Hourly and Intra-Hourly Simulated Wind Generation Profiles at 150 Locations

1988-2018

PREPARED FOR:
Independent Electricity System Operator

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AWS Truepower LLC.
463 New Karner Road | Albany, New York 12205 | USA
www.ul.com/renewables

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

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A	May 31, 2019	Draft Report
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EXECUTIVE SUMMARY

AWS Truepower, LLC, a UL company, (“UL”) was retained by the Independent Electricity System Operator (“IESO”) to generate hourly and intra-hour (5-minute) wind power profiles at operational and hypothetical wind plants across Ontario for the period of 1988-2018. The purpose of this work was to provide a long term dataset of realistic wind power production behavior that is suitable for power system assessment, grid integration planning, and reliability analysis.

Operational wind plant details were compiled for 63 sites from public and private data sources to ensure completeness and accuracy of the fleet to be modeled. The plant layout and other static details were reviewed and verified, then used to model each plant as close to reality as possible. Historical generation data from the operational plants were collected and quality-controlled for use in the adjustment process for the power profiles. Based on quality thresholds, data from 52 operational plants were suitable for use in the validation process.

Most of Ontario’s operational wind plants are located in the southern portion of the province. For this study, the goal was to identify high quality, geographically-diverse hypothetical wind sites with an installed capacity of at least 100 MW across the province. UL’s in-house site screening tool was used to locate 87 hypothetical sites based on the wind resource and industry-standard exclusions. The locations of these hypothetical sites were then used to develop wind generation profiles using wind plant characteristics anticipated to be deployed across Ontario in the next 5-10 years (2024-2030). As such, UL developed a hypothetical, next-generation wind turbine power curve appropriate for the study area with characteristics expected to reach wide-scale deployment at installations during the target evaluation period. All hypothetical plants were modeled using a 120-meter hub height and a rated capacity of 4 MW.

Mesoscale numerical weather prediction (NWP) models – the same models used for weather forecasting – are the best tools available to simulate the evolving atmospheric conditions. UL utilized the Weather Research and Forecasting (WRF) Model, a leading open-source NWP model to simulate the complex atmospheric processes at a 9-km horizontal resolution and create hourly meteorological time series for each of the operational and hypothetical plant locations. The modeled meteorological time series were corrected for biases using measured data from 19 locations, totaling over 95 years to ensure that the modeled wind resource used in the power conversion method is accurate. The adjusted WRF data was then downscaled to a 200-m grid spacing using a diagnostic mass-conserving model pioneered by UL called WindMap. WindMap attempts to retain as much information as possible from the mesoscale NWP model while accounting for terrain elevation and land cover data.

The adjusted WRF time series served as input to Openwind, UL’s plant design and optimization software used for bankable energy production estimates. Operational plant characteristics and next-generation wind technology at hypothetical plants were used to simulate hourly wind power generation. Openwind’s time series energy capture module was run for two scenarios. The first scenario included only operational wind farms so that the potential wake effect from hypothetical sites was not included. The second scenario included both operational and hypothetical wind plants. This allowed hypothetical plant profiles to include wake losses from nearby operational plants.

The modeled power generation time series from the Openwind software were adjusted using the filtered, historical generation data from operational plants. This adjustment accounts for (i) site-specific plant losses that are not dependent on meteorological conditions (e.g. availability), (ii) unknown operational plant issues (e.g. turbine performance) or (iii) limitations in atmospheric and energy modeling. The operational wind power profiles directly from Openwind had a mean bias close

to 0.7 MW, therefore a simple adjustment of the net power profiles was applied. No adjustment was applied to operational plants with less than one year of operational data or to the hypothetical plants as the mean bias at the operational wind plants was very low.

Once the final profiles for 1988-2018 were created, hourly power profiles without plant availability losses associated with planned or unplanned outages were also created for all 150 plants. This was done by adding back in the availability losses to the standard net power generation profiles.

Lastly, UL applied its statistical downscaling methods to create high-frequency power profiles at a 5-minute interval for the 2014-2018 period which overlays 5-minute fluctuations from actual wind power generation at operational plants on the modeled hourly profiles.

Validation of the synthetic profiles commenced using generation data from the operational plants to verify the simulated profiles reproduced the observed plant behavior with sufficient fidelity. The net capacity factor (NCF) of the final hourly generation profiles varied from 23.2% to 40.9% and averaged 31.8% for the operational plants. The modeled NCFs aligned with the historical generation data which yielded an average net capacity factor of 31.3%. While the hourly observed and modeled net power generation had an hourly coefficient of determination (R^2) averaging around 0.61, this can be expected. The availability losses modeled by Openwind exhibit some hourly randomness; which is substantially lower on a monthly basis, as seen by a monthly R^2 averaging 0.88. The final profiles adequately model the ramp fluctuations in net power generation on an hourly basis at the vast majority of plants, however, at a few sites, temporal variability may not be fully captured.

The synthetic 5-minute wind power time series for the 2014-2018 period were compared to actual power generation data at 52 operational plants in Ontario to ensure that UL's statistical downscaling method captured the dynamic patterns of observed data. The wind power time series were visually inspected to ensure that the synthetic 5-minute profiles matched the previously delivered hourly data on the hour. Further validation revealed that the 5-minute modeled profiles captured the observed generation as well as the hourly data. The annual, monthly and diurnal wind generation patterns are very similar when averaged from the 5-minute or hourly profiles and the modeled power spectral density shows a similar behavior as the observed PSD over the full spectrum up to 10 minutes, the Nyquist frequency. Overall, the annual, monthly and diurnal patterns of the modeled hourly and 5-minute generation data validate well and accurately represent historical generation patterns at individual wind plants and on an aggregate basis.

The UL and IESO team collaborated during project design and execution. Regular meetings were held to review project progress, discuss methods, assumptions, and assess the simulation results. The final deliverables included simulated hourly power generation at 150 plants (63 operational, 87 hypothetical) for the period of 1988-2018 (standard and no availability) and intra-hour profiles of 5-minute generation for the period of 2014-2018. The final data was delivered via file transfer protocol (FTP).

1. INTRODUCTION

AWS Truepower, LLC, a UL company, (“UL”) was retained by the Independent Electricity System Operator (“IESO”) to generate hourly and intra-hour (5-minute) wind power profiles at operational and hypothetical wind plants across Ontario for the period of 1988-2018. UL has developed advanced methods to model operational and hypothetical wind power generation and plant losses that result in realistic power production behavior suitable for power system assessment, planning and reliability analysis. The goal of this scope of work was to: (1) identify geographically-diverse hypothetical wind plants from across the province, (2) define physical and operational characteristics of wind technology representative of those anticipated to be used in projects achieving commercial operation within a 5-10 year horizon and (3) utilize state-of-the-art methods and an adjustment process that aligned operational plant profiles with measured data (and each plant’s inherent loss characteristics) based on the 2017 operational wind fleet configuration.

1.1 Report Overview

This report is divided into five main sections and provides an overview of the methods used to simulate the meteorological conditions as well as wind power generation at 150 wind plants in Ontario.

Section 2 of this report describes the static and dynamic data acquired from public and private sources used to characterize the 63 operational wind plants. This included details such as plant layout, turbine models, etc. and quality control of the operational data from each plant.

Section 3 describes the methods used to select geographically-diverse hypothetical sites with an installed capacity of at least 100 MW. These sites were modeled using turbine characteristics anticipated to be deployed across Ontario in the next 5-10 years (2024-2030). UL developed a hypothetical, next-generation wind turbine power curve appropriate for the study area with characteristics expected to reach wide-scale deployment during the target evaluation period.

Section 4 summarizes the methods used to develop the modeled atmospheric time series using a state-of-the-art NWP model, WRF, for each operational and hypothetical plant location. Resource validation and adjustment is described, as well as the downscaling process used to achieve higher accuracy.

Section 5 describes the conversion of the meteorological time series into wind power generation using Openwind, a state-of-the-art wind resource assessment, and optimization software. The development of availability-adjusted hourly profiles and 5-minute generation is also described.

Section 6 summarizes the results and validation of the hourly and 5-minute generation profiles.

2. OPERATIONAL WIND PLANTS

In order to model the IESO’s operational wind fleet, information was gathered on each wind plant, including the layout, installed capacity and turbine models and historical generation data, where available. Prior to use in the study, this data was reviewed, quality-controlled and verified. Modeling approaches for operational, planned or recently operational plants differed based on the amount of measured data available and other critical factors as described herein.

2.1 Wind Plant Specifications

Wind plant details for 63 plants across Ontario were compiled from the IESO, public and private data sources in order to ensure completeness and accuracy of the operational fleet to be modeled. The IESO provided a summary file of wind plant characteristics including plant capacity, site centroid, in-service date, turbine locations, hub height, rotor diameter, models and rated capacity. This information was reviewed and revised in collaboration with IESO, as needed. The static details of the operational plants are given in Appendix A and include the assigned site number, modeled plant capacity, turbine model(s), rotor diameter and hub height.

The plant layouts were verified based on plant details provided by the IESO and aerial imagery. Turbine locations were visually inspected using satellite imagery to identify mismatches between expected coordinates and the as-built locations. Adjustments were made to align turbine coordinates with imagery and remove turbines suspected to be decommissioned or unbuilt. Finally, an internet and database search was conducted for all plants to verify the compiled data and compare to available layout information provided by relevant stakeholders, e.g. owner, developer or community boards. Revised turbine locations were delivered to IESO for review. Final turbine locations for the operational plants are shown in Figure 2.1.

Once the turbine layouts were confirmed, the installed capacity for each plant was calculated from the respective number of turbines and the turbine rated capacity values provided by the IESO. UL's estimated capacity was compared to the IESO's installed capacity for operational plant to ensure that all turbines had been accounted for. The estimated installed capacity values were also compared to the plant's maximum generation as provided by the IESO. UL's expected installed capacities were aligned with the IESO's plant capacities at the vast majority of sites. Wherever small discrepancies did arise, UL worked with the IESO to finalize the turbine rated capacity and plant capacity for modeling. The final plant capacities as modeled are provided in Appendix A.

The actual turbine models and manufacturer power curves were used for each plant, when available. Based on the number of turbines from the plant layout, some plant capacities were higher than expected likely due to slightly higher turbine megawatt (MW) rating from the manufacturer's standard power curve. The IESO provided the turbine derated capacities and a derated turbine power curve for a specific make and model was used when available. For some turbines (standard or noise-derated), UL was not able to obtain the original equipment manufacturer power curve. When a standard power curve was not available for a turbine, UL used a synthetic composite best approximating the expected behavior of the particular power curve(s) needed. For cases where a de-rated curve was needed, UL approximated a derated curve by manually adjusting the standard air density power curve by capping production at the desired output.

The WRF mesoscale model was configured with vertical levels every 20 meter (m) between 0 and 200 m in altitude. Given that the 7 hub heights are between 77 m and 132 m above ground level, the WRF model outputs were always within 10 m of the hub heights. Listed in Table 2.1 are the unique heights for turbines modeled in this project, along with the height at which they were modeled.

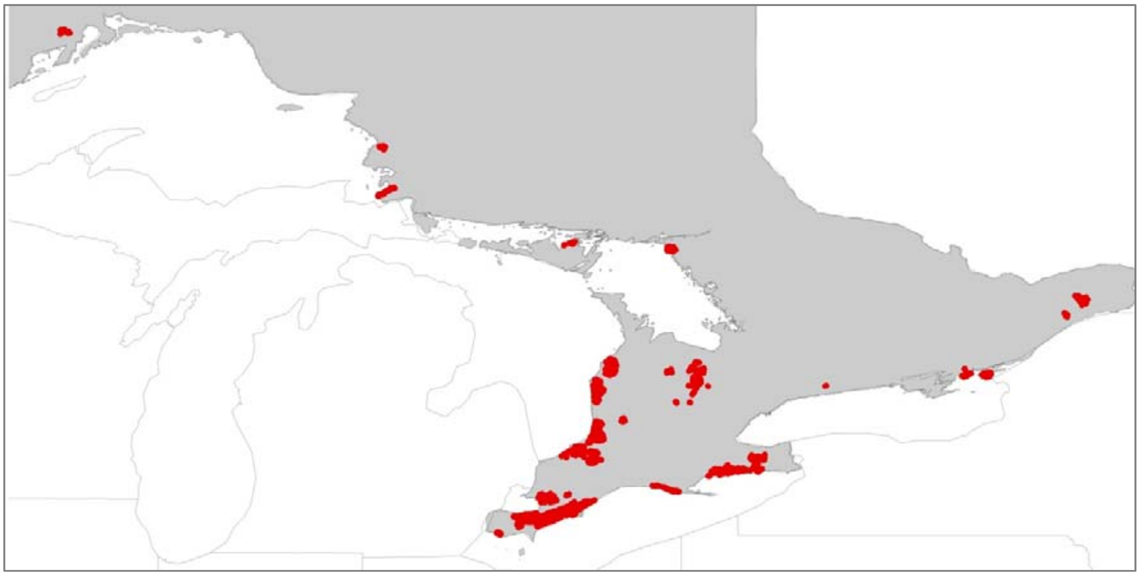

Figure 2.1: Turbine locations for operational plants

Table 2.1: Hub Heights Modeled

Hub Height Modeled (m)	Turbine Hub Heights (m)
75	77
80	78, 80
85	85
95	95, 96
100	98, 98.3, 99.5, 100
125	124
130	132

2.2 Operational Data Review

Historical generation data from the operational plants were collected and quality-controlled for use in the adjustment process for the power profiles. In short, a bias correction is applied to the modeled profiles to remove or reduce the overall bias at each operational plant. Historical, 5-minute generation data was provided at 55 out of 63 operational plants. This data included the actual net power generation as well as a curtailment flag for each 5-minute record. Of the 55 plants, five had a period of record (POR) of less than one year which is UL's threshold to provide meaningful power generation for the validation process.

IESO also provided hourly historical generation data at another five plants. Unfortunately, three of those five sites were missing almost ten consecutive months of data in 2017-2018 and therefore the data recovery was too low to be useful in the validation process. Lastly, three of the 63 plants modeled as "operational" are not in commercial service yet (planned), but are expected to join the operational wind fleet in Ontario. Following this review, a total of 52 operational plants were suitable for use in the validation process. For all other plants (11 in total), UL did not apply any adjustment to the modeled wind power profiles due to short POR or missing operational data.

The operational data from commissioned plants were reviewed to determine the valid start date of measured data after the break-in period. The initial period of commercial operation typically involves fine tuning of the wind turbine/plant operation and usually shows lower availability than normal, which is referred to as the "break-in" period. By default, the first month of data after the commercial operation date were flagged as the "break-in" period and discarded. A visual inspection of the generation data was carried out for each plant to determine if the break-in period extended beyond the first month. At some plants, up to six months of initial generation data were discarded because of data discontinuity with the remainder of the record; e.g., no data, low data recovery, or unusual fluctuations in power generation.

Another important consideration was if plants were considered "waked" by upstream wind farms and when the upstream wind farms were built. Wind farms are known to modulate the wind flow well downstream of their turbine locations. Within the project domain, there are several regions where multiple wind farms have been constructed in close proximity over time; therefore, it is important to understand if a plant was subject to increased waking with time, which may, therefore, be present in the historical generation. Since historical plant generation data was used to adjust the modeled profiles at these wind farms, it is important to only consider only the period of data after which upstream wind farms were built (the "fully waked period"). The fully waked period was determined as follows: (1) the wind rose at hub height was obtained for each plant from UL's windNavigator[2.1] (2) any plants within 20 kilometers (km) upstream of the prevailing wind direction(s) were noted,[2.2] and (3) each upstream plant's installation or latest recorded commissioning date was determined and recorded. The date of the most recently installed upstream wind farm was used as the start of the fully-waked period for plants that were identified as "waked".

The actual power generation data at each operational plant was then quality controlled. The first step was to remove any generation records flagged as curtailed. Then, historical power generation in excess of the plant capacity was discarded. Negative power records were also discarded. It was assumed that the historical generation contained periods of erroneous values if the generation was stuck on a constant value, excluding 0 MW, for a period of six consecutive records or more for the 5-minute data and three consecutive records or more for the hourly data. These constant records were discarded. In UL's experience, power generation data that is stuck on a constant value is oftentimes indicative of data transmission issues. If the wind power generation data was stuck at 0 MW for an extended period of time, UL assumed the data was valid for a period of four consecutive days as plant or grid outages can result in a few days of downtime before the plant restarts. Beyond four days, the operational data was considered erroneous and discarded. A potential drawback to the automated QC procedure is that it may have artificially decreased the net capacity factor in some instance by retaining bad values stuck at 0 MW while in other instances it may have artificially increased the net capacity factor since it discards periods of what may be valid long-lasting plant or grid outages.

The last step in the quality control process was the visual inspection of the actual wind power generation time series, the monthly and diurnal average generation patterns as well as the data recovery. Figure 2.2 shows a typical case of data recovery of the plant generation data at one operational wind farm. As shown in this figure, the actual power generation has a good data recovery (> 80%), however, there is significant curtailment at this plant and therefore data recovery, after filtering out curtailment, is relatively low around 50% on average. It was not unusual to see a high level of curtailment in the plant generation data. The generation data showed that the frequency of

[2.1] Available at: https://dashboards.awstruepower.com/subscriptions/windnavigator

[2.2] UL assumed a typical distance of 20 km for the wind speed downstream of turbine arrays to recover to the free stream wind speed curtailment varied between 0% and 46%. In most cases, the frequency of curtailment was either 0% or 20% approximately.

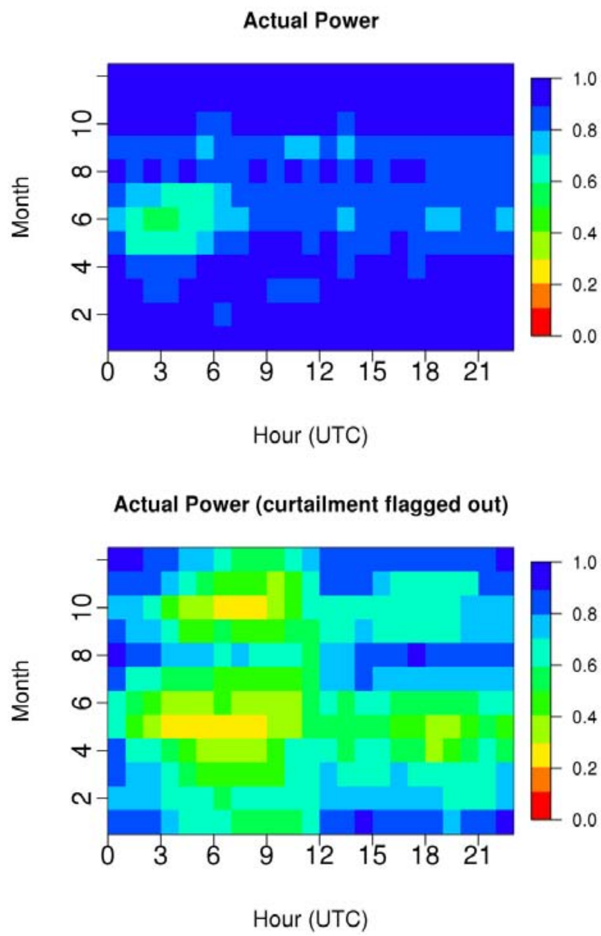

Figure 2.2: Typical data recovery at an operational plant. The top panel corresponds to the actual power generation, including all plant losses. Bottom panel is actual power generation without curtailment.

3. HYPOTHETICAL WIND PLANTS

Most of the operational wind plants in Ontario are located in the southern portion of the province. For this study, the goal was to identify high quality, geographically-diverse hypothetical wind sites of 100-MW site size across the province. UL's in-house site screening tool was used to locate 87 geographically-diverse hypothetical sites based on the wind resource and industry-standard exclusions. The locations of these hypothetical sites were then used to develop wind generation profiles using wind plant characteristics anticipated to be deployed across Ontario in the next 5-10 years (2024-2030). As such, UL developed a hypothetical, next-generation wind turbine power curve appropriate for the study area with characteristics expected to reach wide-scale deployment at installations during the target evaluation period.

3.1 Site Screening for Hypothetical Wind Plants

The first step in the site screening process was to develop a map of the gross capacity factor (GCF) across Ontario as an input to the site screening process. A GCF map was generated using a generic future-technology turbine power curve and UL's proprietary high resolution (200-m) wind speed maps at 120 m above ground level (AGL).[3.3] The wind speed map, along with air density values and speed-frequency distributions, compiled from 15 years of historical mesoscale model runs were used to generate a GCF map at 120 m. The GCF map had a horizontal resolution of 200 m, which is sufficient to reflect the influence of most terrain features and provide a consistent set of resource estimates for ranking and selecting sites.

UL used an automated Geographic Information System (GIS)-based site screening approach to identify sites for potential utility-scale wind projects throughout Ontario. The software application uses the GCF map and a map of the allowable/excluded area to identify sites that may be favored for development based on their gross capacity factor. The program operates in two main steps. In the first step, it finds all sites with a maximum of GCF in the immediate vicinity (i.e., a local maximum) with sufficient area to support a project of a desired size. In the second step, the program allows each of these sites to expand so long as the site average output does not decrease by more than 5%. If the site encounters another site, the site that has a higher mean output is retained and the other is dropped.

The site screening algorithm was run to maximize geographic diversity and reach a desired proportion of hypothetical plants in each zone of Ontario. The entire province of Ontario was divided into 10 zones and a target number of wind speed plants in each zone were identified based on land use constraints and a minimum site separation distance. UL leveraged exclusions compiled for previous modeling efforts and incorporated updated or additional areas for exclusion, as necessary (Table 3.1).[3.4] In addition to standard setbacks and exclusions based on land use, protected status, and terrain slope, a 10-km buffer around operational wind plants was applied. The IESO zones, setbacks, and areas excluded from development are shown in Figure 3.1. The distance to the existing transmission grid was not directly considered in the site screening process.

The site screening process yielded almost 200 sites distributed throughout Ontario. UL worked collaboratively with the IESO using an iterative process to select hypothetical wind sites from the automated site screening results for modeling power production. The hypothetical plants were selected to maximize the geographic diversity of modeled wind profiles across all zones. Particularly in the northern extent of the province (above 50º N in latitude), sites were prioritized based on their proximity to established road networks and areas of interest such as remote communities. Sites were eliminated based on relatively low site-average wind speed, island locality, or relative distance away from transmission. A final listing of these sites by zone is shown in Table 3.2.

[3.3] Available at UL's WindNavigator website: https://dashboards.awstruepower.com/products/gis-data-maps

[3.4] Manobianco, J. (2010). Development of Ontario Regional Wind Resource and Wind Plant Output Data Sets. Prepared for the Ontario Power Authority. AWS Truepower Technical Report.

Table 3.1: Exclusion Areas

Data Layer	Exclusion Applied	Data Source
Land Cover	Open Water	Landsat GeoCover[3.5]
	Urban Areas (500-ft. buffer)	
	Forested Areas	
	Wetlands (100-ft. buffer)	
Land Use	Conservation Easements	Ontario Base Map[3.6]
	Protected Areas & Reserves	
	Parks & Non-Public Federal Lands	
Terrain	Areas which exceed 15% slope	Shuttle Radar Topography Mission[3.7]
Transportation	Airports (10k ft. to 20k ft. buffer for small to medium/large airports)	Environmental System Research Institute (ESRI)[3.8] Vector World Map (VMAP)[3.9]
Operational Plants	Existing turbines (10-km buffer)	Current study

[3.5] Available at: http://www.landcover.org/research/portal/geocover/
[3.6] Available at: https://library.mcmaster.ca/maps/geospatial/ontario-basic-mapping-obm
[3.7] Available at: https://www2.jpl.nasa.gov/srtm/
[3.8] Available at: https://www.arcgis.com
[3.9] Available at: https://mdl.library.utoronto.ca/collections/geospatial-data/vector-world-map-vmap

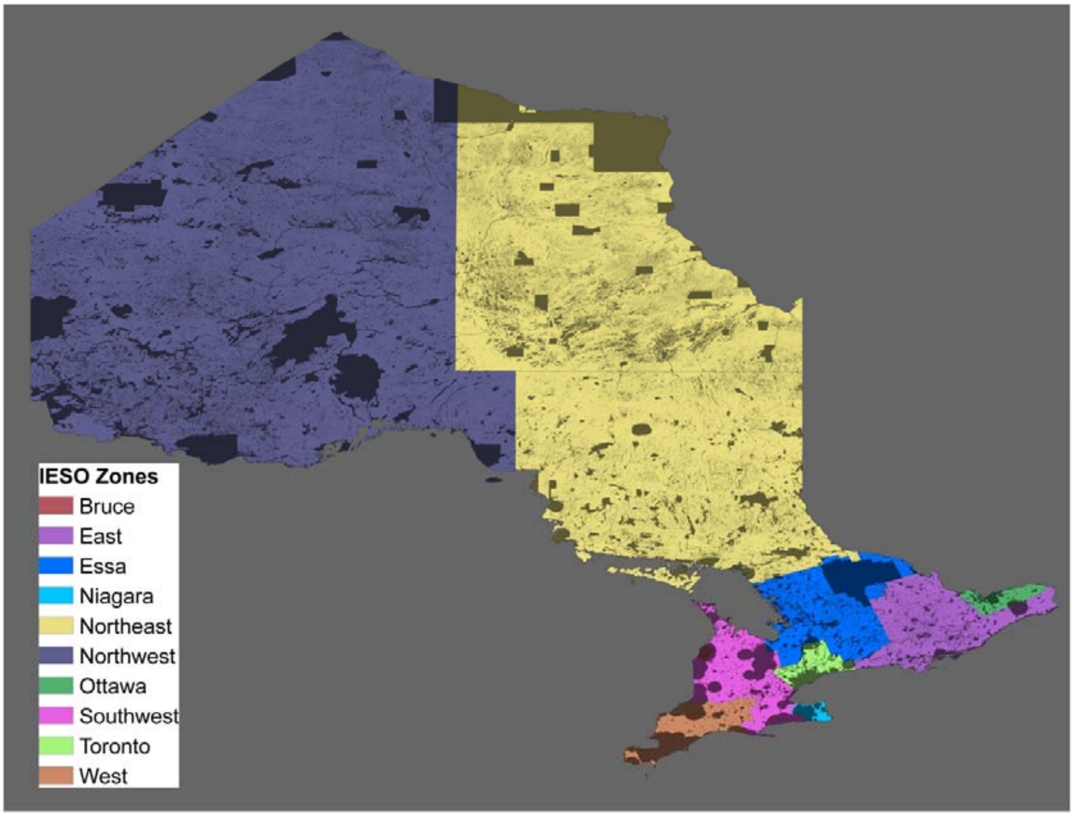

Figure 3.1: Zones of Ontario with excluded areas (grey)

Table 3.2: Summary of Locations for All Plants Modeled

Zone(s)	Operational Site Count	Hypothetical Site Count	Total	Minimum Spacing for Hypothetical (km)
West	24	13	37	10
Southwest, Bruce, and Niagara	26	26	52	10
Toronto and Essa	1	10	11	25
East and Ottawa	4	13	17	25
Northeast < 50°N	7	9	16	50
Northwest < 50°N	1	7	8	50
Above 50°N	0	9	9	50
All Regions	*63*	*87*	*150*	

3.2 Next Generation Wind Turbine Technology

UL developed composite wind turbine characteristics to simulate power production profiles at each of the selected hypothetical sites. The composite turbine was developed based on the physical configuration (e.g., nameplate capacity, hub height, rotor diameter) and operational characteristics (e.g., power curve) of turbines anticipated to reach commercial operation in 2024-2030 i.e., reflecting a “next generation” technology (Table 3.3 and Table 3.4).

To identify representative turbine characteristics, UL reviewed an internal database of recent information compiled from prospective wind projects across Ontario and Canada. The information was used to assess wind developers’ potential application of various future turbine scenarios at sites prior to project financing. When considered in the context of recently installed and operating projects in Ontario, this information, along with estimates on future permitting and market factors, allows a reasonable projection of turbine characteristics for the look-ahead period.

Project economics, as well as turbine technology and transportation advancements, are expected to result in an overall increase in turbine rated capacity and rotor diameter size. It is anticipated that wide-scale deployment of 4 MW turbines will be common in the targeted horizon. Units of this nameplate rating are projected to be achieved with rotor diameters of approximately 150 meters.

Hub height selection for projects anticipated to be operational in the next 5 to 10 years is affected by a number of competing factors. Increasing wind resource with height and larger rotor diameters make higher hub heights attractive, and perhaps necessary. Although component transportation and construction costs generally increase with height, overall project economics and the assumed turbine characteristics anticipated of this next generation turbine technology are expected to necessitate a turbine hub height of 120 m or more. Thus, a 120-m hub height was used for both the site screening process and power production estimation.

The turbine thrust and power curves were developed from a selection of three advanced turbine models with characteristics expected to represent typical fleet-wide installations 5 to 10 years from the present day. These turbine models were selected because the nameplate power to rotor swept area ratios (MW/m²) are similar to the composite future technology turbine. UL normalized the standard air density power curve of the manufacturer turbine power curves and averaged them to develop a synthetic power curve up to 21 m/s. The synthetic turbine was assigned a linear derating from 21-25 m/s to provide representative performance at high winds. The thrust curve was developed with a similar approach.

Table 3.3: Future Technology Static Turbine Characteristics

Nameplate Rating (MW)	Rotor Diameter (m)	Hub Height (m)
4	150	120

Table 3.4: Future Technology Turbine Power and Thrust Curves

Wind Speed (m/s)	Power (MW)	Ct	Wind Speed (m/s)	Power (MW)	Ct
0	0.0000	0.0000	16	4.0000	0.1173
1	0.0000	0.0000	17	4.0000	0.0983
2	0.0000	0.0000	18	4.0000	0.0837
3	0.0662	0.9177	19	4.0000	0.0723
4	0.2609	0.8580	20	4.0000	0.0627
5	0.5730	0.8317	21	4.0000	0.0520
6	1.0430	0.8167	22	3.2000	0.0450
7	1.6870	0.8020	23	2.4000	0.0400
8	2.5274	0.7783	24	1.6000	0.0350
9	3.4285	0.7060	25	0.8000	0.0310
10	3.9216	0.5230	26	0.0000	0.0000
11	4.0000	0.3753	27	0.0000	0.0000
12	4.0000	0.2813	28	0.0000	0.0000
13	4.0000	0.2180	29	0.0000	0.0000
14	4.0000	0.1740	30	0.0000	0.0000
15	4.0000	0.1413			

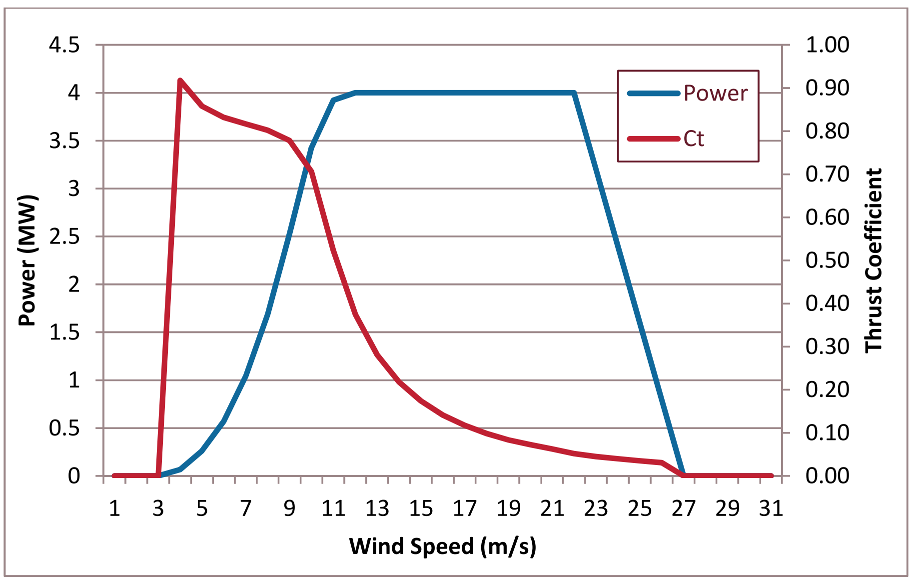

Figure 3.2: Future technology turbine power and thrust curves

4. ATMOSPHERIC MODELING, VALIDATION, AND ADJUSTMENT

Modeling the non-linear, non-stationary atmospheric circulations is challenging. The atmospheric wind flow is part of a complex weather system. Mesoscale numerical weather prediction (NWP) models – the same models used for weather forecasting – are the best tools available to simulate the evolving atmospheric conditions, especially the synoptic scale and mesoscale. Wind is one of the fundamental variables in mesoscale NWP models, but so is temperature, pressure, humidity, etc. Many different atmospheric processes (such as solar radiation, planetary boundary layer, land surface interactions, etc.) are taken into account. In order to capture the relevant scales of atmospheric motion, mesoscale NWP models can have grid resolutions as fine as 1 km or more. Given the computational expense of running mesoscale models at 1-km grid spacing, a microscale wind flow model is necessary to account for the local terrain and land cover conditions at any sites.

4.1 WRF Configuration

For this project, UL utilized the Weather Research and Forecasting (WRF) Model, a leading open-source NWP model developed by National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA) (represented by National Centers for Environmental Prediction), Air Force Weather Agency (AFWA), Naval Research Lab, University of Oklahoma and the Federal Aviation Administration (FAA).[4.10]

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, including radiation, land surface-atmosphere interactions, planetary boundary layer (PBL) turbulence, microphysics, and cloud convection. WRF contains 11 boundary layer schemes, 18 microphysics schemes, and 10 convective parameterization schemes and a three-dimensional (3D) grid to simulate atmospheric processes. The 3D grid can cover a large area, such as a province or state, a country or the globe depending on the grid resolution; a coarser grid can cover a larger area with the same number of grid cells. The vertical levels of NWP models extend far into the stratosphere, typically up to 50 mb, which is roughly equivalent to 20.5 km in altitude, in order to capture the jet stream. An example of such a 3D grid is shown in Figure 4.1.

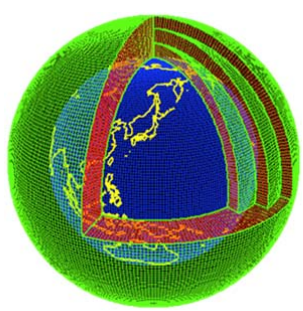

Figure 4.1: Schematic representation of a global 3D grid

WRF simulations were carried out to create the hourly meteorological time series for each of the operational and hypothetical plant locations for the 1988-2018 study period. The WRF model version

[4.10] Skamarock, W. C.et al. (2008). A Description of the Advanced Research WRF Version 3. Boulder: NCAR Technical Note NCAR/TN-475+STR.

3.9.1 with the addition of the Fast-sky Radiation model for Solar applications (FARMS) was used for this project. The WRF model was initialized with the ERA-Interim reanalysis dataset provided by the European Center for Medium Range Weather Forecasting.[4.11] Studies by UL and others show that the third generation reanalysis datasets have superior accuracy in term of their correlation to tall meteorological met mast data.[4.12,4.13,4.14] Another critical aspect is their homogeneity over long time periods, to avoid introducing false trends or spurious discontinuities. The ERA-Interim reanalysis data is available on a 6-hour time interval and supplied the initial and boundary conditions to the WRF simulation. High-resolution terrain, soil, and vegetation data were also used as input where available.

Dynamical downscaling is a method in atmospheric modeling which is designed to provide consistency across different parts of a domain while keeping computational demands manageable. WRF was set up to run two nested grids simultaneously with a horizontal grid spacing of 27 and 9-km (see Figure 4.2). In essence, different scales of motion are resolved by grids with different resolutions. A ratio of 3 between the parent and child grid resolution (e.g. 27 vs. 9-km) ensures a proper energy cascade from the large scales to the small scales, which is mainly due to the non-linear interactions. The two grids, at 27-km (shown in red) and 9-km (shown in green), respectively, resolve successively finer scales across the whole region. The 27-km grid passes the boundary conditions to the innermost 9-km grid, which modifies the atmospheric circulations in response to a consistent set of surface forcings from the terrain elevation, land cover, soil temperature, and moisture, etc. In other words, the data are passed from one grid to the next in a way that allows the model to develop the finest scales in a consistent way.

The model configuration used in this study is summarized in Table 4.1.

[4.11] Dee, D. P., et al. (2011). The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System. Q.J.R. Meteorol. Soc., Vol. 137, pp. 553–597.

[4.12] 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://aws-dewi.ul.com/assets/A-Study-of-Wind-Speed-Variability-Using-Global-Reanalysis-Data2.pdf

[4.13] 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

[4.14] 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

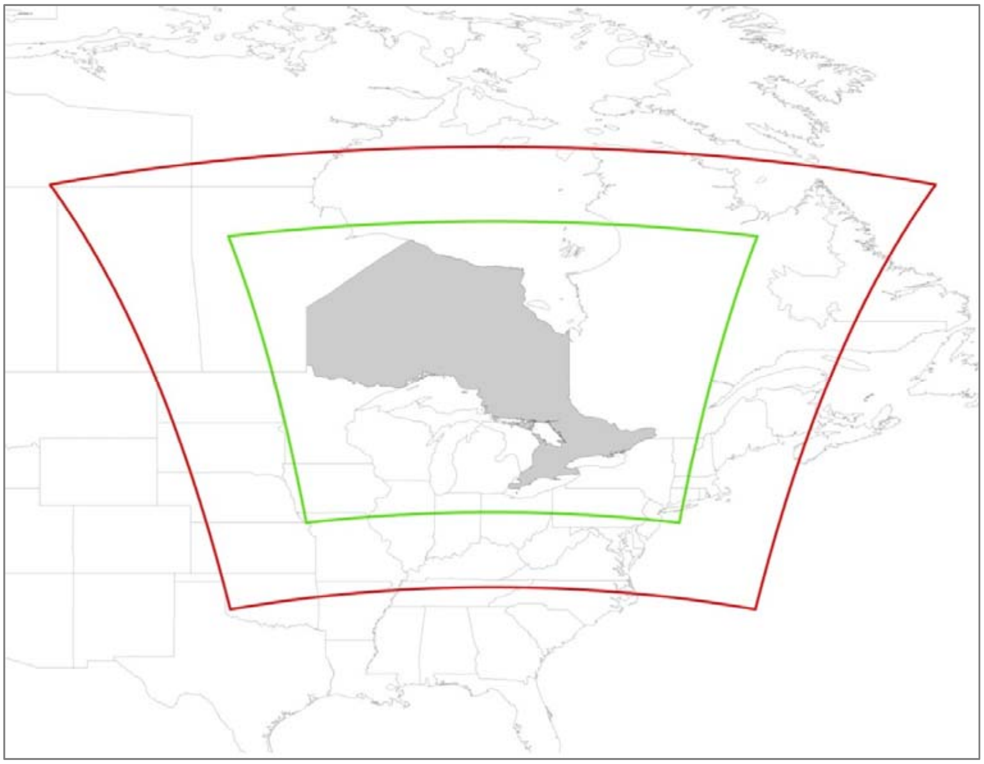

Figure 4.2: WRF nested grids for the study domain

Table 4.1: Model Configuration for WRF Runs

Model	WRF v3.9.1
Initialization Data Source	ERA-Interim
Data Assimilation	Spectral Nudging
PBL Scheme	Mellor-Yamada-Janjic Scheme
Frequency of Data Sampling	1 Hour
Spatial Resolution (Innermost Grid)	9-km

4.2 Resource Validation and Adjustment

Before converting the modeled meteorological time series to wind power generation with the Openwind software, it is first necessary to correct for biases to ensure that the modeled wind resource used in the power conversion method is accurate. This is done by scaling the WRF meteorological variables to match the best estimate of the expected resource average and resource variability at each site. The adjustment and validation of model data requires a sufficiently large sample of observed or measured data. For this project, UL used tall tower datasets from locations within the modeling domain. A vast majority of these towers are located in the southern Ontario region where most of the operational plants are also located. While a number of hypothetical plants are located in the south, these sites are widely distributed across Ontario. Therefore, UL also used tall tower data from northern Ontario in order to accurately characterize the varying wind regimes of the project area. Quality-control was performed on the data included, but not limited to: ensuring the data were not suspiciously below or above the expected wind speed thresholds and analysis of suspect trends or variability. Datasets were discarded if they did not pass the quality-control tests, have a sufficient period of record (at least one year), or provide meaningful values for validation and adjustment.

The final quality-controlled datasets used in the validation and adjustment process consisted of hourly data from 19 towers, totaling over 95 years. UL compared the hourly WRF meteorological time series against the observed measurements for the concurrent period examining the annual, monthly and diurnal pattern. The simulated WRF time series correlated well with the observations, which were primarily used to adjust diurnal wind speeds in the modeled time series.

The observed and adjusted model wind speeds at two tall towers from different regions are shown in Figure 4.3 and Figure 4.4. As shown, the adjusted model time series captures the dynamic behavior of monthly and diurnal wind speeds. The tall tower and adjusted model data exhibit slightly elevated nocturnal wind speeds, but small diurnal variability overall. The overall annual model bias across all tall tower locations is -0.34 m/s. The mean wind speed biases (modeled-observed) range from -0.57 to 0.64 m/s across all tall towers on an hourly basis.

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.

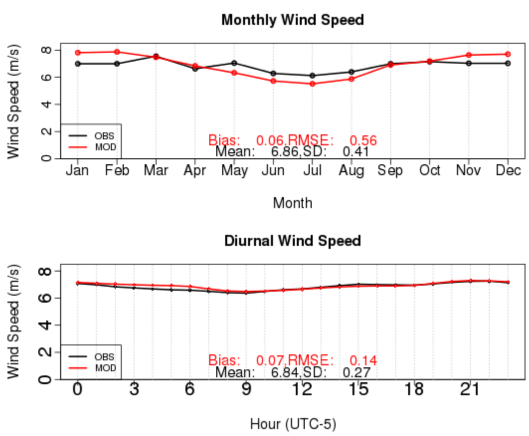

Figure 4.3: Observed and modeled 80-m wind speeds at a tall tower in the Northwest

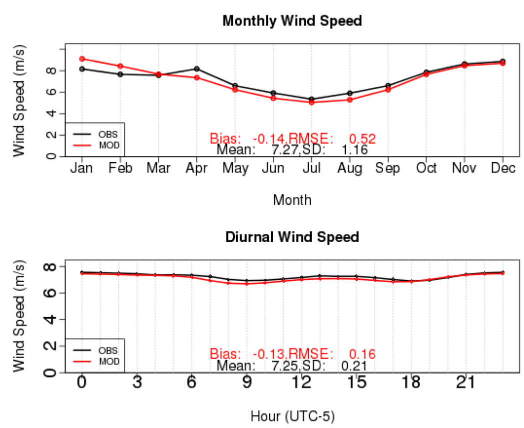

Figure 4.4: Observed and modeled 80-m wind speeds at a tall tower in the Southwest

4.3 Mesoscale-Microscale Modeling

The accurate prediction of a wind plant's energy production is dependent upon an accurate and 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 m.[4.15] UL's modeling system, known as SiteWind, relies on a mesoscale model (i.e., WRF) to properly simulate the atmospheric flow up to the meso-gamma scales (~1 km) then the mean wind flow modeled by the

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

Beaucage, P., M.C. Brower, J. Tensen (2014). Evaluation of four numerical wind flow models for wind resource mapping. Wind Energy, Vol. 17, pp. 197-208.

mesoscale model is downscaled to a 200-m grid spacing using a diagnostic mass-conserving model called WindMap. Atmospheric modeling with a mesoscale model is described in Section 4.1. The WindMap model is a mass conserving model that computes the three-dimensional wind field using the mesoscale NWP model outputs as inputs. WindMap attempts to retain as much information as possible from the mesoscale NWP model while accounting for the high-resolution terrain elevation an land cover data. In order to run the microscale model efficiently and keep file storage manageable, the WindMap simulations were divided into 21 different domains covering all 63 operational wind farms and 87 hypothetical wind farms as shown in Figure 4.5.

The WindMap model outputs are stored in binary wind resource grid (WRG) 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.

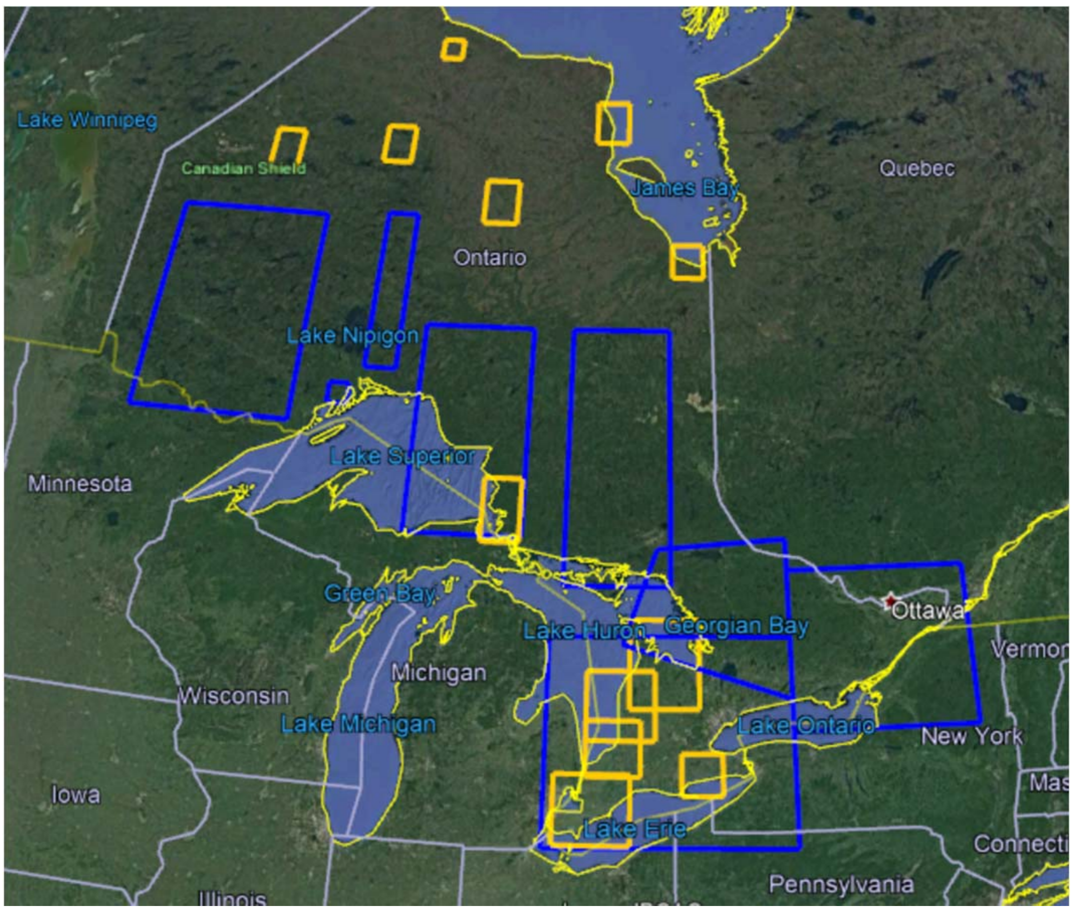

Figure 4.5: WindMap domains for Ontario

5. POWER CONVERSION

Hourly profiles were generated for the period January 1, 1988 to December 31, 2018 at the 63 operational and 87 hypothetical sites. The adjusted WRF time series (Section 4.2) served as input to Openwind, UL's plant design and optimization software used for bankable energy production estimates and reports. Operational plant characteristics as described in Section 2.1 and next-generation wind technology at hypothetical plants (Section 3.2) were used to simulate hourly wind power generation at the sites. The following section describes the Openwind setup and configuration used to simulate gross and net energy production as well as plant losses.

5.1 Openwind Configuration

In order to calculate the expected energy capture, or production, of wind turbines in an array, Openwind requires data files describing the spatial and temporal distribution of the wind resource, information about the local terrain, and a set of parameters describing wind turbine characteristics at each site.

Turbine characteristic files were created for each of the operational and next-generation turbines described in Sections 2.1 and 3.2, respectively. These files include parameters for the hub height and rotor diameter, power and thrust curves, storm control settings, cut-in, cut-out and cut-back-in wind speeds, cold weather package settings, low and high temperature shutdown and temperature de-rating specifications.

Spatial and temporal distributions of the wind resource were provided in the form of binary wind resource grids (WRBs) and hourly WRF meteorological time series. The WRBs generated by UL's coupled mesoscale-microscale modeling system (Section 4.3) defines the wind resource at 60 m, 80 m, 100 m and 130 m above ground level across all the project locations. Data from adjacent heights are used within Openwind to extrapolate to hub heights between these levels. The terrain elevation and surface roughness maps are the same as the ones used for the microscale WindMap simulations. Between 1 and 5 hourly WRF meteorological time series were imported into Openwind as virtual meteorological masts at each wind farm. The WRF data at 60 m, 80 m, 100 m and 130 m above ground level was imported at the operational plant locations, and at 120 m for the hypothetical plant locations.

To estimate the energy production of each turbine location, Openwind extrapolates the WRF wind speeds at the virtual mast locations based on directional speed-up factors derived from the WRB files and applies a temperature adjustment based on terrain elevation. This allows for the weather conditions to vary among the turbines, with turbines at higher elevations typically experiencing lower temperatures, lower air density, and greater icing than turbines at lower elevations.

The Openwind time series energy capture module runs the meteorological time series through the respective power curve at each turbine to estimate gross wind power generation adjusting for the effects of turbulence intensity and air density on the power curve. Details of the energy loss calculations to estimate net power are given in Section 5.2.

The time series energy capture module was run for two scenarios. The first scenario included only operational wind farms so that the operational plant profiles did not include wake effects of hypothetical sites. The second scenario included both operational and hypothetical wind farms. This allowed hypothetical plant profiles to include wake losses from nearby operational plants.

5.2 Openwind Plant Losses

The net energy production is derived by subtracting all the wind plant losses from the gross energy. The net power represents the total power at the electrical connection point of the wind farm to the grid, typically a substation. The losses at any wind plant are classified in the following categories:

- Wake effects:
  - Internal wake effects (inside the project)
  - Wind farm shadowing (wake effects from neighboring wind farms)
- Availability:

  - Scheduled maintenance
  - Outages (substation and utility grid, plant restart after grid outage, force majeure)
- Environmental:
  - Icing
  - Low temperature shutdowns
  - High temperature shutdowns
  - High Wind Hysteresis
  - Blade degradation
- Electrical:
  - Electrical efficiency (transformers, electrical collection system, etc.)
  - Power consumption of wind turbines (lighting, O&M facility, cold weather package, de-icing system, etc.)
- Turbine performance:
  - Sub-optimal operation (yaw and blade pitch misalignments, control anemometer calibration, etc.)
  - Power curve adjustment (expected turbine performance relative to advertised power curve)
- Curtailments:
  - Directional curtailments (for turbines spaced less than 3 rotor diameter distance from each other)
  - Environmental curtailments (habitat concerns, noise constraints, shadow flicker, etc.)
  - Grid-related or power purchase agreement curtailments

UL estimated gross and net energy production as well as losses for the following categories: wake, availability, environmental and electrical. Three losses mentioned above were not included: turbine performance, blade degradation, and curtailment. IESO sought profiles to represent power generation with no grid curtailment losses. UL did not have a clear indication of turbine performance issues in Ontario and therefore assumed that the power generation of all turbines followed their advertised power curve. Finally, blade degradation is marginal and difficult to estimate accurately.

5.2.1 Wake Effects

In projects involving more than a handful of wind turbines, wake effects typically reduce power production by anywhere from 3% to 15% on an annual average. Furthermore, wake-induced turbulence can cause wear on the components of turbines, and for this reason, turbines are usually spaced no closer than three rotor diameters, and they may have to be shut down under certain conditions to satisfy the manufacturer's warranty.

UL uses the Deep Array Wake Model (DAWM) inside Openwind to calculate wake losses.[5.16] The DAWM actually contains two separate wake models operating independently: (1) the Eddy Viscosity model, which is based on the Navier-Stokes equations rate of wake dissipation[5.17] and (2) a second model designed to better capture wake losses in deep (multi-row) arrays of wind turbines loosely based on a theory developed by Frandsen (2007) to treat each turbine as an isolated island of roughness.[5.18] 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 thus, the roughness model is employed.

[5.16] 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.

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

[5.18] 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.

In addition to wake effects from turbines within the same wind farm, i.e. internal wakes, the turbine-induced wakes from a neighboring wind farm located upstream can impact the energy production. As a general rule inter-plant wake losses are assumed to be negligible on average for plant spacings greater than about 50 rotor diameters (about 5 km). To the extent they occur, Openwind takes them into account since the simulation domains cover multiple projects at a time.

5.2.2 Availability

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 issues requiring retrofits, and other 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 operation.[5.19]

The time-varying wind plant availability was modeled in the Openwind software using a Markov chain method. The Markov chain sets a random process in motion to simulate the transition from one plant state to another. The states are defined in this case as the number of turbines that are available for production at a given time. The availability model simulates the change in number of turbines that are available, and therefore the change in availability loss, from one time step to the next.

The main component of the Markov chain is a transition matrix, which indicates the probability of transitioning from any given current state any other state in the next time step. For a given availability state, specific turbines are selected at random to be switched off within Openwind. 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 are selected in order to model the persistence of turbine downtime patterns.

Transition matrix probabilities were constructed using SCADA data from operational projects in a similar climate as Ontario providing a total of 52 wind-farm years of data, and thus the outcome reflects actual plant behavior. Separate transition matrices were applied during different parts of the year in order to account for seasonal variation in maintenance scheduling. One transition matrix covered the winter season from December 1st through March 31st, when routine maintenance is not performed. The second matrix represents the remainder of the year, i.e. April 1st through November 30th.

Table 5.1 and Table 5.2 show the transition matrices for each period, spring/summer/fall and winter respectively. The rows correspond to the current state and the columns to the subsequent or future state.[5.20] The bins are defined as a percent of total capacity so that the transition matrices are independent of the size of the wind farms. However, when applied in Openwind, the percent availability is multiplied by the total number of turbines in the plant and rounded to an integer number of turbines offline at one time. 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.

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

[5.20] Note that each row sums to 1, corresponding to a 100% probability that a plant, no matter its initial availability, will arrive at an availability between 0 and 1 in the next time step.

Table 5.1: Transition Matrix for the Spring/Summer/Fall seasons. The left-most cell in each row represents the initial state, the header of each column the next state. The value in a cell is the probability of transitioning from the initial state to the next state (rounded to the nearest percentage).

Summer Availability	(0.99,1]	(0.95,0.99]	(0.85,0.95]	(0.75,0.85]	…	(0.05,0.15]	(0.01,0.05]	(0,0.01]
(0.99,1]	92%	7%	0%	0%	…	0%	0%	0%
(0.95,0.99]	7%	89%	4%	0%	…	0%	0%	0%
(0.85,0.95]	1%	13%	84%	2%	…	0%	0%	0%
(0.75,0.85]	1%	2%	13%	77%	…	0%	0%	0%
…	…	…	…	…	…	…	…	…
(0.05,0.15]	4%	2%	2%	1%	…	68%	7%	2%
(0.01,0.05]	1%	1%	2%	2%	…	3%	75%	6%
(0,0.01]	2%	0%	7%	7%	…	8%	6%	35%

Table 5.2: Transition Matrix for the Winter Season, as defined in Table 5.1.

Winter Availability	(0.99,1]	(0.95,0.99]	(0.85,0.95]	(0.75,0.85]	…	(0.05,0.15]	(0.01,0.05]	(0,0.01]
(0.99,1]	92%	8%	0%	0%	…	0%	0%	0%
(0.95,0.99]	8%	89%	4%	0%	…	0%	0%	0%
(0.85,0.95]	1%	8%	88%	2%	…	0%	0%	0%
(0.75,0.85]	1%	1%	12%	80%	…	0%	0%	0%
…	…	…	…	…	…	…	…	…
(0.05,0.15]	1%	0%	0%	1%	…	80%	5%	1%
(0.01,0.05]	1%	0%	1%	1%	…	6%	79%	6%
(0,0.01]	0%	0%	0%	0%	…	0%	2%	96%

5.2.3 Environmental - Icing

There are two main types of icing mechanisms: (a) in-cloud icing (which forms rime ice) and (b) precipitation icing (which forms glaze ice). The proportion of rime icing over precipitation icing varies based on the local climate and topography, but the most severe icing effects come from ice storms, i.e. precipitation icing. Freezing rain and wet snow are the most common forms of precipitation icing, which result in clear, solid glaze ice. Ontario's harsh winters mean that energy losses due to icing may be one of the leading causes of lost production at many wind projects.

To create a wind power time series including icing losses, the onset, and duration of icing conditions must be well represented by the modeling system. The timing of icing events should be captured at least partially by the WRF model, however predicting the ice accretion rate on the surface of the blades is more challenging, as it is a function of the icing type, blade characteristics, e.g. shape, size and composition, as well as atmospheric conditions, e.g. temperature, relative humidity, and precipitation. Each type of ice has a different density, liquid water content, and adhesion properties, and theoretical formulation of ice accretion rates are limited, and complicated by the shape of a blade, and several efficiency factors, i.e. collision, sticking and accretion, that must be estimated. A complicating factor is that the rotor blades rotate when there's enough wind for the turbine to generate electricity.

Due to the complexity and non-linear interactions between the weather conditions and the actual lost energy from icing, UL has been relying on a pragmatic icing loss model. The icing model in Openwind was initially developed using the SCADA data from 40 operational wind-farm years in a similar climate as Ontario. The icing model was built using non-linear relationships between four met variables from the WRF model (i.e. predictors) and the lost energy due to icing (predictand) derived from the operational data. A Generalized Additive Model simulates the icing energy loss based on the WRF model outputs, specifically temperature, relative humidity, precipitation and wind speed.

5.2.4 Environmental - Temperature shutdown

Turbine shutdowns can be triggered by very low or very high temperatures. Temperature shutdown losses vary with climate, but for most wind farms in the mid-latitudes, these energy losses are typically below 1% on an annual average. During the winter, turbines equipped with a cold weather package can safely operate down to -25°C or -30°C depending on the turbine model. In warm weather, turbines can operate to temperatures of at least 35°C. Temperatures in Ontario very rarely reach such highs.

Openwind models the low- and high-temperature shutdown behavior for each turbine type. The turbine characteristic files which serve as inputs to the Openwind software include several wind turbine control set points such as the minimum and maximum threshold for temperature shutdowns and power curve derating, if applicable.

5.2.5 Environmental - High Wind Hysteresis

Wind turbines typically cut out under sustained wind speeds averaging about 22 to 25 m/s over a 10-minute period depending on the turbine model.[5.21] Once the turbine is shut down due to high winds, it is brought back online only after wind speeds have typically dropped by 3 m/s from the cut-out wind speed. This type of wind energy loss is called high wind hysteresis. This behavior is modeled in Openwind based on the turbine characteristic files, which include the cut-in, cut-out and cut-back-in wind speed information for each turbine model as well as the power curve derating (i.e. storm control system) if applicable.

5.2.6 Electrical Losses

Electrical losses are experienced by all electrical components of a wind farm, including the padmount and substation transformers, electrical collection system as well as the power consumption of cold weather packages and de-icing systems.

5.2.6.1 Electrical Efficiency

The electrical efficiency of a wind farm is primarily driven by losses associated with the transformers and the collector system. It appears as a difference between the sum of individual turbine energy output measured at each padmount transformer, and the power measured at the revenue meter on the high-voltage side of the substation as it passes into the grid. The Openwind software includes an electrical efficiency model which was derived from operational data from approximately 20 wind farms in a similar climate as Ontario.

[5.21] The turbine is switched off and their blades feathered to minimize loads.

5.2.6.2 Turbine Power Consumption

Modern wind turbines consume power to run equipment such as yaw mechanisms, blade-pitch controls, aircraft warning lights, oil heaters, pumps, and coolers for the gearbox and hydraulic brakes for locking blades down in high winds, etc. The sum of these sources of turbine power consumption is typically much less than 1%, even for wind turbines equipped with a cold weather package. The Openwind software includes a turbine consumption model which was derived from operational data from approximately 10 wind farms in a similar climate as Ontario. Not every turbine model reports negative net power generation, meaning instances where the turbines were net consumers of electrical power.

De-icing systems such as rotor blade heating system consume a lot more power than the electrical equipment on the turbines or the cold weather packages. Note that UL did not model the power consumption of de-icing systems since there was no indication that such de-icing systems were in place at wind farms in Ontario.

5.3 Modeled Time Series Adjustment

The modeled power generation time series from the Openwind software were adjusted using the filtered, historical generation data from operational plants described in Section 2.2. The main purpose for this adjustment is to account for (i) site-specific plant losses that are not dependent on meteorological conditions (e.g. availability), (ii) unknown operational plant issues (e.g. turbine performance) or (iii) limitations in atmospheric and energy modeling. For instance, UL assumed approximately 5% time-weighted availability loss at all the operational (and hypothetical) plants which is a typical value for modern wind farms in North America. We do expect plants in Ontario to deviate from the average plant loss, however, no information specifically related to the availability losses at each operational plant was available. In addition, some plants might be experiencing technical difficulties such as turbine underperformance that are either uncommon or unknown. Finally, while state-of-the-art atmospheric models (i.e. WRF) and energy conversion tools (i.e. Openwind) are employed, models are not perfect. In the end, the goal of the adjustment process is to remove or reduce the bias on the modeled net power generation, if needed.

The operational wind power profiles directly from the Openwind software had a mean bias close to 0.7 MW, UL selected a simple approach for the adjustment of the net power profiles. The availability and wake losses were tuned up or down with a scaling factor in order to bring the mean bias in the net power profiles closer to 0 MW at each plant. This adjustment of the availability and wake losses was applied only to plants having an absolute mean bias above 1 MW. No adjustment was applied to operational plants with less than one year of operational data or to the hypothetical plants as the mean bias was close to 0 MW at the operational wind farms. UL requires a minimum of one year of historical generation data so that no seasonal biases are introduced by the bias correction method. As mentioned in Section 2.2, 52 out of the 63 operational plants (83%) had a sufficiently long record of operational plant data to apply an adjustment.

5.4 Availability-Loss Adjusted Time Series

The IESO also desired hourly power profiles that did not include plant availability losses associated with planned or unplanned outages. Therefore, once the net wind power time series were generated by the Openwind software and adjusted, as applicable, a new set of net power time series were created by adding back the availability loss in the net power generation.

5.5 High Frequency 5-Minute Time Series

UL's in-house statistical downscaling method was adapted to create synthetic 5-minute interval time series for the 2014-2018 period based on the modeled hourly net power profiles. The hourly wind power time series were heavily based on UL's mesoscale numerical weather prediction model and the Openwind software. Since there are computational limitations in running mesoscale models with a high spatial resolution for the entire province of Ontario, statistical methods were employed to overlay 5-minute fluctuations from actual wind power generation at operational plants on the modeled hourly profiles.

UL's statistical downscaling approach requires high-frequency observations to properly mimic the 5-minute wind power fluctuations at operational sites. As detailed in Section 2.2, good quality 5-minute wind power data was available at 52 of the 63 operational wind farms. Whenever possible, the actual 5-minute power generation at the operational plant itself was used to downscale the modeled hourly profiles to 5 minutes. For the 11 operational wind farms without operational plant data and the 87 hypothetical wind farms, the 5-minute actual generation from a nearby operational plant was selected based on closest distance, high data recovery and similarity in plant capacity.

To produce the 5-minute wind power time series, 5-minute fluctuations from the operational plants were overlaid on the modeled hourly profiles (Figure 5.1). UL's statistical downscaling approach was used with four-hour windows of historical 5-minute data. First, the hourly trends were removed from the data using a bicubic fitting procedure. Next, the residuals were added to the simulated hourly output for each site by selecting randomly a window of actual five-minute fluctuations within a similar capacity factor bin as the hourly capacity factor at that time.

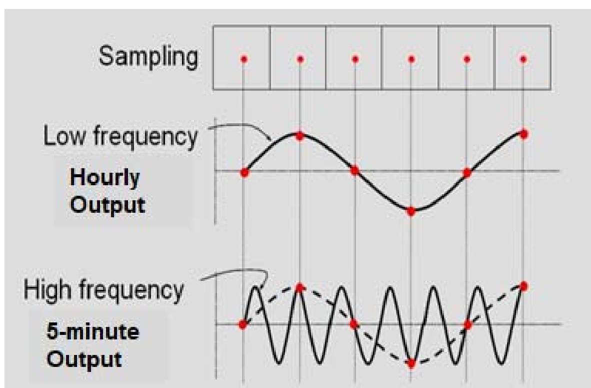

Figure 5.1: Schematic Representation of High-Frequency Output Synthesis

Finally, 5-minute wind power time series can be generated at any specific location. UL's statistical method was used to create, 5-minute wind power profiles at 63 operational plants and 87 hypothetical plants. Figure 5.2 shows a typical sample of 5-minute observed and modeled (normalized) wind power generation at one operational plant. The modeled 5-minute wind power displays similarities to the observed data even though the modeled fluctuations do not necessarily align with the observed data, which is expected due to the statistical method. In addition, Figure 5.2 suggests that while the 9-km WRF simulation is able to capture the larger scale temporal variations in wind speed, and therefore in power generation, it does not necessarily get the timing right due to phase errors which are intrinsic to mesoscale modeling (and data assimilation).

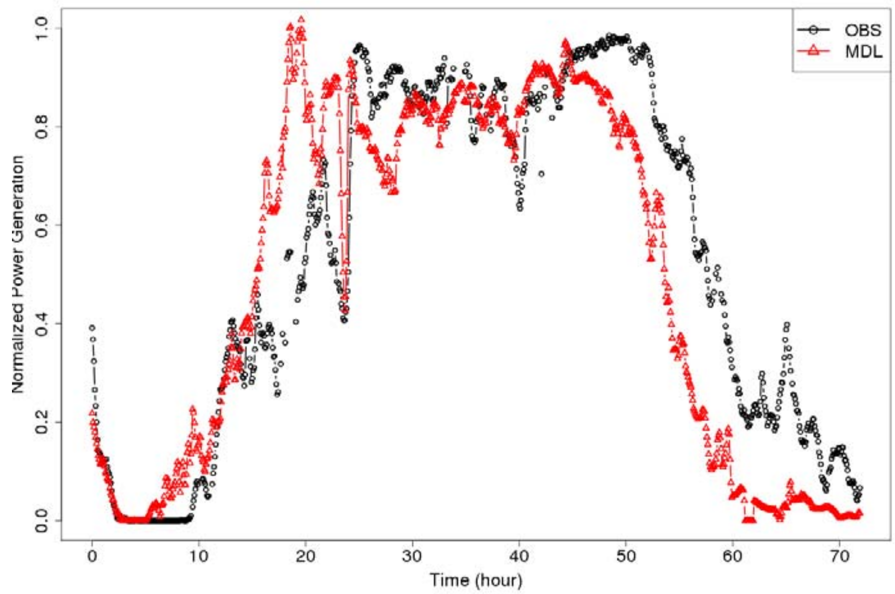

Figure 5.2: 72-hour sample of 5-minute normalized power generation on February 6 to 8, 2014. The black curve is actual power generation at an operational plant and the red curve corresponds to modeled generation.

6. RESULTS AND VALIDATION

6.1 Hourly Wind Power Profiles

Hourly net power generation profiles were simulated for the period 1988-2018 across 63 operational and 87 hypothetical plants within the IESO domain. The net capacity factors of the final generation profiles varied from 23.2% to 40.9% with an average of 31.8% at the operational plants. The modeled net capacity factors are well aligned with the historical generation data which yields an average net capacity factor of 31.3%. The modeled total plant losses average around 20% and 22% for the operational and hypothetical plants respectively, which are reasonable values for plants in North America.[6.22] The main reason for the difference in total plant loss between the operational and hypothetical plants is that wake losses were 2% higher at the hypothetical sites most likely due to the larger rotors. It is also worth noting that 16 hypothetical plants had low temperature shutdown losses above 1% due to their location in cold climates further north in Ontario. In comparison, only two operational plants had losses due to low temperature shutdown above 1%. On average, the low temperature shutdown loss is around 0.2% and 0.9% at the operational and hypothetical plants in Ontario, respectively, according to the models.

As described in Section 5.3, a simple adjustment was applied to the raw modeled generation profiles created by Openwind software to remove or reduce the mean bias in net power generation where the absolute mean bias in net power was greater than 1 MW. Figure 6.1 and Figure 6.2 show how much the mean net power bias has changed after the adjustment was applied. The histogram of the mean

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

biases before (Figure 6.1) and after (Figure 6.2) the adjustment show that biases were significantly reduced. Figure 6.2 indicates that the mean biases at all the operational plants are more closely centered on 0 MW. The range of the mean biases for the raw net power profiles was -6.0 to 8.5 MW with an average around 0.69 MW at the 52 operational plants available for validation. These results indicate our models validate extremely well as demonstrated by the small overall bias despite limited knowledge about plant operations and related assumptions used for modeling the plants, availability losses in particular. In comparison, the range of the mean biases for the final net power profiles, after adjustment is -2.6 to 3.3 MW with an average of 0.20 MW. For perspective, the plant capacities of the operational wind plants range between 6.15 and 270.0 MW with an average around 83.4 MW (and a median around 78 MW).

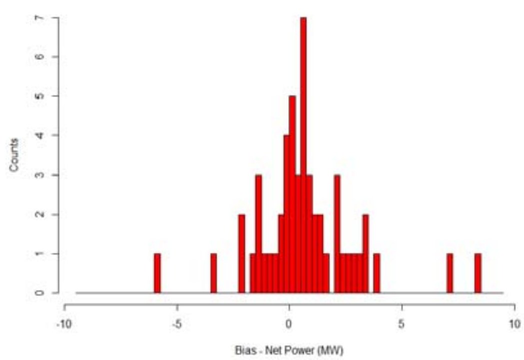

Figure 6.1: Histogram (counts) of mean net power bias (MW) for the raw profiles at the 52 operational plants available for validation

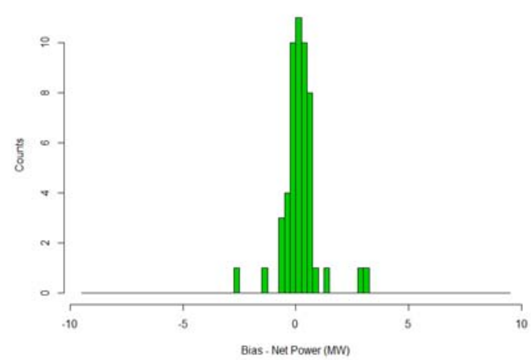

Figure 6.2: Histogram (counts) of mean net power bias (MW) for the final profiles at the 52 operational plants available for validation

A thorough validation of the adjusted net power profiles was performed by comparing concurrent records only for the observed (historical) and modeled profiles. Note, however, that the observed generation at the 52 operational plants used for validation covered a period between 1 and 5 years, not the full 1988-2018 period that was modeled. At most operational plants, the final modeled annual and monthly patterns align very well with the (observed) actual generation data. The monthly patterns show a clear peak in wind power generation in the winter in Ontario across all sites. The diurnal patterns vary quite a bit from site to site, some showing a peak in wind power generation during nighttime, others in the early to mid afternoon and some without a clear peak throughout the day on average. The diurnal profiles are generally well captured by the final profiles although there are some exceptions where the diurnal profiles between hour 0 and 12 UTC (7 pm to 7 am EST) do not match as well as the rest of the day (hour 13 to 23 UTC). The scatterplots of hourly observed and modeled net power generation show a lot of spread with hourly R^2 averaging around 0.61. The availability losses model by the Markov chain in the Openwind software is most likely the main reason for the low correlation on an hourly basis. The Markov chain is a statistical process with some randomness to it and therefore the modeled turbine downtime and outages are unlikely to occur at the same time as observed in plant generation data. Although randomness due to the Markov chain may still impact monthly patterns, it is expected to be substantially limited compared to the hourly profiles. As such, the correlation on a monthly basis aligns better with an R^2 averaging 0.88 across all operational plants. As an example of the strong agreement in monthly averaged net power generation, Figure 6.3 and Figure 6.4 show the observed and modeled wind generation at two operational plants. These two operational plants, Site 1 and Site 34, were chosen as they represent a typical case and the worst case in terms of mean net power bias.

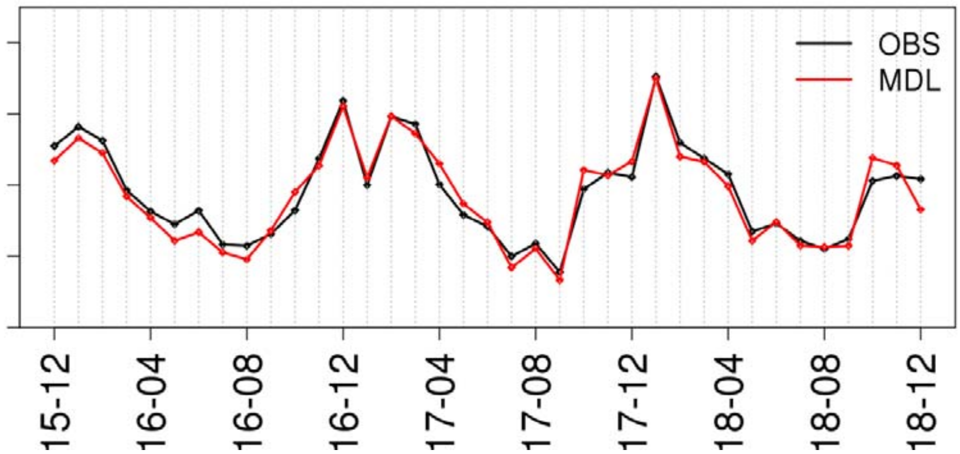

Figure 6.3: Monthly time series of observed (OBS) and final (MDL) net power profiles at Site 1. The Y axis is net power generation.

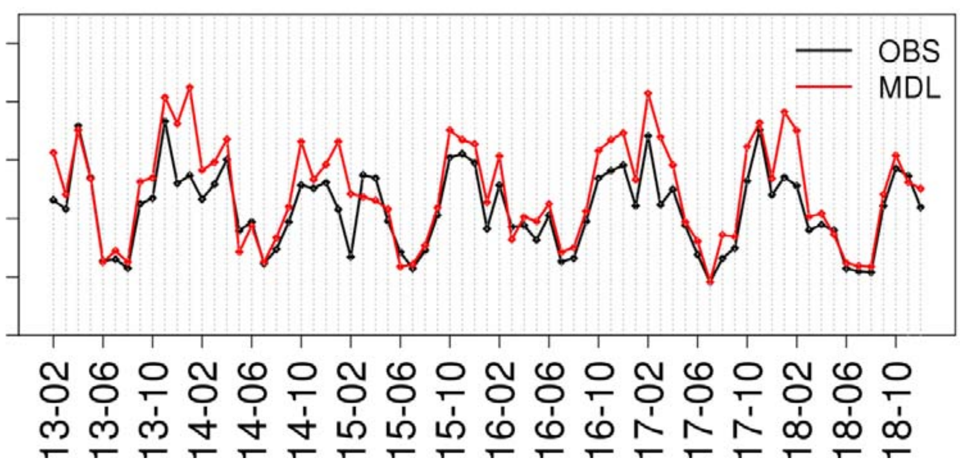

Figure 6.4: Monthly time series of observed (OBS) and final (MDL) net power profiles at Site 34. The Y axis is net power generation.

For an overview of the accuracy of the final net power profiles, Figure 6.5 and Figure 6.6 show the validation results for a typical case (Site 1) and the worst case (Site 34) in terms of mean net power bias. These 4-panel plots provide an evaluation of the final profiles at different time scales: annual, seasonal/monthly, diurnal (hour-of-the-day) and hourly. Even in the worst case at Site 34, the modeled annual, monthly and diurnal patterns align well with the observed pattern in a relative sense, albeit with an overall positive bias around 3 MW (~ 3% of plant capacity). Based on the monthly patterns, the adjusted profile at Site 34 has a larger error in the winter season than in the summer. It is possible that the icing losses are not properly captured at this site although the closest neighboring plant (Site 33) does not exhibit significant bias in the winter season, except for the month of February. It is also possible that wake losses at this site are more severe due to the lake effect and stable boundary layer resulting from the westerly flow in the winter. Without a time series of the plant losses from the actual plants, it is not possible to determine the exact cause of the discrepancy.

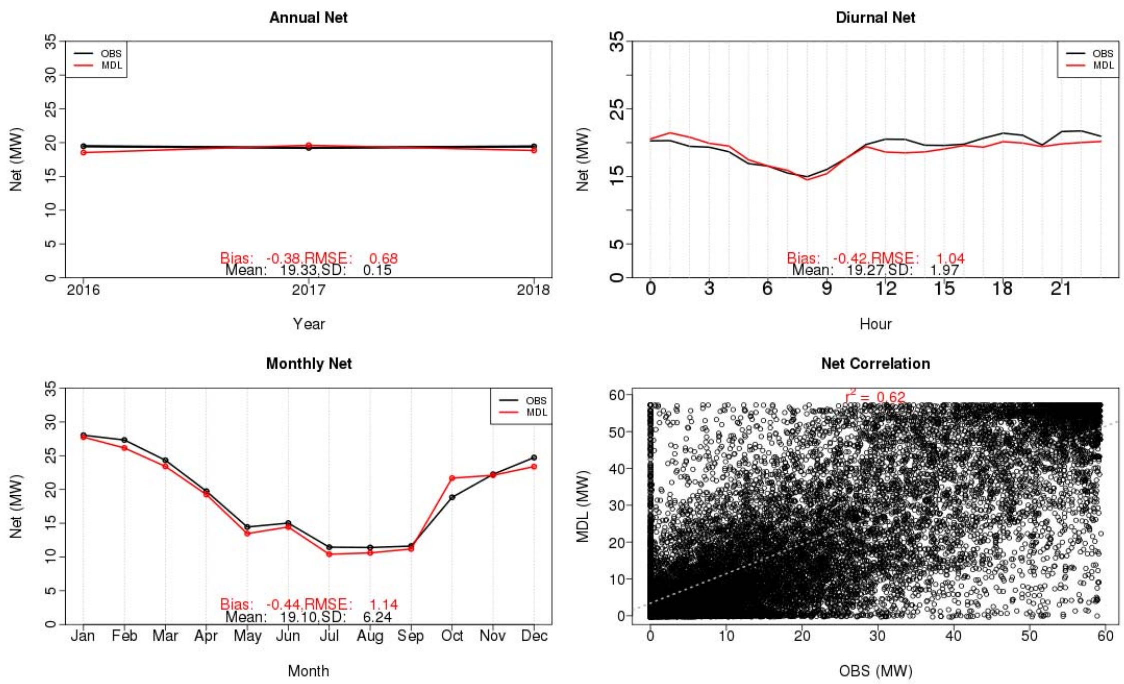

Figure 6.5: Observed (OBS) and final (MDL) net power profiles at Site 1 with annual (top left), monthly (bottom left), diurnal (top right) and scatterplot (bottom right). Hours are in UTC.

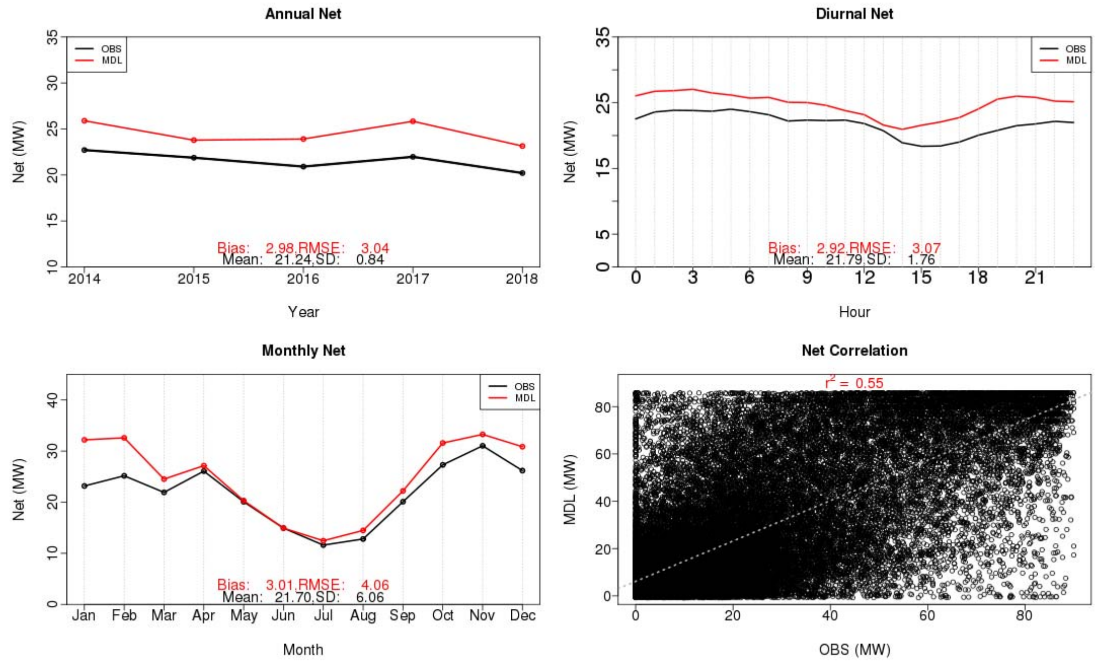

Figure 6.6: Observed (OBS) and final (MDL) net power profiles at Site 34 with annual (top left), monthly (bottom left), diurnal (top right) and scatterplot (bottom right). Hours are in UTC.

In addition, a validation of the hourly ramps was performed to ensure that the final profiles exhibit the proper fluctuations in net power generation. Figure 6.7 and Figure 6.8 provide two typical cases of net power ramp distributions seen at the operational plants. In general, the ramp distributions in Ontario follow a similar shape as seen in other studies.[6.23,6.24,6.25] Figure 6.7 for Site 1 illustrates that the final profiles adequately model the fluctuations in net power generation on an hourly basis, but may not fully capture the temporal variability. In contrast, the modeled ramp distribution at Site 34 (Figure 6.8) is almost perfectly aligned with the observed ramp distribution and the behavior of the final profile looks very reasonable. Note, that the observed net power generation represents a 5-minute average even though historical data on the hour only was used to validate the final profiles, suggesting that our modeling system with WRF and Openwind was able to properly account for the 5-minute fluctuations.

[6.23] Brower, M. (2009). “Development of Eastern Regional Wind Resource and Wind Plant Output Datasets”. Technical report from AWS Truewind LLC, NREL/SR-550-46764, 64 pp. Available at: https://www.nrel.gov/docs/fy10osti/46764.pdf

[6.24] Manobianco, J., C. Alonge, J. Frank and M. Brower (2010). “Development of Regional Wind Resource and Wind Plant Output Datasets for the Hawaiian Islands”. Technical report from AWS Truewind LLC, NREL/SR-550-48680, 32 pp. Available to: https://www.nrel.gov/docs/fy10osti/48680.pdf

[6.25] Anvari, M., G. Lohmann, M. Wächter, P. Milan, E. Lorenz, D. Heinemann, M. R. R. Tabar and J. Peinke (2016). “Short term fluctuations of wind and solar power systems”. New J. Phys. Vol. 18, 063027

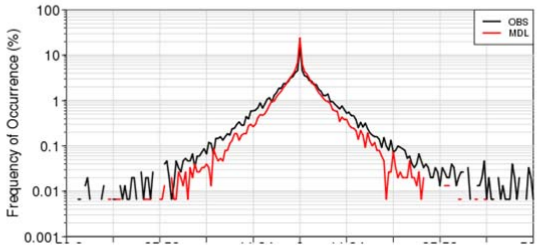

Figure 6.7: Ramps distribution from the observed (OBS) and final (MDL) net power profiles at Site 1.

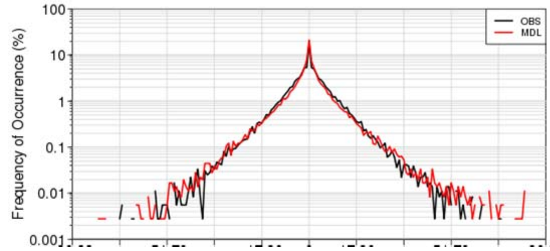

Figure 6.8: Ramps distribution from the observed (OBS) and final (MDL) net power profiles at Site 34.

Lastly, the final generation profiles were examined for reasonableness at the aggregate level of 7 operational plants (totaling a capacity of 190 MW) having at least one year of historical generation data and data recovery above 80%. Although operational data was available from 52 wind farms for the validation exercise, the majority of them had low data recovery due to curtailment which significantly reduces the sample size available when creating aggregates of concurrent plant data. Only 7 operational plants had sufficient data recovery to create an aggregate with a decent sampling size. It is also important to note that these 7 plants do not represent a domain-wide aggregate and the plant capacities range from 9 to 49 MW, which is much lower than the average or median plant capacity within the IESO fleet.

Figure 6.9 illustrates that the monthly pattern and ramp distribution from the final profiles agree with the observed generation, although diurnal and generation plot does not for this aggregate. Upon review, the adjusted profiles at two of the 7 plants composing this aggregate were not well aligned with the observed diurnal pattern. Figure 6.10 includes the histogram and the duration curve for all concurrent, hourly historical and final net power time series for the 7 plants. This analysis shows that final net power profiles are able to accurately capture the dynamic behavior of those 7 operational wind plants.

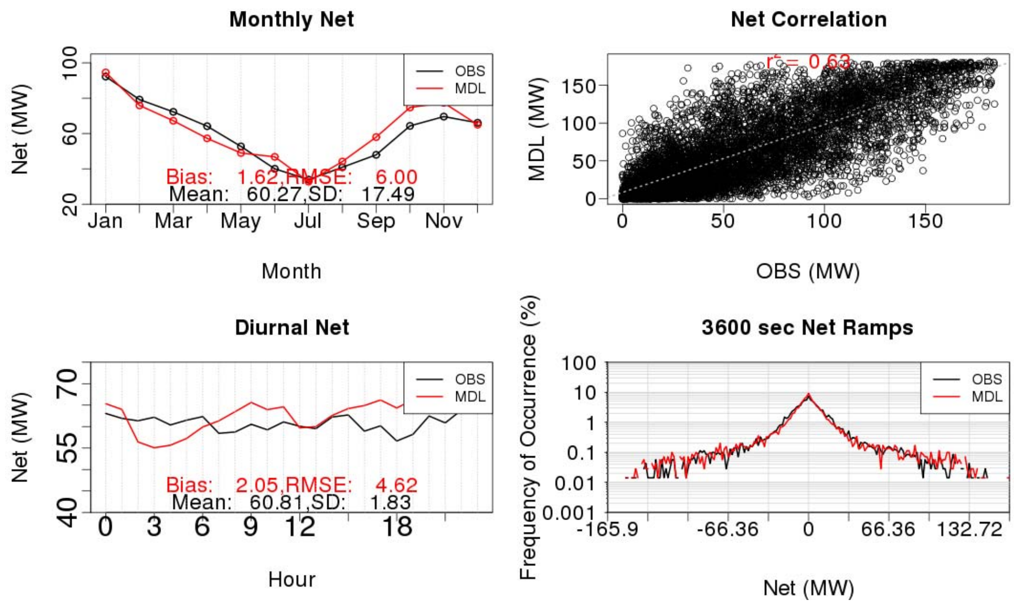

Figure 6.9: Observed (OBS) and final (MDL) net power profiles at an aggregate of 7 plants with monthly (top left), diurnal (bottom left), scatterplot (top right) and ramp distribution (bottom right). Hours are in UTC.

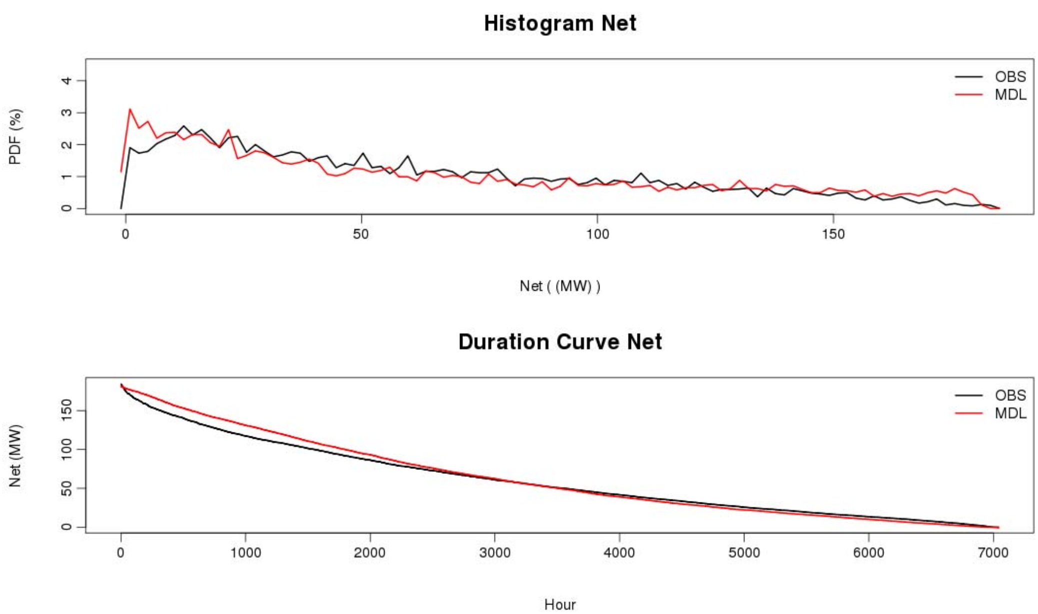

Figure 6.10: Observed (OBS) and final (MDL) net power histogram (top panel) and duration curve (bottom panel) at an aggregate of 7 plants.

6.2 5-Minute Wind Power Profiles

The synthetic 5-minute wind power time series for the 2014-2018 period were compared to actual power generation data at 52 operational plants in Ontario to ensure that UL's statistical downscaling method captures the dynamic patterns of real data. The wind power time series were visually inspected to ensure that the synthetic 5-minute profiles matched the previously delivered hourly data on the hourly values which indicated that the 5-minute wind power time series are perfectly aligned with the hourly time series. For example, the monthly and diurnal patterns (left panels) show biases close to 0 MW and the scatterplot (upper right panel) exhibits a perfect correlation of 1.0. Note that one difference between the 5-minute and hourly profiles is that the 5-minute profiles do not include any negative generation records, unlike the hourly profiles. Negative net power can occur during calm wind speed events due to the turbine power consumption or in the winter when the cold weather package is engaged. The hourly profiles modeled by Openwind include this plant loss. However, the statistical downscaling used to create the 5-minute generation profiles is based on actual plant generation data which does not include negative power records. This explains why the bias between 5-minute and hourly profiles is not exactly 0 MW.

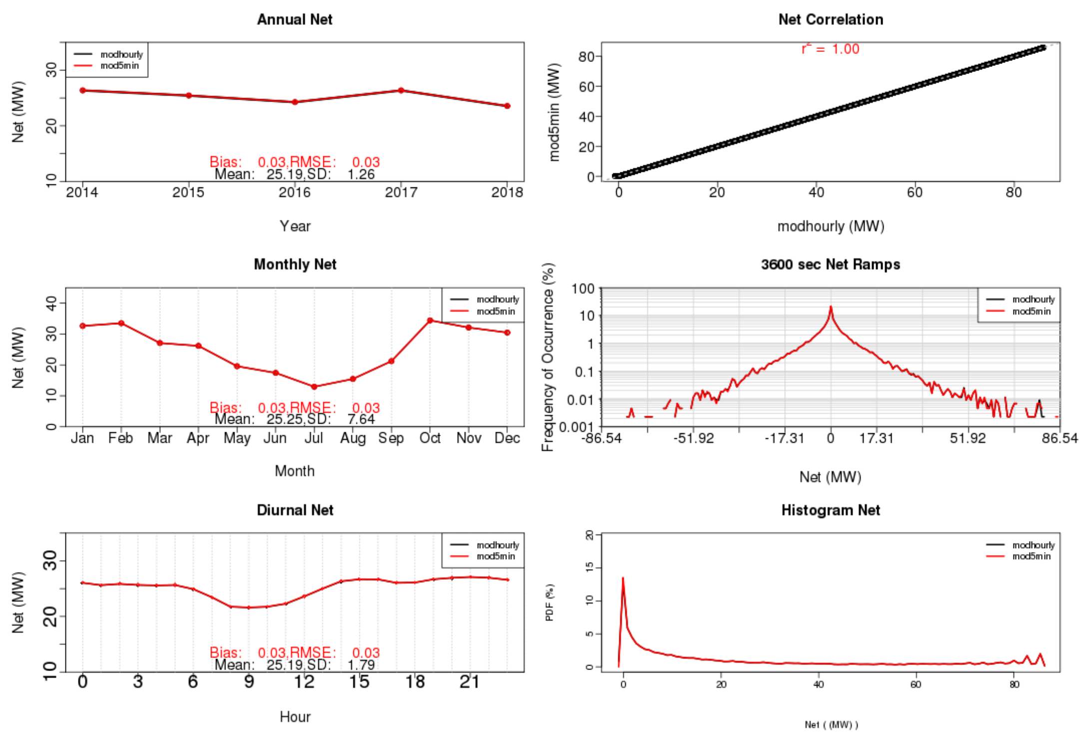

Figure 6.11: Comparison of hourly (black) and 5-minute (red) modeled wind power generation at Site 34. The panel plots include annual, monthly, and diurnal mean wind speed on the left and a scatterplot, ramp frequency distribution, and histogram on the right. Hours are in UTC.

Five-minute modeled wind power profiles were compared to actual power generation at the operational plants over their concurrent period. Figure 6.12 demonstrates that the 5-minute profiles (red) capture the observed (black) wind power generation just as well as they did on an hourly basis (see Figure 6.6). Additionally, the annual, monthly and diurnal wind generation patterns are very similar when averaged from the 5-minute (Figure 6.12) or hourly profiles (Figure 6.6). The 5-minute R^2 correlation is also similar to the hourly R^2 correlation. More importantly, Figure 6.12 shows that modeled 5-minute ramp distribution aligns well with the observed distribution. This is a strong indication that the statistical downscaling method produced realistic 5-minute wind power time series.

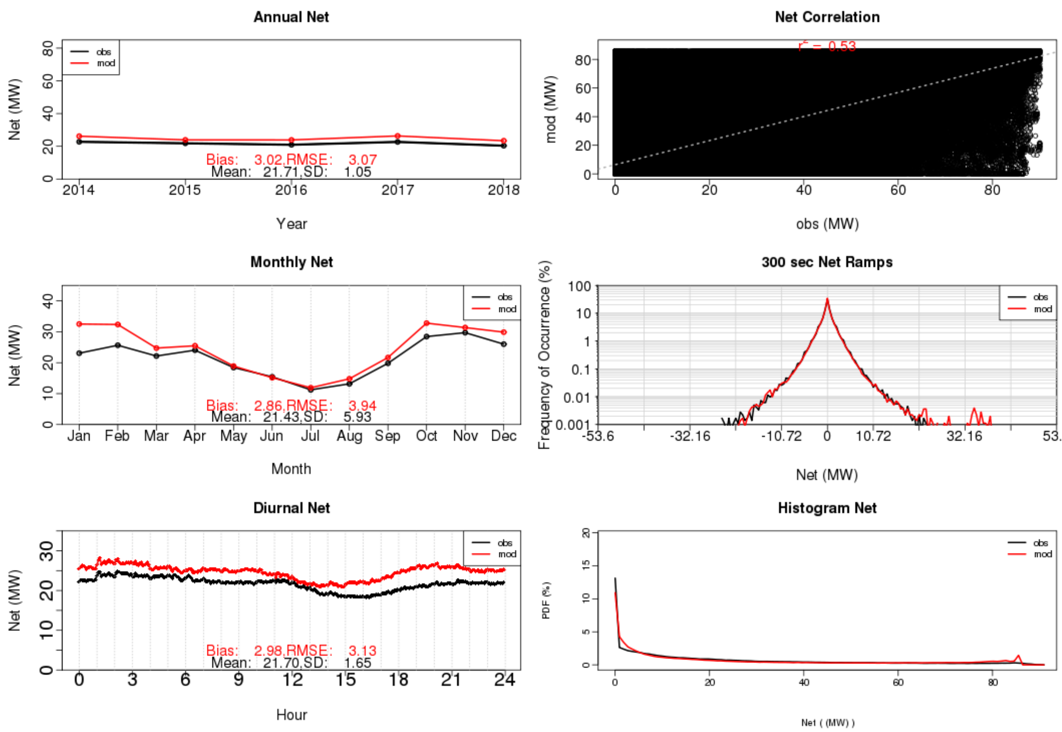

Figure 6.12: Comparison of observed (black) and modeled (red) 5-minute wind power generation at Site 34. The panel plots include annual, monthly, and diurnal mean wind speed on the left and a scatterplot, ramps frequency distribution and histogram on the right. Hours in UTC.

The high-frequency fluctuations from the observed and modeled 5-minute time series were also analyzed by evaluating the power spectral density (PSD). Kolmogorov's second hypothesis of similarity predicts that the power spectrum of wind velocity should vary as $f^{-5/3}$ for atmospheric flows (i.e. large Reynolds number).[6.26] Studies have shown that the frequency spectrum of the wind plant power generation follows a power law with a slope between $f^{-5/3}$ and f^{-2}.[6.27,6.28,6.29] The power spectrum at one of the operational wind farm follows an f^{-2} slope over multiple orders of magnitude in frequency (see **Error! Reference source not found.**). More importantly, the modeled PSD shows a similar behavior as the observed PSD throughout the frequency range up to 10 minutes, the Nyquist frequency.[6.30]

[6.26] Wilcox, D.C. (2006). Turbulence modeling for CFD, 3rd Edition, DCW Industries, Inc. 522 pp.

[6.27] Apt, J. (2007). "The spectrum of power from wind turbines", J. Power Sources, vol. 169, pp. 369-374

[6.28] Bossuyt, J. C. Meneveau and J. Meyers (2017). "Wind farm power fluctuations and spatial sampling of turbulent boundary layers", vol 823, pp. 329-344.

[6.29] Katzenstein, W, E. Fertig, J. Apt (2010). "The variability of interconnected wind plants". Energy Policy, vol. 38, pp. 4400-4410.

[6.30] The Nyquist frequency is twice the highest frequency in the time series.

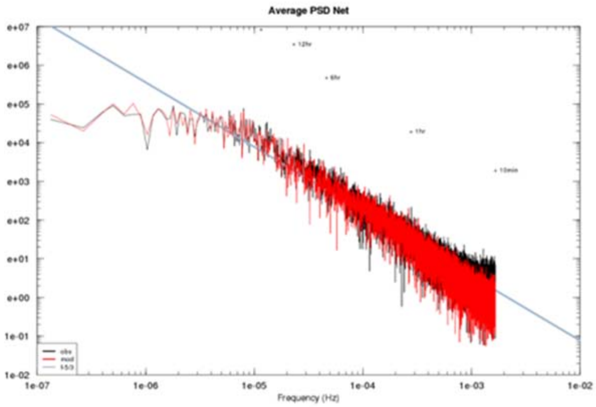

Figure 6.13: Power spectral density of observed (black) and modeled (red) 5-minute wind power generation at Site 1. The Kolmogorov spectrum ($f^{-5/3}$) is represented by the grey line.

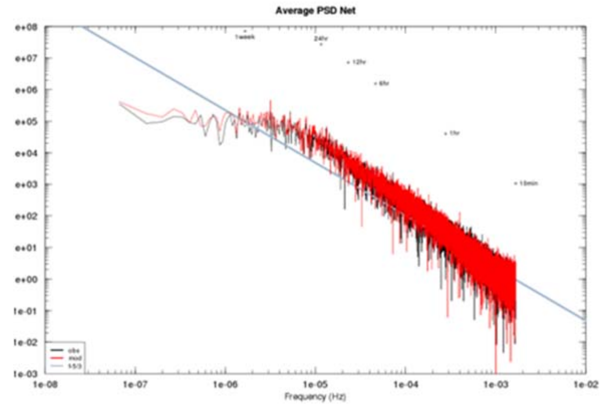

Figure 6.14: Power spectral density of observed (black) and modeled (red) 5-minute wind power generation at Site 34. The Kolmogorov spectrum ($f^{-5/3}$) is represented by the grey line.

7. CONCLUSION

UL was retained by IESO to simulate hourly and intrahour wind generation for the period 1988-2018 for 150 operitonal and hypothetical plants. The goal of this work was to provide high-fidelity power profiles for the operational plants and to identify and simulate hypothetical plants. Due to the low bias seen in the operational fleet, the hypothetical profiles were not adjusted. It has been shown that the simulated wind data accurately represents historical generation patterns at individual wind plants and on an aggregate basis, at the hourly and 5-minute time intervals.

The final hourly profiles represent uncurtailed generation, current operational plant-on-plant wake conditions (where applicable), and operational plant losses (where applicable) as derived from historical generation data. It is important to note that the generation profiles assume the current configuration of the 2017 IESO wind fleet as applied to an extended historical weather record (1988-2018). Therefore, as a result of using the 2017 fleet configuration without curtailment historical generation at a given plant or for a given time period may not entirely agree with the simulated profiles; especially at sites that are curtailed frequently or where plant-on-plant wake losses have been introduced over time.

APPENDIX A - STATIC DETAILS FOR OPERATIONAL PLANTS

Site #	Modeled Cap (MW)	Hub Height (m)	Rotor Diameter (m)	WTG Model(s)	Data Review
1	59.92	80	100	GE.1.62	
2	74.112	99.5	113	Siemens SWT-3.2-113	< 1 year
3	178.651	99.5	101	Siemens SWT-2.3-101	
4	99.819	99.5	113	Siemens SWT-3.2-113	
5	59.94	80	100	GE.1.6	
6	72.9	80	100	GE.1.6	
7	19.44	96	100	GE.1.6	
8	38.88	96	100	GE.1.6	
9	100.065	99.5	113	Siemens SWT-2.3-113	
10	82.8	80	101	Siemens SWT-2.3-101	
11	82.8	80	101	Siemens SWT-2.3-101	
12	78	80	82.5	GE.1.5xle	
13	99	80	90	Vestas V90 1.8	
14	99	80	90	Vestas V90 1.8	
15	39.6	80	80	Vestas V80 1.8	
16	50.6	80	101	Siemens SWT-2.3-101	
17	102.06	80	100	GE.1.6	
18	148.617	99.5	101	Siemens SWT-2.3-101	
19	98.9	80	101	Siemens SWT-2.3-101	
20	40	99.5	113	Siemens SWT-3.0-113	
21	149.04	80	100	GE.1.6	
22	269.957	99.5	101	Siemens SWT-2.3-101	
23	39.978	99.5	113	Siemens SWT-2.3-113	
24	59.99	98.3	103	GE.2.75-103	
25	67.5	80	77	GE.1.5sle	
26	132	80	77	GE.1.5sle	
27	24.952	99.5	113	Siemens S2.3-113	
28	99.12	99.5	113	Siemens SWT-3.2-113	< 1 year
29	48.6	80	90	Vestas V90 1.8	
30	101.2	80	93	Siemens SWT-2.3-93	
31	101.2	80	93	Siemens SWT-2.3-93	
32	99	80	77	GE.1.5sle	
33	99	80	77	GE.1.5sle	
34	90	80	77	GE.1.5sle	
35	269.749	99.5	101	Siemens SWT-2.3-101	
36	77.9	77	82	Enercon E82 2.0	
37	104.4	95	90	Vestas V90 1.8	
38	91.687	80	100	GE.1.6, GE.2.75-103	
39	98.9	80	101	Siemens SWT-2.3-101	

Site #	Modeled Cap (MW)	Hub Height (m)	Rotor Diameter (m)	WTG Model(s)	Data Review
40	124.3	80	101	Siemens SWT-2.3-101	
41	181.5	80	82	Vestas V82 1.65	
42	233.2	124	101	Enercon E101 3.0	
43	197.8	80	93	Siemens SWT-2.3-93	< 1 year
44	99.32	99.5	113	Siemens SWT-3.0-113	
45	99	132	136	Vestas V136 3.45 MW	Planned –None Available
46	300.15	132	126	Vestas V136 3.45 MW	Planned –None Available
47	60.15	132	136	Vestas V136 3.6 MW	Planned –None Available
48	22.921	80	101	Siemens SWT-2.3-101	
49	29.7	80	82	Vestas V82 1.65	
50	22.68	80	100	GE.1.6.100xle	
51	10.25	98	82	Enercon E82 2.0	< 1 year
52	17.6	100	92.5	REpower MM92	NA
53	10.25	78	82	Enercon E82 2.0	
54	28.7	100	92.5	REpower MM92	NA
55	39.6	80	82	Vestas V82 1.65	
56	20	85	100	GE.2.5xl	< 1 year
57	9.9	80	82	Vestas V82 1.65	
58	27	80	82.5	GE.1.5xle	
59	10.25	78	82	Enercon E82 2.0	NA
60	30	99.5	113	Siemens SWT-3.0-113	
61	8.2	100	92.5	REpower MM92	
62	32.2	99.5	101	Siemens SWT-2.3-101	
63	6.15	100	92.5	REpower MM92	