PREPARED FOR

ELECTRIC RELIABILTY COUNCIL OF TEXAS

SIMULATION OF WIND GENERATION PATTERNS FOR THE ERCOT SERVICE AREA

MARCH 27, 2015

SUBMITTED BY:

AWS Truepower, LLC

463 New Karner Road

Albany, NY 12205

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

On behalf of the Electric Reliability Council of Texas (ERCOT), AWS Truepower (AWST) simulated historical wind power data for existing, planned, and hypothetical sites for the period of 1997-2013. The Weather Research and Forecasting (WRF) Model, a leading open-source community model, was used to generate the historical wind variables necessary to simulate wind power production. WRF, a mesoscale numerical weather prediction (NWP) model, simulates the fundamental physics of the atmosphere, including conservation of mass, momentum, energy, and the moisture phases, using a variety of online, global geophysical and meteorological databases. Wind variables were computed and stored for hourly power simulations at 228 sites spanning the period of 1 January 1997 to 1 January 2013. Previous work by AWST utilized the Mesoscale Atmospheric Simulation System (MASS), a proprietary numerical weather prediction model, to simulate 15 years of historical wind power data (1997-2011).[1] This report presents an overview of the methods, results, and validation of the current dataset.

2. SITE SELECTION

In 2012, AWST and ERCOT identified over 25 GW of onshore sites and 1500 MW of offshore sites throughout their service area. A total number of 228 sites were identified, including 84 existing, 11 queued, 130 hypothetical, and 3 offshore. The 2012 sites and their plant characteristics were used for the simulation in this study.

3. MESOSCALE MODELING

WRF is an open-source, state-of-the-art global or regional numerical weather prediction (NWP) model designed to simulate synoptic and mesoscale atmospheric circulations. WRF solves the fully compressible, non-hydrostatic Navier-Stokes equations (i.e. conservation of mass, momentum and energy), and includes a complete suite of physics parameterization schemes: radiation, land surface-atmosphere interactions, planetary boundary layer (PBL) turbulence, microphysics, cloud convection, etc. The latest version of WRF contains 11 boundary layer schemes, 18 microphysics schemes, and 10 convective parameterization schemes. AWS Truepower uses previously vetted physical parameterizations to best simulate the near-surface wind resource.

For this study, AWS Truepower used WRF simulations initialized by the ERA-Interim reanalysis dataset. ERA-Interim, a historic global weather archive provided by the European Center for Medium Range Weather Forecast (ECMWF), supplied the model initialization and boundary conditions. This data provides a snapshot of atmospheric conditions around the world at all levels of the atmosphere at intervals of six hours. Several studies[2,3,4] by AWS Truepower and others show that third generation reanalysis datasets such as ERA-Interim have superior accuracy in terms of their correlation to tall

---

[1] AWS Truepower, LLC, "Simulation of Wind Generation Patterns for the ERCOT Service Area", Report to ERCOT, May 2012.

[2] Brower, M.C, M.S. Barton, L. Lledo, and J. Dubois (2013)."A study of wind speed variability using global reanalysis data". Technical report from AWS Truepower. 11 pp. Available at: https://www.awstruepower.com/knowledge-center/technical-papers/

[3] Lileo, S. and O. Petrik (2011). "Investigation on the use of NCEP/NCAR, MERRA and NCEP/CFSR reanalysis data in wind resource analysis". Presentation given at the EWEA conference, Brussels, Belgium

[4] Decker, M., M.A. Brunke, Z. Wang, K. Sakaguchi, X. Zeng, and M.G. Bosilovich (2012). "Evaluation of the Reanalysis Products from GSFC, NCEP, and ECMWF Using Flux Tower Observations". Journal of Climate, Vol. 25, pp. 1916-1944

meteorological mast data. High-resolution terrain, soil, and vegetation data were also used as input. The WRF model determines the evolution of atmospheric conditions within the region based on interactions amongst different elements in the atmosphere, and between the atmosphere and the surface. As the model is integrated forward in time, it is nudged toward the selected (re)analysis data with the spectral nudging technique.

The ERA-Interim data are on a relatively coarse grid (about 80-km spacing). To avoid generating noise at the boundaries that can result from large jumps in grid cell size, it is recommended that mesoscale models such as WRF be run on nested grids of successively finer mesh size until the desired grid scale is reached. In this configuration, the outer grid provides initial fields and updated lateral boundary conditions for each subsequent nest of an inner grid.

For this study, a nested grid scheme with horizontal resolutions of 27-km and 9-km was used (Figure 1). The model simulations include both the ERCOT service area and nearby offshore waters for the period of 1 January 1997 to 1 January 2014. Table 1 summarizes the model configuration used in this study.

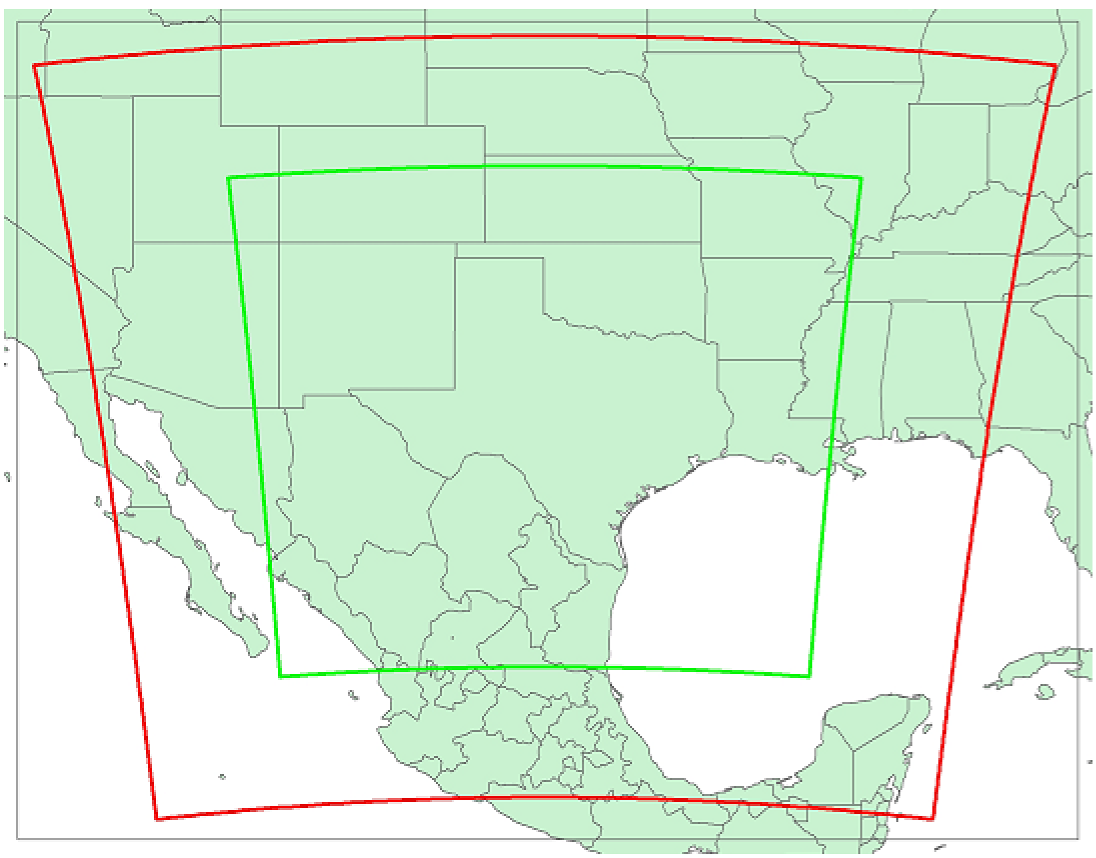

Figure 1. ERCOT study area and mesoscale model grids. The model configuration includes nested grids of 27-km (red) and 9-km (green) grid spacing.

Table 1. Model configuration for WRF runs.

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

4. SIMULATED ELECTRICITY GENERATION AND OUTPUT DATA

An hourly time series of net power output was simulated for the period spanning 1 January 1997 to 1 January 2014. The power conversion process largely follows the 2012 methodology, and is summarized below. An AWST algorithm was used to convert the meteorological data generated by the mesoscale model to wind plant output. Hourly wind speeds from historical model runs were extracted and their speeds were scaled to 200-m resolution speed maps. Diurnal mean wind speed patterns were adjusted using seven tall towers to correct for model biases. The observed time series from these towers were updated to reflect the long-term wind speeds at their locations. Tall tower data was used to correct the model bias for onshore sites only. The time series of offshore sites were not adjusted to the tall tower data due to large differences in expected diurnal patterns between inland and offshore or coastal locations. Wind speeds at all locations were adjusted to account for wake effects and blade soiling, and a random factor based on the predicted turbulence was added to the wind speeds to account for local gusts that may not be well represented by the 9-km grid spacing.

AWST composite power curves were used for the power conversion process of hypothetical and offshore sites. The most appropriate IEC class turbine power curve was selected and used to convert wind speed to power output at the individual sites. Actual power curves were used for existing and queued sites. An in-depth explanation of the methods used to develop the power generation time series can be found in AWST (2012). In 2015, the same loss assumptions used in the 2012 study were applied. No additional adjustment was necessary to correlate wind speed and power output in the diurnal ramp profiles.

A 17-year time series of hourly power output was created at each site. The dataset was grouped into yearly files for both onshore and offshore sites. A sample text file of site output is shown in Table 2. The header includes the site number and rated capacity of each site. The time series are given in local time (Central Standard Time, CST). The data was delivered on 20 March 2014 and is licensed to ERCOT with full permission for use per license agreement.

Table 2. Sample yearly data file.

YYYYMMDD	HHMM (CST)	SITE_20001: capacity= 500.0	SITE_20002: capacity= 500.0	SITE_20003: capacity= 500.0
19970101	0000	79.9	84.1	82.3
19970101	0100	79.4	122.2	47.8
19970101	0200	70.1	119.2	57.7
19970101	0300	48.6	100.6	111.5
19970101	0400	37.2	35.3	52.5

5. VALIDATION

The final power production data sets underwent a rigorous validation process to ensure the results were consistent with actual meteorological and power generation observations, and previous efforts. The observed datasets used to validate the results of this study included nine National Weather Service Automatic Surface Observing System (ASOS) stations, seven tall towers, and wind power output from 10 ERCOT generation facilities. The analysis below highlights key results from this process.

Nine ASOS stations across Texas were used to validate the WRF modeled wind speeds. Figure 2 demonstrates results from this analysis, showing the observed annual wind speed values at the Abilene ASOS station and the nearest corresponding modeled grid point. The simulated wind speeds compare well with the observed wind speed at all nine locations. The model trends close to observations, with an average monthly coefficient of determination (R^2) of 0.707 for all nine stations.

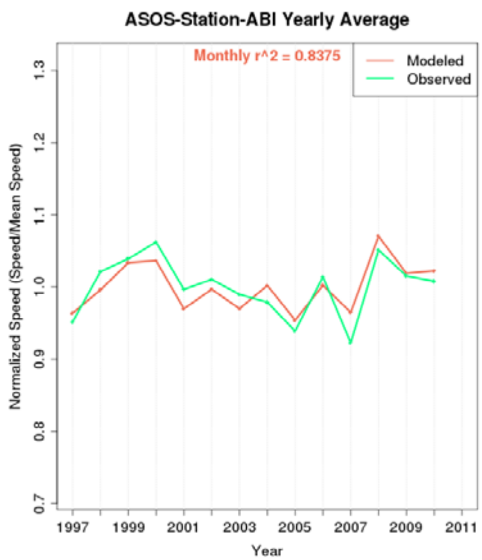

Figure 2. Comparison of the modeled and observed annual wind speeds at the Abilene ASOS station (10-m AGL). The monthly coefficient of determination (R^2) is noted in red.

The modeled 80-m wind speeds were validated using 60-m wind speeds measured at seven tall towers (sheared to 80 m by assuming a shear coefficient derived from 40 m and 60 m AGL measurements). A comparison of these results for both WRF and MASS model output is shown in Table 3 below. These results show that the WRF model is better able to capture the short-term variations in the local climate, as seen in an improvement in the hourly wind speed values.

Table 3. Hourly coefficients of determination (R^2) between observed and modeled 80-m wind speed datasets at validation towers.

Tower	WRF	MASS
1	0.5937	0.5295
2	0.6292	0.4932
3	0.6222	0.5249
4	0.6393	0.5
5	0.5589	0.4804
6	0.5833	0.5383
7	0.4979	0.4011
Mean	0.5892	0.4953

The wind power data was compared to actual power generation data for ten power plants in the ERCOT region to validate model output. The analysis shows that the model is able to capture the dynamic behavior of the wind plants in Texas quite well on a diurnal and monthly basis, as shown in Figure 3 and Figure 4. The model is able to reproduce the increased power generation during nighttime hours (when the height of the boundary layer is considerably lower and winds are stronger), while predicting the seasonally dependent wind climate with acceptable accuracy.

The frequency distribution of hourly step changes in power output was evaluated to ensure that the model captures the variability of actual wind farms. The aggregated results for 3 ERCOT sites are shown in Figure 5. The changes in power output are shown as a percentage of plant capacity, with the y-axis shown on a logarithmic scale to emphasize large ramps. The model variability compares well with the observed values at both individual (not shown) and aggregate sites.

Lastly, the aggregate power of all sites was evaluated. Average diurnal profiles of the aggregated power time series for each year are shown in Figure 6. There is consistency in the diurnal profiles for individual years, despite year-to-year variability in the magnitude of generated power.

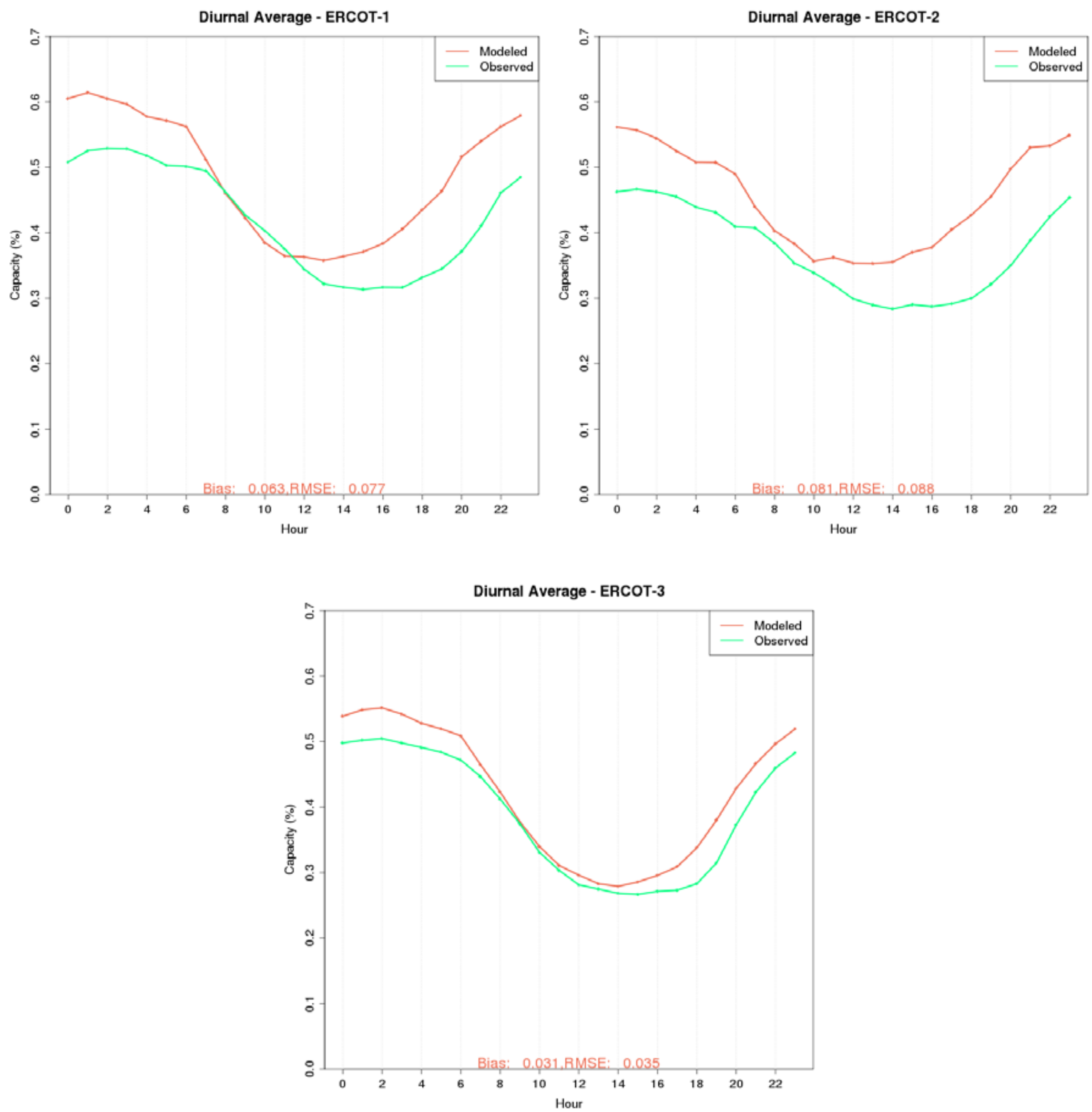

Figure 3. Comparison of diurnally averaged capacity factors for three ERCOT power stations (in Central Standard Time).

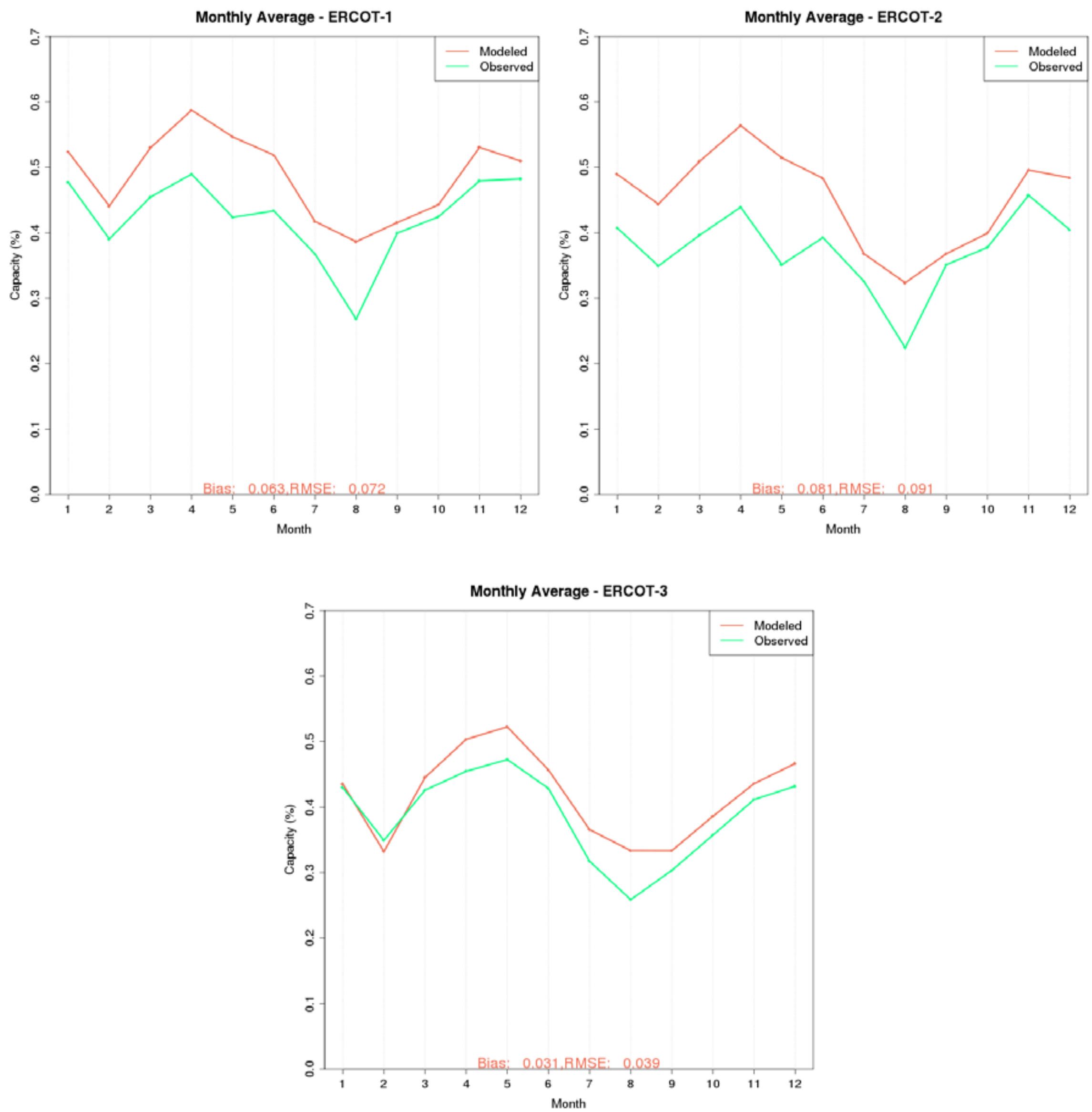

Figure 4. Comparison of monthly averaged capacity factors for three ERCOT power stations.

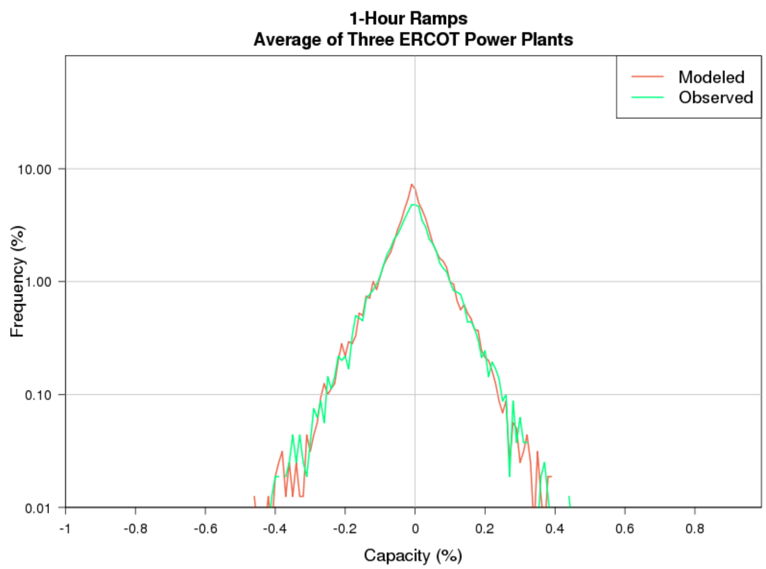

Figure 5. The 60-minute changes in power output measured on a logarithmic scale (aggregate of the three previously shown ERCOT power generating facilities).

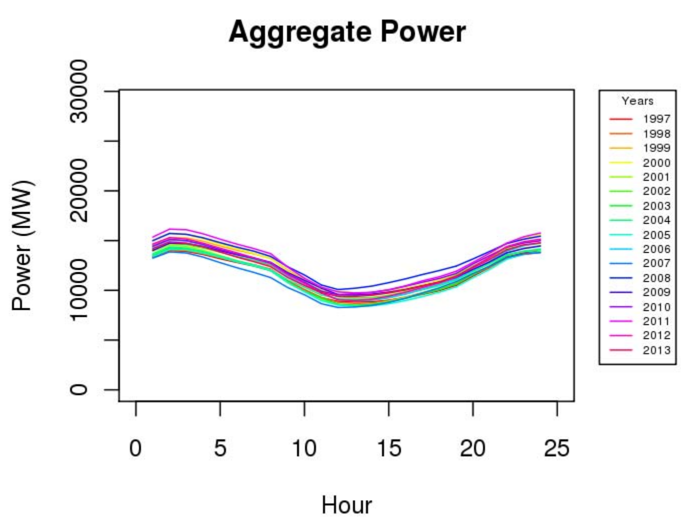

Figure 6. Average diurnal power profile for the years 1997-2013 using the WRF model (aggregate of all sites).

6. SUMMARY

AWS Truepower simulated an hourly wind plant output dataset at 228 wind plants spanning the period of 1 January 1997 to 1 January 2013. Historical wind speed time series at each wind plant, and at validation sites, was generated using the WRF mesoscale model. Power output profiles were developed for each site using common commercially available turbine power curves as of May 2012, and AWST's standard power conversion and loss estimation techniques. Validation results show that the modeled wind speeds compare well with the values observed from a variety of monitoring stations, for both short-term, hourly records and on monthly or annual timescales. The modeled time series of power output was compared to historical generation data at existing facilities, and results show that these time series capture the dynamic behavior of actual wind farms. The resulting data passed quality control measures and files were delivered to ERCOT in March of 2015.