Dallas | 1204 | 1274 | 5035 |
| Houston | 878 | 1448 | 5118 |
| San Antonio | 326 | 321 | 1330 |

### 2.3.1 Operational DGPV Data Screening

Hourly DGPV generation data, aggregated by zip code, was obtained for a sampling of rooftop installations across the four metro areas. The historical generation time series for each zip code was quality controlled similarly to the utility-scale data; this included verifying that the variability of generation was reasonable and that power generation did to exceed the installed capacity. Additionally, no suspect fluctuations in generation were detected (which would indicate an unexpected change in capacity or temporal reporting convention).

# 3. ATMOSPHERIC MODELING

Historical meteorological conditions were simulated over the project using the Weather Research and Forecasting (WRF) model and leveraging data stored from previous modeling efforts performed on behalf of ERCOT to support annual wind generation profiles.[1.1] The record of these model runs was extended through 2018. In summary, WRF, a leading open-source numerical weather prediction (NWP) model, generated the historical atmospheric variables necessary to simulate solar power production at each location. WRF simulates the fundamental physics of the atmosphere, including conservation of mass, momentum, energy, and the moisture phases (water vapor, cloud, ice, rain, and snow), using a variety of online, global geophysical and meteorological databases. A nested grid scheme with horizontal resolutions of 27 kilometers (km) and 9 km was used. Hourly global horizontal, direct normal, and diffuse horizontal irradiance; 2-meter (m) temperature; 10-m wind speed; and precipitation values were extracted from the 9-km resolution model runs for the period 1980-2018.

## 3.1 Solar Irradiance Time Series

High-quality surface stations with solar irradiance measurements (both global horizontal and irradiance components, DNI and DHI, when available) were used to validate and adjust the modeled irradiance time series. The measured data were quality-controlled, which included but was not limited to: correcting for negative nighttime irradiance values, ensuring data were not suspiciously below or above the expected clear sky irradiance values, comparing measurements at redundant sensors or nearby stations, 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, or provide meaningful values for validation and adjustment. Some datasets were truncated to a period that was considered valid.

Data from 16 reference stations were compiled and used to adjust the modeled irradiance resource (totaling over 155 years' worth of valid hourly observations). The frequency distribution of the 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 nineteen validation stations, resulting in an average bias of 2.8, -8.0, and 0.3% for GHI, DHI, and DNI, respectively. The root-mean-squared error (RMSE) after adjustment is 4.8, 11.5, and 5.8% for GHI, DHI, and DNI.

# 4. GENERATION PROFILES

Hourly power generation profiles were modeled for the period of January 1, 1980, through December 31, 2018, at 23 operational plants, 139 hypothetical utility-scale sites, and 12 DGPV aggregate sites. The adjusted WRF time series (Section 3.1) served as input to UL's proprietary power conversion software to synthesize the solar PV generation profiles. Operational plants were modeled with their plant-specific static details. Near-current technology assumptions were developed to model hypothetical utility-scale sites and DGPV aggregate sites using a look-ahead period of five years (2019-2024). All plants were modeled as “must take”, with no limit. All power profiles represent simulated PV generation only, with no battery storage system.

## 4.1 Near-Current Composite Technology

Representative near-current PV technology specifications for hypothetical sites were developed with UL's industry knowledge and survey of technology trends from VDMA (Verband Deutscher Maschinen- und Anlagenbau, German Engineering Federation). Leveraging future technology assumptions developed for the previous modeling study (AWST 2017), efficiency gains for the utility-scale and rooftop composite modules were updated based on projected technology innovation and trends predicted in VDMA's International Technology Roadmap for Photovoltaics (ITRPV).[4.10] The composite module specifications (Table 4.1) are based on simplified assumptions from the ITRPV. The near-current module technology only accounts for crystalline modules; thin film and bifacial technology is not represented. The efficiency specifications in Table 4.1 assume the market share in 2024 will primarily consist of aluminum Back Surface Field (Al-BSF) and Passivated Emitter and Rear Cell (PERC) modules.

**Table 4.1: Module Specifications for Near-Current Technology**

| Module | Rated Capacity (W) | Efficiency (%) | Temperature Coefficient of Power (%) | Area ($m^2$) |
|---|---|---|---|---|
| Utility-Scale | 325 | 18.9 | -0.41 | 1.94 |
| Rooftop | 261 | 18.4 | -0.42 | 1.63 |

## 4.2 Conversion to Power

UL simulated hourly generation using the adjusted WRF modeled time series collocated with the utility-scale sites and DGPV aggregate sites. Atmospheric variables that impact module performance and power conversion were extracted from the WRF numerical data output and the modeled irradiance was converted to solar PV output using UL's power conversion software. Operational sites were modeled with plant-specific parameters as agreed upon by the ERCOT and UL. Hypothetical sites were modeled with the generic site characteristics listed in Table 4.2 and the near-current composite modules described in Section 4.1. All hypothetical utility-scale systems were assumed to be facing south, and single-axis sites were assumed to be tilted horizontally.[4.11] DGPV systems were

[4.10] International Technology Roadmap for Photovoltaics (ITRPV) 8th edition. Verband Deutscher Maschinen- und Anlagenbau, German Engineering Federation, 2017 (http://www.itrpv.net)

[4.11] Single-axis hypothetical sites were assumed to be tilted to the mean latitude of the site in AWST 2017.

assumed to be tilted to 22.6 degrees (a common rooftop pitch in Texas) and were modeled using a variety of azimuths to capture real-world scenarios in which roofs may not be optimally oriented.

**Table 4.2: Static Plant Details for Hypothetical Sites**

| Plant Type | Tracking System | Tracking Type | Tilt (°) | Azimuth(s) (° from S) | DC:AC ratio |
|---|---|---|---|---|---|
| Utility | Single | N-S | 0 | 0 | 1.30 |
| Utility | Dual | NA | NA | 0 | 1.25 |
| Aggregate DGPV | Fixed | NA | 22.6 | +/-45, 0 | 1.25 |

The power conversion process follows UL (2017) with the following updates:

- The solar geometry calculation was improved to incorporate a time-varying solar constant, which improves the plane-of-array irradiance calculation, particularly on a monthly basis.
- Single-axis tracking sites were modeled with a 60º horizontal tracking limit to better approximate the diurnal profiles of real-world tracking plants, resulting in a slightly narrower diurnal profile than the previous study.[4.12]
- Inverter derating with increasing operating temperature is now modeled, when applicable.
- Static loss assumptions have been revised to be in line with current industry-accepted standards (Table 4.3). Some losses are now accounted for post-inverter.
- For utility-scale plants, a static power factor of 0.95 was applied to satisfy reactive power requirements. For DGPV, no grid tie was assumed, and a power factor of 1.0 was used.

**Table 4.3: Static PV Loss Assumptions**

| Loss Source | % |
|---|---|
| Non-STC Operation (Irradiance) | 0.50 |
| Initial Light-Induced Degradation (Crystalline, Thin Film) | 1.50, 2.00 |
| Module Quality (Crystalline, Thin Film) | 1.00, -1.00 |
| Module Mismatch | 1.25 |
| Inverter Efficiency | 1.50 |
| DC wiring | 0.80 |
| Tracking System Performance (if applicable) | 0.20 |
| Availability of System and Substation | 0.80 |
| HVAC and Auxiliary Components | 0.00 |
| Yearly Module Degradation | 0 |
| AC wiring | 0.80 |
| Transformers | 1.75 |
| Transmission | 0.00 |

## 4.3 Tuning Simulated Results to Observed Generation Data, and Validation

The modeled generation data were adjusted using the hour-ending, filtered, historical generation data from operational plants (described in Section 2.1.1) to more accurately reflect real 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

[4.12] Backtracking was not explicitly modeled. Rotation angle limits were not incorporated in dual-axis plants. Both the effects of backtracking and dual-axis rotation limits are accounted for in the adjustment to historical data, described in Section 4.3.

the modeling process. The final adjustment process applied a two-dimensional correction matrix specific for each plant based on concurrent observed and modeled power generation at every month and hour. A composite adjustment developed from all operational plants with valid data was used to adjust the hypothetical profiles.

### 4.3.1 Utility-Scale Plants

Although the majority of the operational plants had a sufficiently long record of historical generation data to build the correction matrices, 6 of the 20 plants modeled had less than a full calendar year of historical power generation. For these plants, an aggregated, composite matrix was developed for the missing months from sites of the same type (i.e., from all single-axis sites with a full year of data for a single-axis site) and applied to the corresponding hypothetical sites profiles. 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.

After adjustment to monthly and diurnal expected values, the overall generation time series were scaled to the observed maximum value at each plant. Additional generation data from January to June of 2019 were used to calculate the observed maximum value for two recently operational plants, which had less than one month of operational data during the 2018 study period. Therefore, modeled generation will reach 100% of the nameplate $MW_{AC}$ capacity at the operational sites if the historical data reach 100% capacity. For hypothetical sites, the modeled generation reaches 100% of the $MW_{AC}$ capacity (50 $MW_{AC}$).

The final generation profiles were examined for reasonableness at the plant level and as an aggregate of all 14 operational plants with at least one year of historical generation data (Figure 4.1). The adjusted modeled generation time series match the observed monthly and diurnal patterns (as expected with an adjustment based on month and hour) and also capture the observed hourly ramp frequency distribution well. The final dataset has a bias of -0.2% on generation and an hourly coefficient of determination ($R^2$) of 0.93. Depicted in Figure 4.2 is the frequency duration curve for all concurrent, hourly historical and adjusted model data for the same 14 plants. This analysis shows that the final dataset accurately captures the dynamic behavior of utility-scale solar plants.

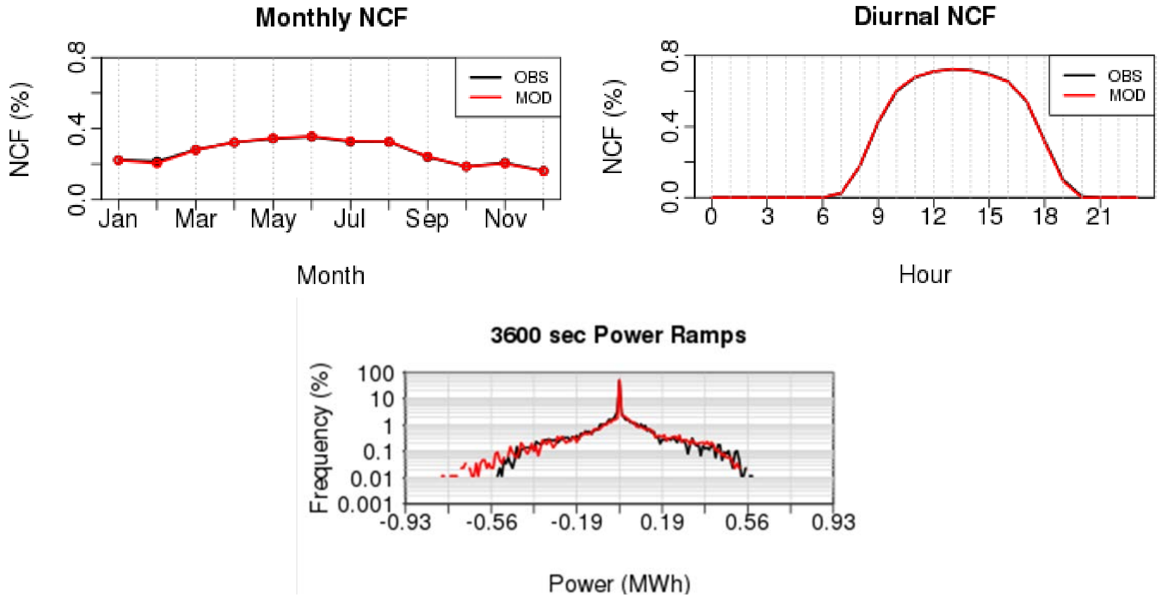


**Figure 4.1: Net power for concurrent, hourly historical (black) and adjusted-modeled (red) data from an aggregate of 14 operational plants**

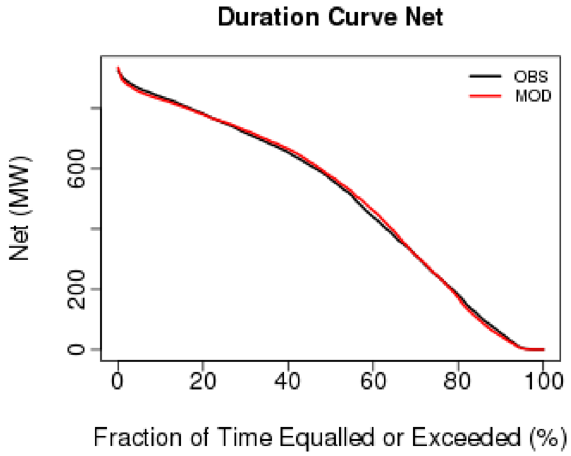


**Figure 4.2: Net load duration curve for operational plants**

### 4.3.2 Distributed Rooftop Generation

Adjustment of the twelve DGPV aggregate sites across the four metro areas proceeded similarly to the adjustment of the hypothetical utility-scale PV profiles. The zip code-level historical rooftop generation data were aggregated across metro areas, and a composite matrix was developed for each separate metro area to adjust the modeled DGPV time series. All DGPV aggregate sites (categorized by the intensity of development in Section 2.3) were adjusted using the composite adjustment matrix for their corresponding metro area. The resulting data were scaled to the maximum observed over the period; therefore, DGPV profiles reach 97.5% of the assumed $MW_{AC}$ capacity.

The final generation profiles were examined for reasonableness at the site level and as an aggregate of all the zip codes for which rooftop generation data was obtained (Figure 4.3). As with the modeled utility-scale generation time series, these modeled DGPV generation time series accurately depict the diurnal and monthly mean patterns of observed generation data. The model overestimates the largest ramps, which provides a conservative estimate of the hourly ramping potential of DGPV across these metro areas. The final dataset has a bias of -0.2% on generation and an hourly coefficient of determination ($R^2$) of 0.82. Depicted in Figure 4.4 is the frequency duration curve for all concurrent, hourly historical and adjusted model data for generation data across the four metro areas. This analysis shows that final dataset accurately captures the dynamic behavior of distributed rooftop generation.

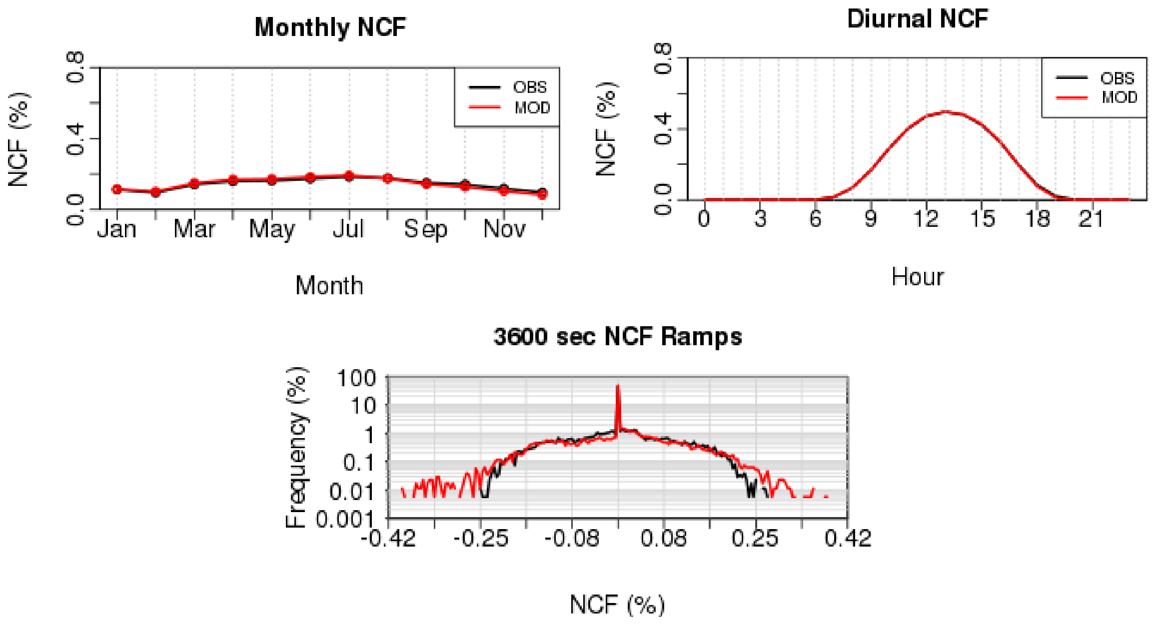


**Figure 4.3: Net power for concurrent, hourly historical (black) and adjusted modeled (red) data from an aggregate of sampled rooftop data**

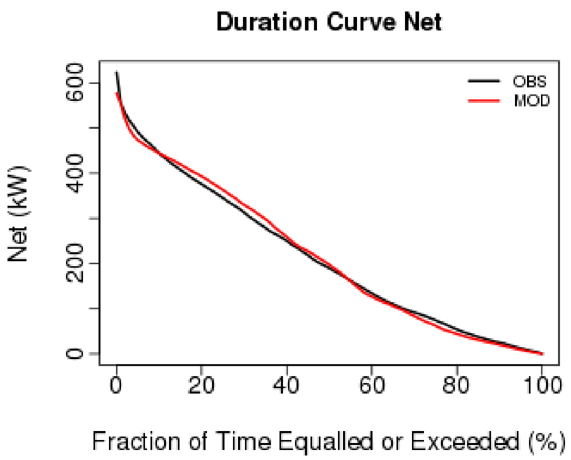


**Figure 4.4: Net load duration for an aggregate of sampled rooftop data**

## 4.4 Results

Hour-ending time series of generation profiles were developed for 139 hypothetical sites (single- and dual-axis see Appendix A - Utility-Scale Hypothetical Sites by County), 23 operational or planned utility-scale plants, and 12 DGPV aggregate sites (representing three land use classes in four metro regions) for the years 1980-2018. The location of these sites is depicted in Figure 4.5. The profiles were delivered in final form on July 31, 2019.

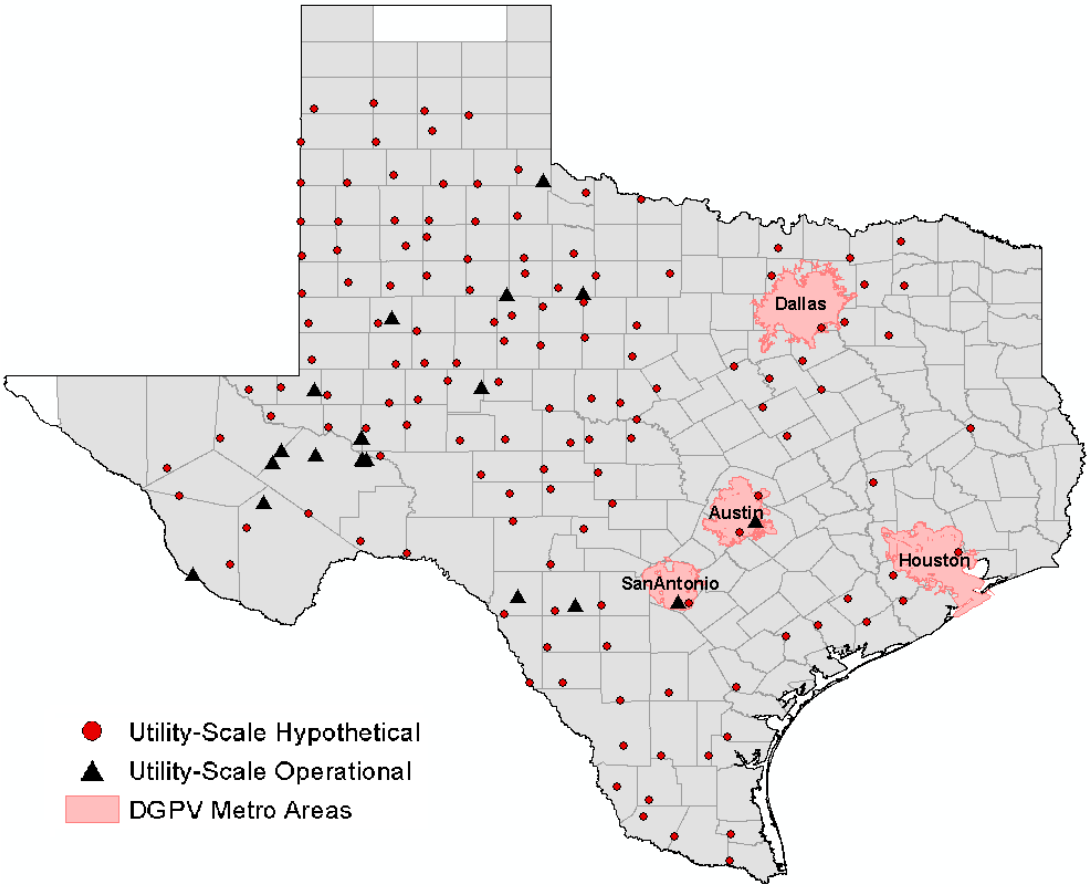


**Figure 4.5: Solar PV sites modeled within ERCOT territory (grey)**

The range of net capacity factors (NCF) for each site type can be found in Table 4.4. Two operational plants have NCF values of 20 to 21%, matching the operational data at these sites. The NCFs for the remainder of the operational plants fall within the range of the modeled hypothetical plant values.

**Table 4.4: Range of Net Capacity Factor for Modeled Time Series**

| PV Generator Type | Range NCF (%) |
|---|---|
| Operational Utility-Scale | 20.1 – 31.1 |
| Utility-Scale Hypothetical (Single-Axis) | 24.3 – 33.5 |
| Utility-Scale Hypothetical (Dual-Axis) | 24.6 – 32.8 |
| Distributed Rooftop | 16.6 – 18.0 |

Single-axis and dual-axis hypothetical plants have similar mean NCF, with single-axis occasionally exhibiting a higher NCF than the dual-axis counterpart. Since this phenomenon was also found in nearly collocated single- and dual-axis operational plants, it is likely due to the adjustment process in which the profiles are scaled to historical generation. 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). A comparison of the single- and dual-axis profiles at a sample hypothetical site is shown in Figure 4.6. As expected, the dual-axis profiles exhibit higher NCF 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.[4.13] This difference is more pronounced with increasing latitude (not shown).

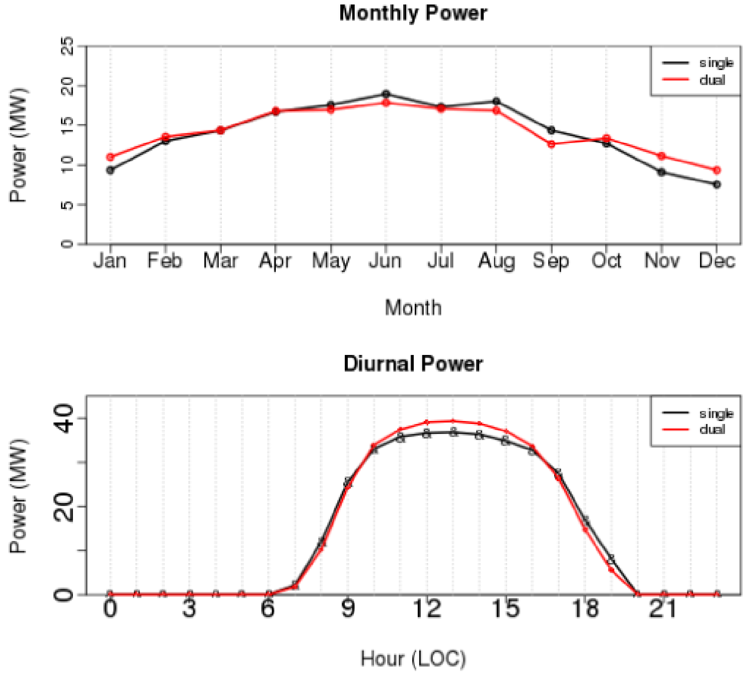


**Figure 4.6: Monthly (top) and diurnal (bottom) mean net power at a sample hypothetical site modeled as single-axis (black) and dual-axis (red) tracking**

The distributed rooftop generation profiles were examined to understand differences in the potential generation across the metro areas. As shown in Figure 4.7, the overall net capacity factor varies little across the different land use classes within individual metro areas, but the normalized generation does vary across the four metro areas, due to differences in local climates. Further analysis also shows a difference in the timing of generation across these four metro areas, as shown by the average diurnal NCF calculated as a sum of all three land class sites per metro area (Figure 4.8). All profiles achieve non-zero generation at the same hours (06:00 and 19:00 LST) and peak generation at the same hour (13:00 LST). However, the effect of longitude on relative solar position can be seen in the mean diurnal NCF, with Houston power generation commencing the earliest, followed by Dallas, Austin, and San Antonio, from east to west. The opposite pattern, although less well pronounced, is seen in the afternoon. The influence of increased cloudiness in eastern Texas is seen in the lower NCF in Houston, particularly in the afternoon.

The diurnal profile of generation was compared to neighboring utility-scale hypothetical sites (Figure 4.9). As shown, the overall peak amplitude and shape of the diurnal profile varies substantially between distributed rooftop PV generation profiles and their utility-scale neighbors. These differences are largely due to lower efficiency for the rooftop composite module technology and assumption of fixed rooftop PV compared to tracking utility-scale systems.

[4.13] 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 observed generation data where this is seen. .

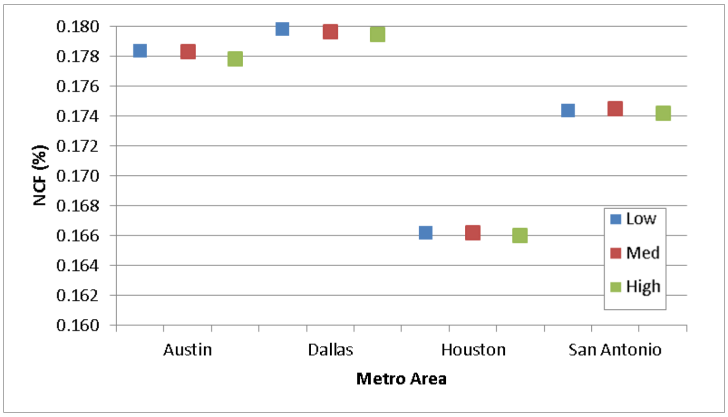


**Figure 4.7: Net capacity factor for the 12 DGPV aggregate sites**

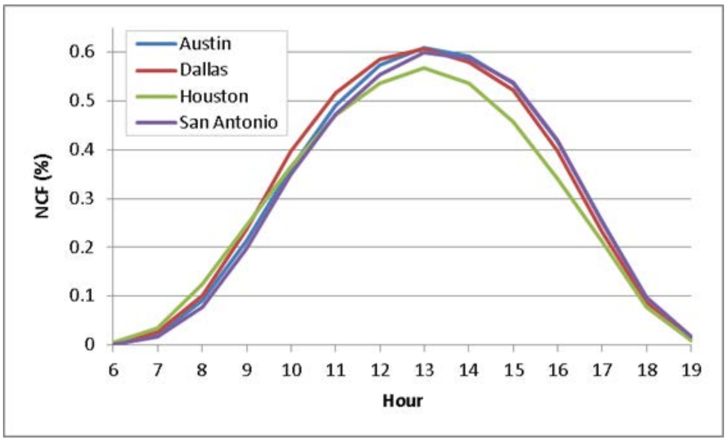


**Figure 4.8: Diurnal net capacity factor for aggregate metro areas**

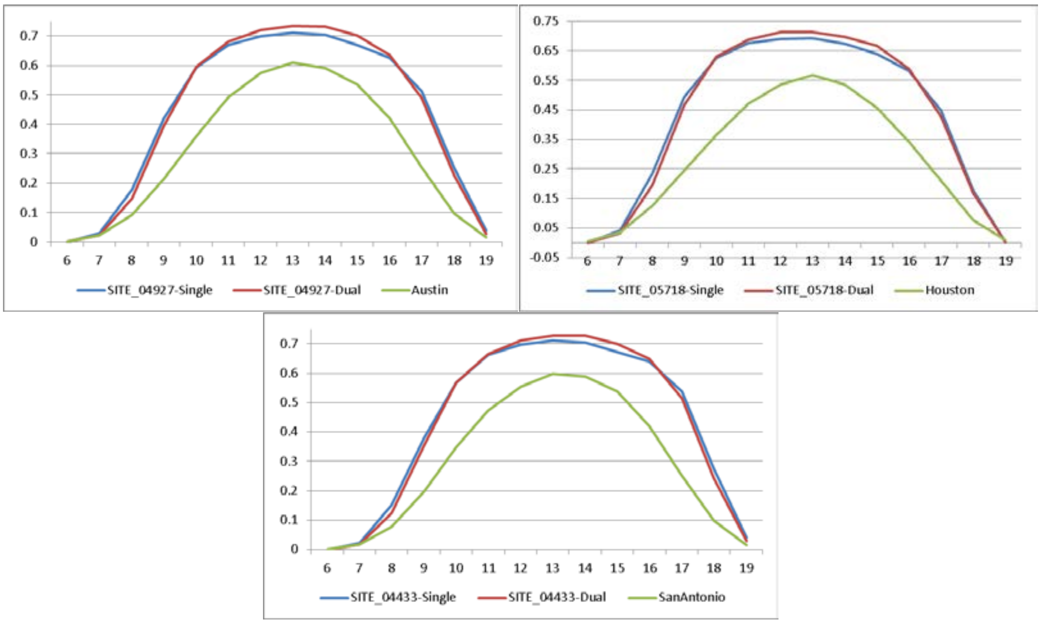


**Figure 4.9: Comparison of NCF for aggregated metro areas and intersecting hypothetical sites**

The generation profiles were compared to those developed in the previous study (AWST 2017). Differences exist due to assumptions in technology (near-current vs future[4.14]) and tilt angle (horizontal tilt vs tilted to latitude); advancements made to the power conversion process; and integration of substantially more observed data for adjustment (both for the solar resource and PV generation). These advancements to the modeling process ensure the latest profiles represent improved estimates of the solar PV generation at the project sites. In general, the NCF values at utility-scale sites are 2-3% lower than in the previous study, largely due to differences in technology[4.14] and tuning to observed generation data. The NCF values in the current study are approximately 4% lower at DGPV aggregate sites than in AWST (2017), again not only due to a different technology assumption but also due to adjustment using much more observed generation data (here an aggregate of rooftop generation across multiple zip codes, compared to a single rooftop site in the previous study). A comparison of a single-axis hypothetical site modeled in 2016 (red) and 2019 (black) is shown in Figure 4.10. The difference in the shape of the profiles is largely due to the adjustment to historical generation. This reduces the generation over most months and adjusts the shape of the diurnal profile (to account for different tracking specifications and to represent hour-ending averages). The resulting 2019 profiles better reflect currently operating plants.

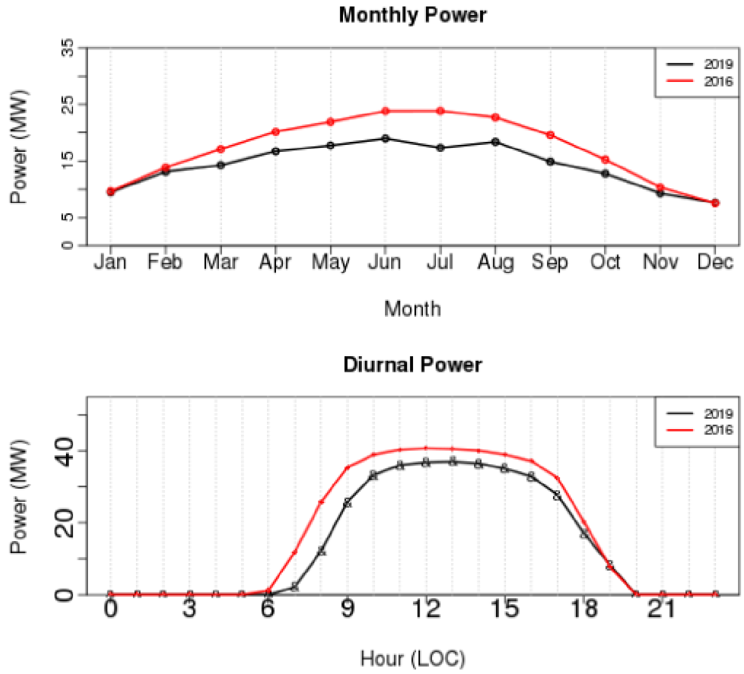


**Figure 4.10: Monthly (top) and diurnal (bottom) mean net power modeled in 2016 (red) and 2019 (black) at a sample hypothetical site**

# 5. DATASET USAGE

The solar data provided were developed specifically for use in large-scale regional planning studies for the purpose of observing the relative changes in solar PV generation across space and time. Of concern to ERCOT was the ability to realistically simulate the hourly generation variability. Results show the data realistically capture the diurnal and monthly mean patterns, ramp frequency

[4.14] The near-current PV technology composite module efficiencies for the utility-scale and distributed rooftop scenarios in this study are 18.9 and 18.4%, respectively. In the previous study (AWST 2017), the future-technology composite module efficiencies for these scenarios were 20.7 and 20.2%, respectively.

distribution, and net load duration curves compared to historical generation, both at individual plants and across the ERCOT territory.

The hypothetical 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 profiles were modeled at a 9-km horizontal resolution. While this resolution captures much of the spatial variability in solar resource across the state of Texas, some details in the weather patterns may not be resolved at this scale. However, the 9-km resolution is considered sufficient for hourly studies (as indicated by the ramp plots provided).

Finally, it should be noted that modeled data is not a replacement for onsite measurements and should not be used as the only basis for investment decisions.

# APPENDIX A - UTILITY-SCALE HYPOTHETICAL SITES BY COUNTY

**Table A.1: Net Capacity Factor for Hypothetical & Queued Sites in Counties A-Ki**

| SITE ID | County | Type | NCF Single | NCF Dual |
|---|---|---|---|---|
| 745 | Andrews | 4 | 31.16 | 30.91 |
| 5726 | Angelina | 1 | 24.42 | 24.58 |
| 2804 | Armstrong | 4 | 28.66 | 28.97 |
| 1115 | Bailey | 4 | 30.56 | 30.56 |
| 4753 | Bee | 1 | 25.65 | 25.49 |
| 4433 | Bexar | 2 | 25.26 | 25.12 |
| 1403 | Borden | 2 | 29.60 | 29.51 |
| 4051 | Bosque | 1 | 26.31 | 26.45 |
| 5922 | Brazoria | 1 | 24.83 | 24.83 |
| 30 | Brewster | 4 | 32.73 | 31.95 |
| 2695 | Briscoe | 2 | 28.90 | 29.09 |
| 3202 | Brown | 4 | 27.34 | 27.32 |
| 2864 | Callahan | 2 | 27.94 | 27.98 |
| 2740 | Cameron | 2 | 26.98 | 26.80 |
| 2946 | Carson | 4 | 28.62 | 28.95 |
| 1908 | Castro | 2 | 29.88 | 30.01 |
| 3846 | Childress | 1 | 27.71 | 28.04 |
| 945 | Cochran | 4 | 30.70 | 30.60 |
| 2326 | Coke | 2 | 28.84 | 28.74 |
| 2925 | Coleman | 2 | 27.74 | 27.68 |
| 3511 | Comanche | 1 | 27.21 | 27.22 |
| 2168 | Concho | 2 | 28.07 | 27.92 |
| 4971 | Cooke | 1 | 25.56 | 25.84 |
| 3415 | Cottle | 2 | 28.02 | 28.27 |
| 577 | Crane | 4 | 31.05 | 30.83 |
| 805 | Crockett | 2 | 30.10 | 29.82 |
| 2101 | Crosby | 2 | 29.39 | 29.45 |
| 176 | Culberson | 4 | 33.33 | 32.69 |
| 5018 | Dallas | 2 | 25.18 | 25.39 |
| 1136 | Dawson | 2 | 30.06 | 29.93 |
| 1348 | Deaf Smith | 4 | 30.15 | 30.30 |
| 4831 | Denton | 1 | 25.76 | 26.02 |
| 2759 | Dickens | 2 | 28.74 | 28.86 |
| 1713 | Dimmit | 4 | 26.79 | 26.50 |
| 3405 | Donley | 4 | 28.22 | 28.55 |
| 2436 | Duval | 2 | 26.01 | 25.79 |
| 3116 | Eastland | 2 | 27.41 | 27.46 |

| SITE ID | County | Type | NCF Single | NCF Dual |
|---|---|---|---|---|
| 651 | Ector | 2 | 31.10 | 30.84 |
| 1720 | Edwards | 4 | 28.07 | 27.74 |
| 4779 | Ellis | 1 | 25.44 | 25.60 |
| 4963 | Falls | 1 | 25.46 | 25.58 |
| 5516 | Fannin | 1 | 24.95 | 25.23 |
| 2173 | Fisher | 3 | 28.51 | 28.55 |
| 2560 | Floyd | 2 | 29.32 | 29.43 |
| 5961 | Fort Bend | 1 | 24.77 | 24.79 |
| 2688 | Frio | 4 | 26.09 | 25.87 |
| 831 | Gaines | 4 | 31.05 | 30.86 |
| 1980 | Garza | 2 | 29.47 | 29.50 |
| 2437 | Gillespie | 4 | 27.27 | 27.05 |
| 1008 | Glasscock | 2 | 29.57 | 29.36 |
| 5597 | Grimes | 1 | 24.65 | 24.73 |
| 2062 | Hale | 2 | 29.56 | 29.65 |
| 3399 | Hall | 2 | 28.27 | 28.55 |
| 4156 | Hardeman | 1 | 27.21 | 27.53 |
| 5718 | Harris | 2 | 24.93 | 24.97 |
| 3061 | Haskell | 4 | 27.88 | 28.03 |
| 1545 | Hidalgo | 2 | 27.26 | 27.01 |
| 4458 | Hill | 1 | 25.62 | 25.78 |
| 1238 | Hockley | 2 | 30.33 | 30.28 |
| 6003 | Hopkins | 1 | 24.45 | 24.69 |
| 1217 | Howard | 2 | 29.48 | 29.34 |
| 5790 | Hunt | 1 | 24.81 | 25.07 |
| 1117 | Irion | 4 | 29.02 | 28.76 |
| 5417 | Jackson | 1 | 25.07 | 25.01 |
| 105 | Jeff Davis | 4 | 33.49 | 32.79 |
| 1309 | Jim Hogg | 4 | 27.10 | 26.84 |
| 4553 | Jim Wells | 1 | 25.96 | 25.78 |
| 2638 | Jones | 4 | 28.26 | 28.36 |
| 5366 | Kaufman | 1 | 24.92 | 25.12 |
| 2154 | Kent | 2 | 28.91 | 28.97 |
| 2405 | Kerr | 4 | 27.15 | 26.83 |
| 2134 | Kimble | 4 | 27.67 | 27.40 |
| 3022 | King | 4 | 28.05 | 28.22 |
| 1923 | Kinney | 4 | 27.18 | 26.89 |

**Table A.2: Net Capacity Factor for Hypothetical & Queued Sites in Counties Kn-Z**

| SITE ID | County | Type | NCF Single | NCF Dual |
|---|---|---|---|---|
| 3443 | Knox | 4 | 27.64 | 27.84 |
| 2351 | La Salle | 4 | 26.37 | 26.14 |
| 6025 | Lamar | 1 | 24.31 | 24.58 |
| 1336 | Lamb | 2 | 30.04 | 30.09 |
| 672 | Loving | 2 | 31.63 | 31.38 |
| 1992 | Lubbock | 2 | 29.47 | 29.51 |
| 1475 | Lynn | 4 | 29.77 | 29.71 |
| 1047 | Martin | 2 | 29.89 | 29.73 |
| 2346 | Mason | 2 | 27.60 | 27.43 |
| 5892 | Matagorda | 1 | 24.85 | 24.81 |
| 1715 | Maverick | 4 | 27.12 | 26.80 |
| 2279 | McCulloch | 4 | 27.79 | 27.69 |
| 4657 | McLennan | 1 | 25.78 | 25.88 |
| 2870 | McMullen | 4 | 25.82 | 25.64 |
| 3480 | Medina | 1 | 25.90 | 25.66 |
| 1999 | Menard | 4 | 28.18 | 27.92 |
| 896 | Midland | 4 | 30.14 | 29.92 |
| 3397 | Mills | 4 | 27.06 | 27.03 |
| 1618 | Mitchell | 2 | 29.18 | 29.08 |
| 3062 | Motley | 2 | 28.70 | 28.86 |
| 4946 | Navarro | 1 | 25.14 | 25.29 |
| 1957 | Nolan | 2 | 28.95 | 28.91 |
| 4515 | Nueces | 1 | 25.92 | 25.74 |
| 2338 | Oldham | 4 | 29.81 | 30.12 |
| 1233 | Parmer | 2 | 30.42 | 30.52 |
| 136 | Pecos | 4 | 32.01 | 31.35 |
| 3188 | Potter | 4 | 29.04 | 29.37 |
| 4 | Presidio | 4 | 33.27 | 32.55 |
| 2512 | Randall | 4 | 29.48 | 29.72 |
| 906 | Reagan | 4 | 29.71 | 29.47 |
| 3236 | Real | 2 | 26.87 | 26.55 |
| 439 | Reeves | 4 | 32.21 | 31.79 |
| 2548 | Runnels | 4 | 28.12 | 28.03 |
| 3005 | San Saba | 4 | 27.35 | 27.29 |
| 1487 | Schleicher | 4 | 28.41 | 28.10 |
| 2010 | Scurry | 4 | 28.75 | 28.75 |
| 3075 | Shackelford | 2 | 27.73 | 27.85 |

| SITE ID | County | Type | NCF Single | NCF Dual |
|---|---|---|---|---|
| 1161 | Starr | 4 | 27.36 | 27.11 |
| 3284 | Stephens | 4 | 27.24 | 27.38 |
| 1488 | Sterling | 2 | 29.30 | 29.13 |
| 2791 | Stonewall | 2 | 28.18 | 28.33 |
| 1633 | Sutton | 4 | 28.22 | 27.92 |
| 2536 | Swisher | 2 | 29.34 | 29.52 |
| 2416 | Taylor | 4 | 28.53 | 28.53 |
| 509 | Terrell | 4 | 30.98 | 30.60 |
| 1162 | Terry | 4 | 30.29 | 30.22 |
| 3225 | Throckmorton | 3 | 27.51 | 27.69 |
| 1919 | Tom Green | 4 | 28.61 | 28.43 |
| 5044 | Travis | 2 | 25.18 | 25.13 |
| 647 | Upton | 2 | 30.76 | 30.54 |
| 2723 | Uvalde | 3 | 26.34 | 26.07 |
| 736 | Val Verde | 4 | 29.94 | 29.67 |
| 5375 | Van Zandt | 1 | 24.66 | 24.85 |
| 5198 | Victoria | 1 | 25.21 | 25.12 |
| 555 | Ward | 2 | 31.57 | 31.31 |
| 1097 | Webb | 2 | 27.02 | 26.75 |
| 5804 | Wharton | 1 | 24.88 | 24.87 |
| 4671 | Wichita | 1 | 26.59 | 26.89 |
| 2916 | Willacy | 2 | 26.76 | 26.56 |
| 4927 | Williamson | 1 | 25.41 | 25.44 |
| 704 | Winkler | 4 | 31.40 | 31.16 |
| 903 | Yoakum | 2 | 30.83 | 30.66 |
| 3839 | Young | 1 | 26.79 | 27.02 |
| 1158 | Zapata | 4 | 27.07 | 26.82 |
| 1914 | Zavala | 4 | 26.64 | 26.38 |