Application of Weather and Other Environmental Inputs in PowerWorld Simulator Version 24

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Overview

- The purpose of this presentation is to show the benefits of having weather information become a standard part of power flow analysis and more broadly electric grid planning, and to show how everyone can easily begin using weather data today (at least for North America)
  - The results also apply to related applications such as optimal power flow (OPF), contingency analysis, security-constrained OPF
- This presentation builds on the one I gave in April 2024, covering some of the many recent developments with a tutorial focus
  - A few of the more recent PowerWorld developments are covered, including what is in the newly released Version 24 (March 2025)

Aside: Upcoming Short Courses

- At Texas A&M in College Station TX in 2025
  - Full details at **epg.engr.tamu.edu/short-courses-main/**
  - **Electric Grid Impacts of Geomagnetic Disturbances** (March 18-19)
  - **Primer on the Planning and Operation of Large-Scale Electric Grids** (Sept 9-11)
  - **Fundamentals of Electric Transmission System Planning** (Oct 7-9)
  - **Introduction of Artificial Intelligence in Power Systems (**Nov 4-6**)**

Using Weather with PowerWorld Simulator

- Over the last three years PowerWorld has gained a lot of weather modeling related capability, and is continuing to gain more
- Currently
  - Past, present and future weather data can be loaded into Simulator
    - This can be done using *.pww, *.aux, or *.csv files
    - Hourly past data is available from 1940 to five days behind real time; present data is available from measurements; future is hourly up to 16 days
  - The weather impacts the power system models using PFW (Power Flow Weather or Power Flow Whatever) models; PFW models can be thought of like the stability models: they are applied to power system objects (e.g., a generator or line) and different classes of models can be defined
  - PFW models can be applied automatically in the **Time Step Simulation**, and applied (currently) on demand in the other applications like power flow

PowerWorld Simulator Version and Build Date

- The weather functionality started being available in Version 23, particularly ones with later build dates, with much more now in 24 Currently available as an add-on included in the base package
- Much of the weather does not require cases with geographic values, but more can be done when available
- Since new Version 24 patches are frequently released, what is available depends on the build date; the Simulator version and build date are available by selecting **Window, About**
- We desire your suggestions on what should be included moving forward

The Power Flow and Weather

- Human activity depends on the weather, and this has always been reflected in the electric load
- Traditionally some power flow parameters have depended on the weather (e.g., line ratings, turbine max MW, line resistance)
- Over the last several decades this dependence has grown substantially with the increase in wind and solar generation
  - They now (all of 2024) provide about 17% of US electric energy; there are times when most of the electricity in regions is supplied by these sources
  - They are extremely dependent on the weather
- Major power system input parameters are now heavily weather dependent (e.g., wind and solar generator Max MW)

Planning, Weather and Other Resiliency Events

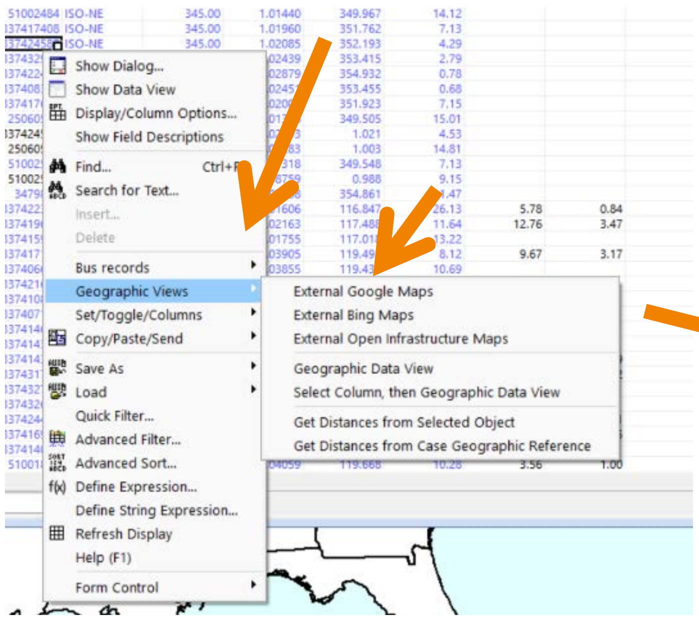
- As defined by NERC, planning assessment for large-scale grids is, “Documented evaluation of future transmission system performance and corrective action plans to remedy identified deficiencies”
  - Planning is forward looking, leveraging historical information
- Planning can consider timeframes from near real-time to decades
- Weather and other resiliency considerations can include
  - Inputs to set weather dependent power flow values such as wind, solar (irradiation), temperature for transmission line and transfer limits
  - Extreme weather including hurricanes, ice storms, derechos, tornados
  - Other events such as earthquakes, wildfires, geomagnetic disturbances (GMDs), volcanic events, eclipses
  - This are collectively referred to here as Environmental Inputs (ENIs)

Using Weather and Related Data in the Power Flow

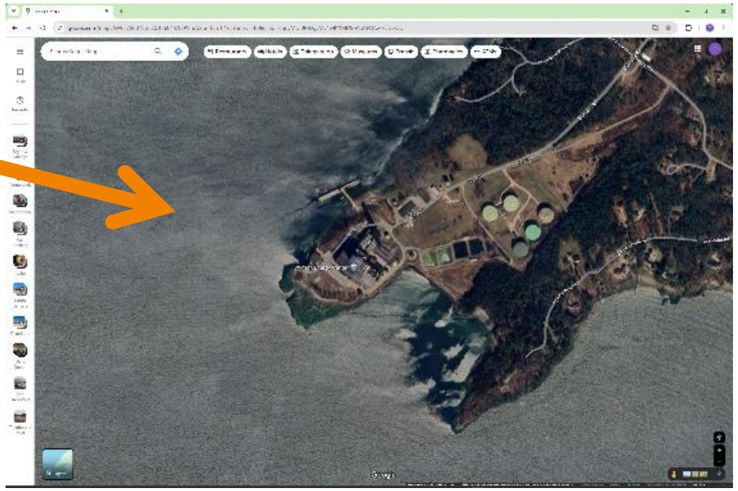
- To use weather data and other ENIs in the power flow requires
  - The availability of geographic information mapping buses to substations, and then geocoordinates for the substations
    - This is now mostly available for North American grids; PowerWorld has long stored it mostly with the substation records (sometimes the buses)
    - Large-scale synthetic grids with geographic information are also available
  - Convenient access to available ENIs (e.g., weather information) over the footprint of interest
    - For planning often the footprint is large, beyond a single utility
  - The availability of models that represent the impact of weather and other ENIs on electric grid components

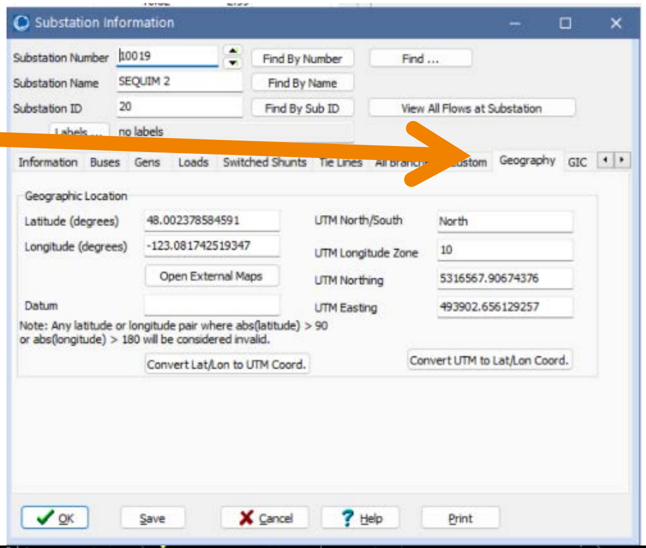
Example Simulator Geographic Displays

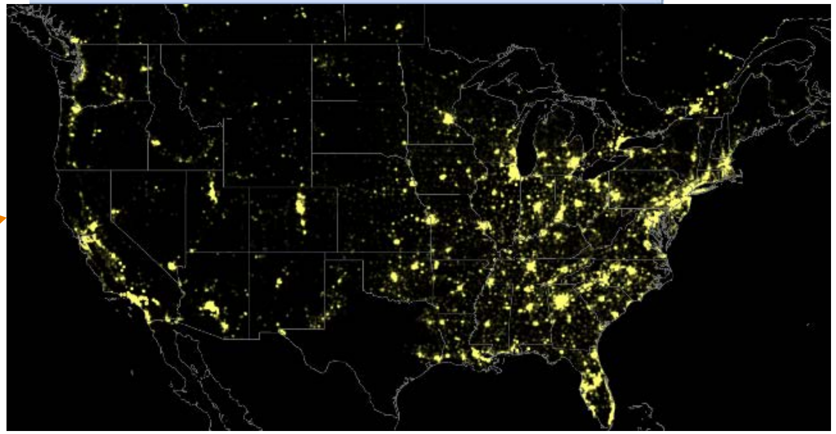
- Starting with version 24, external maps can easily be displayed using the right-click menu



Geography page from the substation objects



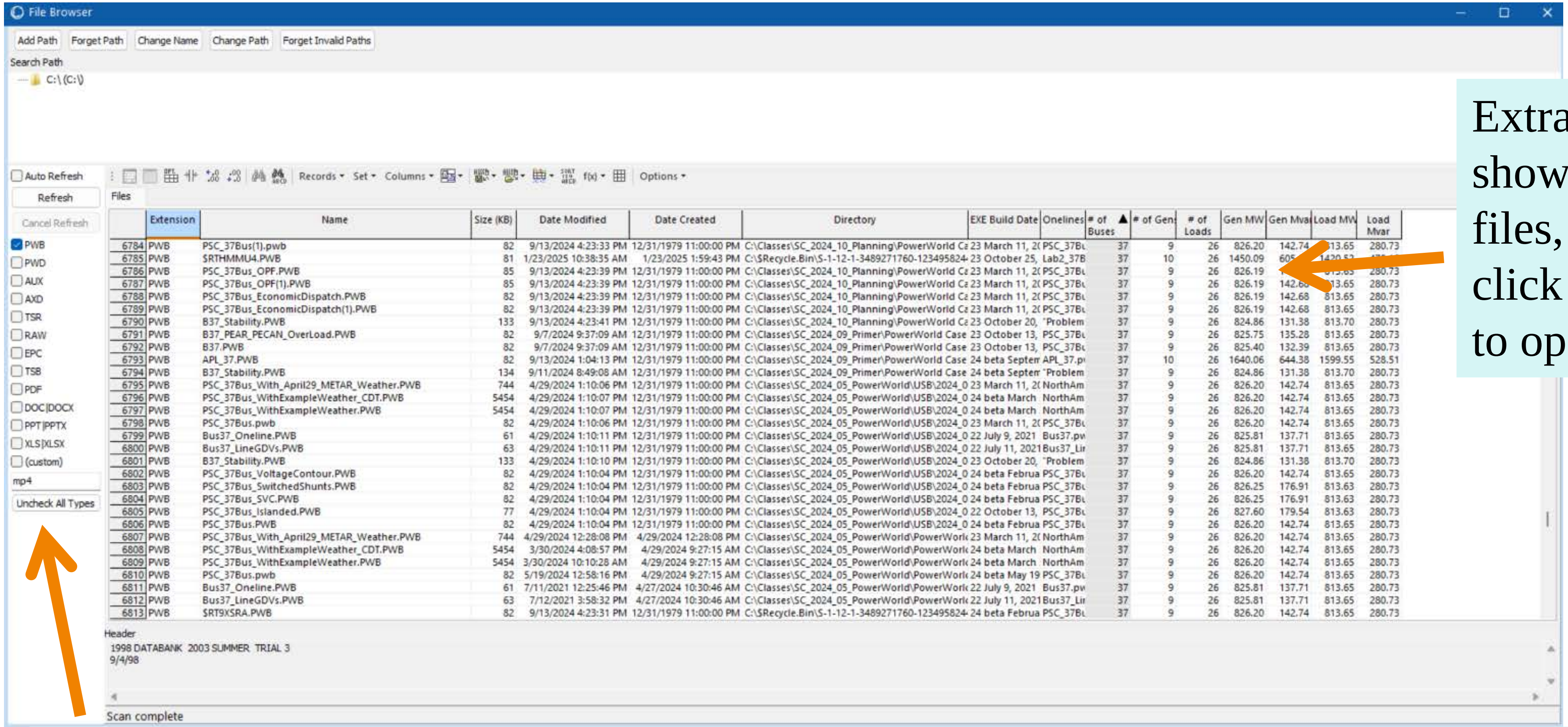




Power flow load density contour created leveraging geographic information

Aside: Rapidly Finding Files Using Simulator

- To quickly find stored files, select **File, General File Browser**



Extra information is shown for *.pwb files, and the right-click menu can used to open the file

This display can be used to find and open files of any time (e.g., *.ppt, *.xls, etc.)

Availability of Weather Information

- We started this effort three years back by using historical weather station measurements (mostly identified by their ICAOs [International Civil Aviation Organization], e.g. KLIT, KCLL)
  - We had lots of data, but much of it had missing values; we also only had surface wind values and no direct solar measurements
  - Such measurements at specific locations can still be very useful (e.g., at electrical substations)
- There are many other sources of free weather information, with good coverage provided by *Weather DataSet Needs for Planning and Analyzing Modern Power Systems*, Energy Systems Integration Group (ESIG), October 2023
  - www.esig.energy/wp-content/uploads/2023/10/ESIG-Weather-Datasets-summary-report-2023.pdf

ESIG Report (10/2023)

- “These widespread changes lead to the increasing weather-dependence of supply and demand, making power system planning dramatically more complex and requiring much more comprehensive weather data for robust system planning.”
- “The work required to achieve a long-term solution to weather data needs is not trivial, but it is manageable and is much less costly than blindly building trillions of dollars of infrastructure without the basic tools to cost effectively optimize it and assess its reliability.”
- PowerWorld had started working in planning weather integration about a year before the ESIG report appeared, but much progress has been made in the last 18 months

TABLE 2

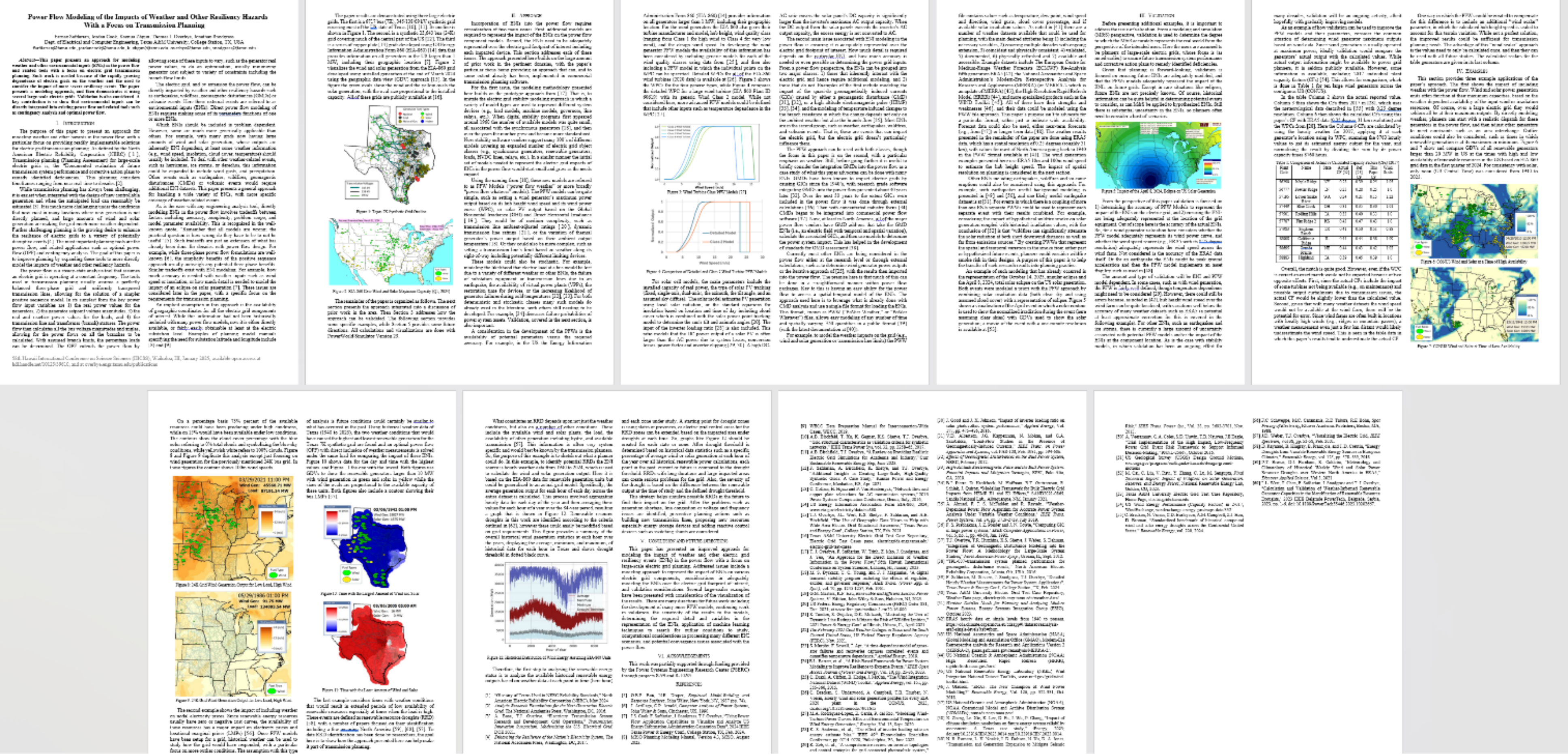
Summary of Current Power System Modeling Weather Input Data Sources

	Spatial Resolution	Temporal Resolution	Length	Continuously Extended	Correct Variables/ Levels	Coincident and Coherent	Validated/Uncertainty Quantified for Power System Use	Detailed Documentation	Future-Proofed	Availability/ Ease of Access	Curation and Advice	Region Covered
MERRA-2[a]	~60 km	60 min	1980–present	Yes	Yes/No	Yes	No		Probably		Basic	Global
ERA5[b]	~30 km	60 min	1940–present	Yes	Yes/No	Yes	Some		Yes		Good	Global
HRRR[c]	3 km	15 min	2014–present	Yes	Yes/No	Yes/No	No		Unideal		Basic	U.S.
WIND Toolkit[d]	2 km	5 min	2007–2014	No	Yes/Yes	Yes	Yes		No		Basic	Various
WTK-LED[e]	2 km/4 km	5 min	3 year/ 20 year	No	Yes/Yes	Yes	Not yet	Not yet	No	Unknown, dataset not yet available		Various
NSRDB[f]	4 km/ 60 km	30 min	1998–present	Yes	Yes/No	Solar only	Yes		Yes		Basic	Most of globe
CERRA[g]	11 km/5.5 km	60 min	1980–present		No/Yes	No solar	Yes		Possibly		Basic	Europe
CONUS404[h]	4 km	60 min/ 15 min (precip)	1980–2020	No	Unknown/ Probably	Yes	Not the intended use					Continental U.S.
BARRA[i]	12 km/ 1.5 km	60 min	1990–2019	No	Yes/ Probably	Yes				Fee-based		Australia/ New Zealand
Public Observing Networks[j]	Non-uniform, variable density	1 hr or less	Variable	Yes	Yes/No	Mostly	Varies. Not for power systems	Varies	Usually	Usually easy	Varies	Global
Renewable Energy Project Data[k]	Non-uniform, variable density	Usually minutes	Variable but rarely more than 10 years	Varies	Yes/ Usually	Yes	Usually	Varies, but usually poor	Varies	Usually poor	Usually none	Very limited
Proprietary Statistically Derived VRE Shapes[l]	Non-uniform, variable density	Usually hourly	Variable. Rarely reliable long records.	Varies	Usually incomplete	No	Partial	See note	No		None	Very limited

■ Fully Met ■ Close to Being Met ■ Partially Met ■ Met in a Very Limited Way ■ Not Met at All ■ Not Enough Info. for Determination

HICSS 2025 Paper on Power Flow Weather Modeling

- I have a paper in the 59th Hawaii International Conference on System Sciences (HICSS) titled, “Power Flow Modeling of the Impacts of Weather and Other Resiliency Hazards With a Focus on Transmission Planning,”; available at overbye.engr.tamu.edu/publications



Simulator Weather Data Access

- With respect to weather, PowerWorld's goal is to make it easy to use a wide variety of weather information in all power system planning timeframes, ranging from near real-time to long duration
- We're working on a variety of ways to make weather information available
- The Power Weather (*.pww) files use a binary format to store weather information and potentially other environmental inputs for a set of time points and a set of locations (e.g., weather stations); the format is relatively general
  - The timepoints can be either uniformly spaced (e.g., hourly) or individually specified (as is the case with forecasts)
  - The weather stations **do not** need to be on a uniform grid

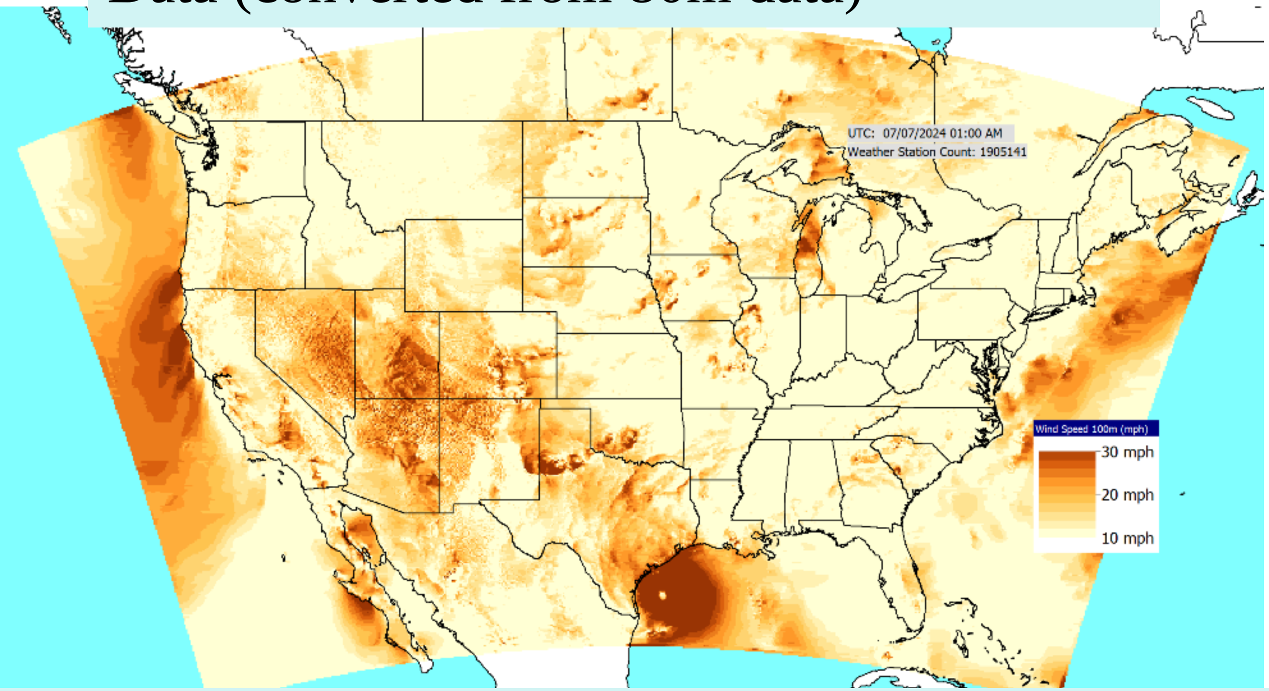
ERA5

- One of the datasets we use is ERA5, which is state-of-the art (fifth generation) reanalysis of global climate and weather since 1940
  - It is available hourly on a 0.25 degree grid and includes 10m and 100m wind, and solar global horizontal irradiance and direct horizontal irradiance
  - ERA5 comes from European Centre for Medium-Range Weather Forecasts (ECMWF), (ERA = ECMWF Re-Analysis) with more details on ERA5 available at rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803; available in GRIB and GRIB2
- The ESIG comment on ERA5 is,
  - "However, while ERA5 is unquestionably the best global reanalysis dataset currently available, it is not a panacea. Average validation statistics are very good, but the horizontal grid spacing of 30 km is insufficient to produce detailed meteorological fields present in complex topography, fields that are crucial to resolve for estimating renewable generation in these areas."

HRRR

- A second dataset is the HRRR (High-Resolution Rapid Refresh), which is provided by the US National Oceanic and Atmospheric Administration (NOAA)
- HRRR is a 3-km resolution, hourly-updated assimilation/ modeling system provided by the NOAA National Center for Environmental Prediction (NCEP)
  - Data is provided on a grid with a total of 1.9 million elements

Simulator Contour of HRRR 100m Wind Data (converted from 80m data)



HRRR uses a Lambert Conformal projection (a conic projection)

Ref: rapidrefresh.noaa.gov/hrrr/

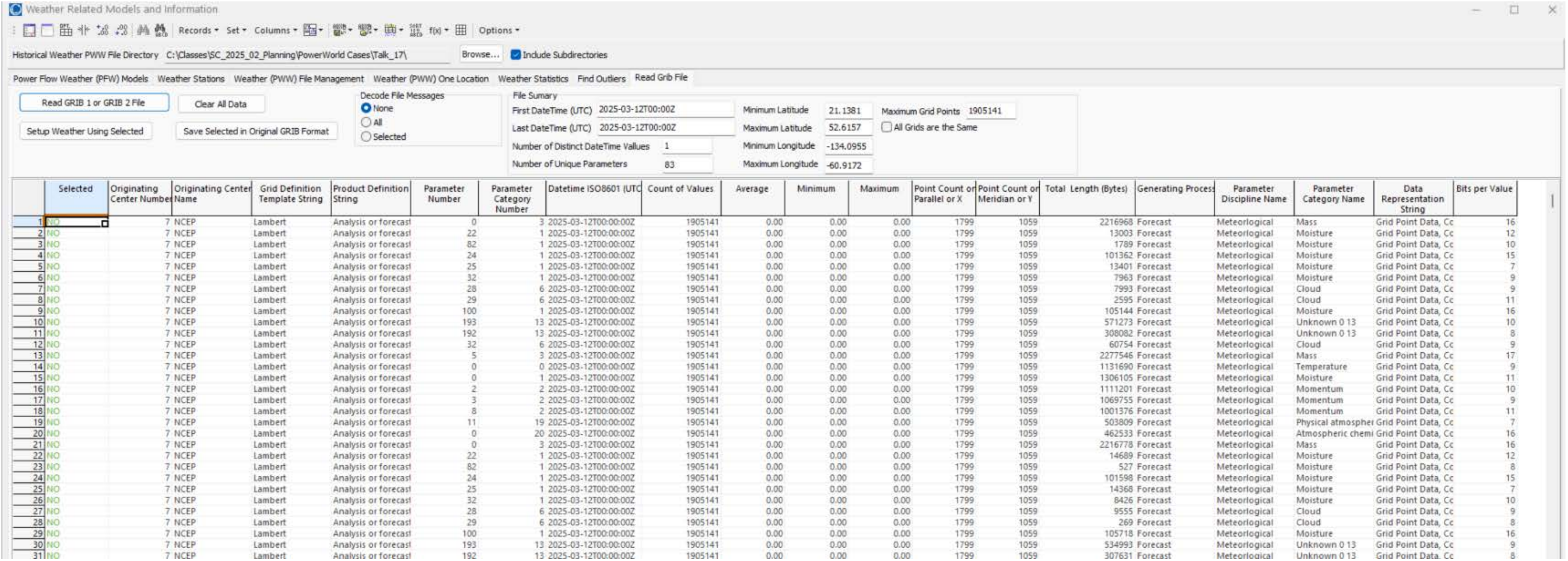
Simulator Weather Data Access, cont.

- Coming soon to a Version 24 patch, Simulator will be able to directly load power system planning related weather information from GRIB or GRIB2 format files
- GRIB (Gridded Binary or General-Regularly-distributed Information in Binary form) is a very common format for the storage and exchange of historical and forecast weather data
  - It is standardized by the World Meteorological Organization (WMO), with GRIB released in 1994 and GRIB2 initially 2003
  - Both GRIB and GRIB2 are widely used, including for the ERA5 and HRRR datasets

References: en.wikipedia.org/wiki/GRIB, climatedataguide.ucar.edu/climate-tools/common-climate-data-formats-overview

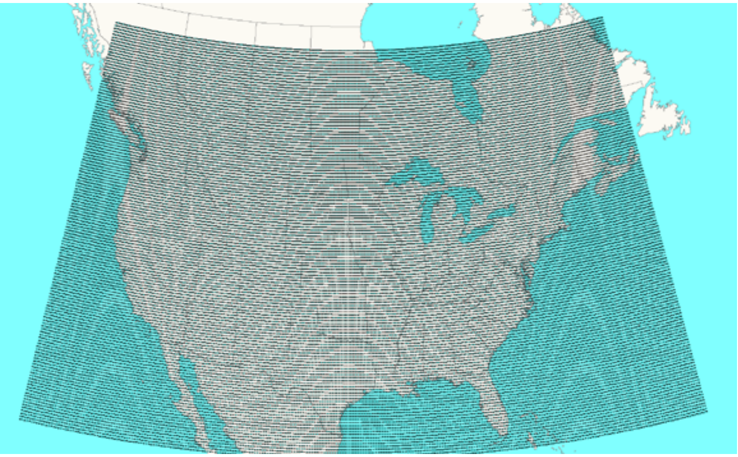
Simulator Weather Data Access, cont.

- Image shows soon to be released functionality to directly load GRIB and GRIB2 data
  - Current HRRR data is available at www.nco.ncep.noaa.gov/pmb/products/hrrr/



Easy Power Flow Access to ERA5

- ERA5 is available worldwide about five days behind real-time
- We convert it to pww format files, and place it at electricgrids.engr.tamu.edu/weather-data/



- Currently we provided data for most of North America and then smaller files for just Texas
  - For each hour the pww files store eight weather values (temperature, dew point, cloud cover percent, wind speed (10m), wind direction (10m), wind speed (100m), global horizontal irradiance, direct horizontal irradiance, wind gusts
  - The North America pww files have 38,497 data points; with 9 values per hour, this is about 247 MB per month, or about 250 GB for the total set
- This data is public so it can be freely used and shared

Electricgrids.engr.tamu.edu/weather-data/

Weather Data

This dataset contains historical and forecast weather data for Texas and North America. The historical data starts from 1940 and extends to almost present (5 days from current date). The list of weather values include, temperture, dew point, wind speed, wind direction, wind speed at 100m, cloud cover, global horizontal irradiance, and direct horizontal irradance for a 0.25 degree latitude and longitude grid across much of North America.

Please contact Thomas Overbye (overbye@tamu.edu) or Farnaz Safdarian (fsafdarian@tamu.edu) for any questions regarding this data.

View Available Weather for Download

Weather Data Information and PWW Format Description

References

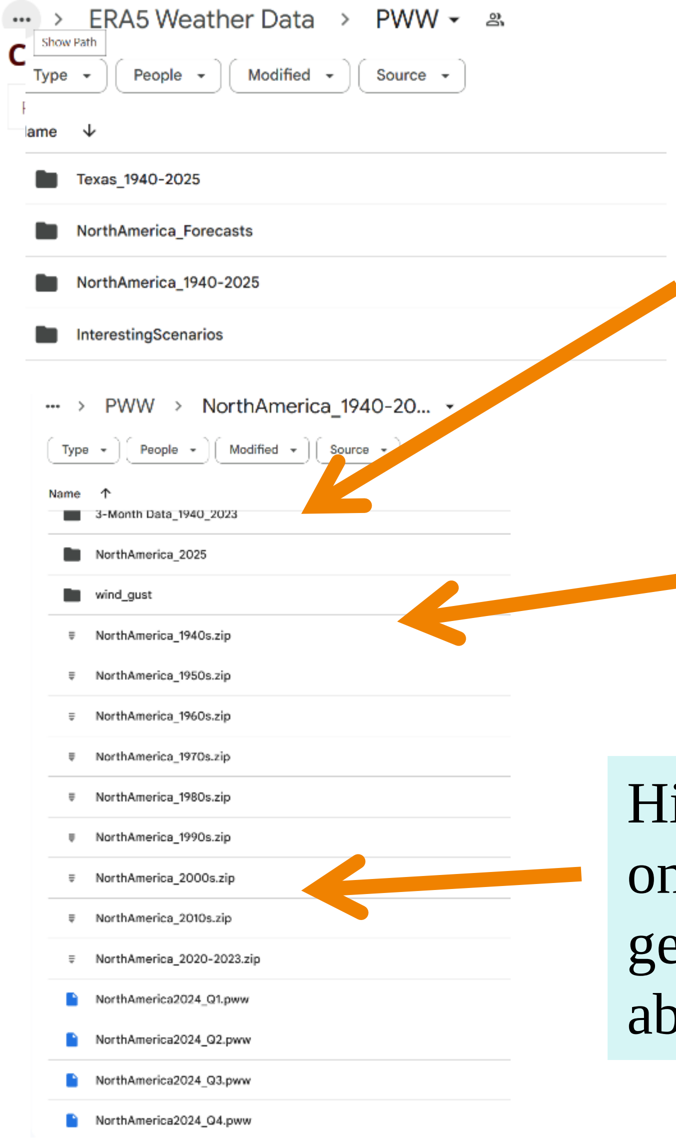
If you use these datasets in publications, please cite the following papers, and acknowledge the ERA5 data as described below:

T. J. Overbye, F. Safdarian, W. Trinh, Z. Mao, J. Snodgrass, and J. Yeo, "An Approach for the Direct Inclusion of Weather Information in the Power Flow," *Proc. 56th Hawaii International Conference on System Sciences (HICSS)*, January 2023.

F. Safdarian, M. Stevens, J. Snodgrass, T. J. Overbye, "Detailed Hourly Weather Measurements for Power System Applications," 2024 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, Feb. 2024.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (Accessed on 23-01-2024)

Please refer to How to acknowledge, cite and reference data published on the Climate Data Store for complete details on citing the ERA5 data.



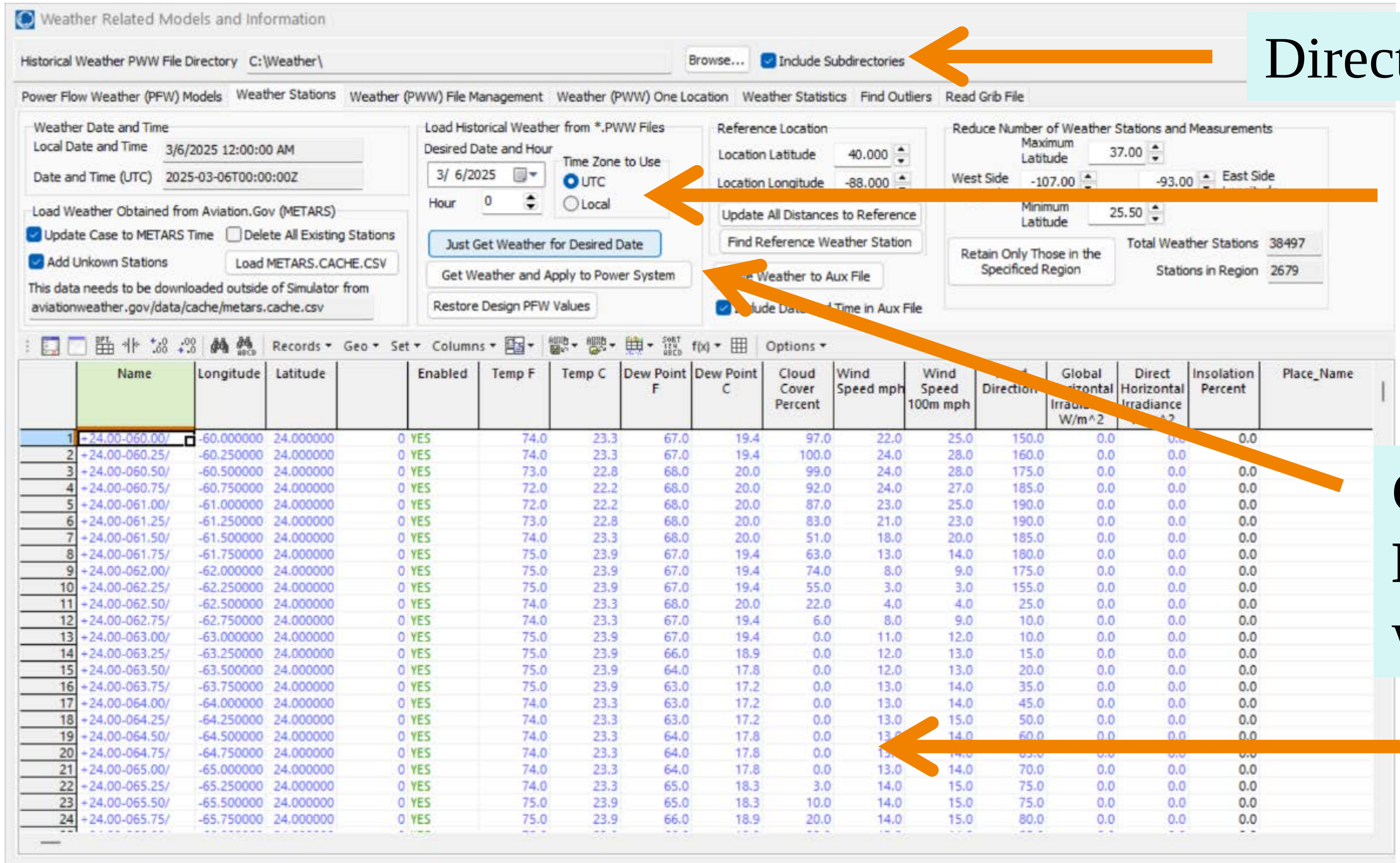
Only get the 3-month data if your download speed is slow

Data for current year, updated daily

Historical data; that is, a onetime download; getting a decade took me about 4 minutes

Viewing Weather for an Hour

- Goto **Tools, Weather, Weather Models and Information**, **Weather Stations** Page to view the weather for any valid time



	Name	Longitude	Latitude		Enabled	Temp F	Temp C	Dew Point F	Dew Point C	Cloud Cover Percent	Wind Speed mph	Wind Speed 100m mph	Direction	Global Horizontal Irradiance W/m^2	Direct Horizontal Irradiance	Insolation Percent	Place_Name
1	+24.00-060.00/	-60.000000	24.000000	0	YES	74.0	23.3	67.0	19.4	97.0	22.0	25.0	150.0	0.0	[illegible]	0.0	
2	+24.00-060.25/	-60.250000	24.000000	0	YES	74.0	23.3	67.0	19.4	100.0	24.0	28.0	160.0	0.0	0.0	[illegible]	
3	+24.00-060.50/	-60.500000	24.000000	0	YES	73.0	22.8	68.0	20.0	99.0	24.0	28.0	175.0	0.0	0.0	0.0	
4	+24.00-060.75/	-60.750000	24.000000	0	YES	72.0	22.2	68.0	20.0	92.0	24.0	27.0	185.0	0.0	0.0	0.0	
5	+24.00-061.00/	-61.000000	24.000000	0	YES	72.0	22.2	68.0	20.0	87.0	23.0	25.0	190.0	0.0	0.0	0.0	
6	+24.00-061.25/	-61.250000	24.000000	0	YES	73.0	22.8	68.0	20.0	83.0	21.0	23.0	190.0	0.0	0.0	0.0	
7	+24.00-061.50/	-61.500000	24.000000	0	YES	74.0	23.3	68.0	20.0	51.0	18.0	20.0	185.0	0.0	0.0	0.0	
8	+24.00-061.75/	-61.750000	24.000000	0	YES	75.0	23.9	67.0	19.4	63.0	13.0	14.0	180.0	0.0	0.0	0.0	
9	+24.00-062.00/	-62.000000	24.000000	0	YES	75.0	23.9	67.0	19.4	74.0	8.0	9.0	175.0	0.0	0.0	0.0	
10	+24.00-062.25/	-62.250000	24.000000	0	YES	75.0	23.9	67.0	19.4	55.0	3.0	3.0	155.0	0.0	0.0	0.0	
11	+24.00-062.50/	-62.500000	24.000000	0	YES	74.0	23.3	68.0	20.0	22.0	4.0	4.0	25.0	0.0	0.0	0.0	
12	+24.00-062.75/	-62.750000	24.000000	0	YES	74.0	23.3	67.0	19.4	6.0	8.0	9.0	10.0	0.0	0.0	0.0	
13	+24.00-063.00/	-63.000000	24.000000	0	YES	75.0	23.9	67.0	19.4	0.0	11.0	12.0	10.0	0.0	0.0	0.0	
14	+24.00-063.25/	-63.250000	24.000000	0	YES	75.0	23.9	66.0	18.9	0.0	12.0	13.0	15.0	0.0	0.0	0.0	
15	+24.00-063.50/	-63.500000	24.000000	0	YES	75.0	23.9	64.0	17.8	0.0	12.0	13.0	20.0	0.0	0.0	0.0	
16	+24.00-063.75/	-63.750000	24.000000	0	YES	75.0	23.9	63.0	17.2	0.0	13.0	14.0	35.0	0.0	0.0	0.0	
17	+24.00-064.00/	-64.000000	24.000000	0	YES	74.0	23.3	63.0	17.2	0.0	13.0	14.0	45.0	0.0	0.0	0.0	
18	+24.00-064.25/	-64.250000	24.000000	0	YES	74.0	23.3	63.0	17.2	0.0	13.0	15.0	50.0	0.0	0.0	0.0	
19	+24.00-064.50/	-64.500000	24.000000	0	YES	74.0	23.3	64.0	17.8	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
20	+24.00-064.75/	-64.750000	24.000000	0	YES	74.0	23.3	64.0	17.8	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
21	+24.00-065.00/	-65.000000	24.000000	0	YES	74.0	23.3	64.0	17.8	0.0	13.0	14.0	70.0	0.0	0.0	0.0	
22	+24.00-065.25/	-65.250000	24.000000	0	YES	74.0	23.3	65.0	18.3	3.0	14.0	15.0	75.0	0.0	0.0	0.0	
23	+24.00-065.50/	-65.500000	24.000000	0	YES	75.0	23.9	65.0	18.3	10.0	14.0	15.0	75.0	0.0	0.0	0.0	
24	+24.00-065.75/	-65.750000	24.000000	0	YES	75.0	23.9	66.0	18.9	20.0	14.0	15.0	80.0	0.0	0.0	0.0	

Directory for pww files

Enter the day and hour; in either Coordinated Universal Time (UTC) or local time

Click **Just Get Weather for Desired Date** to get the weather; it takes about a second

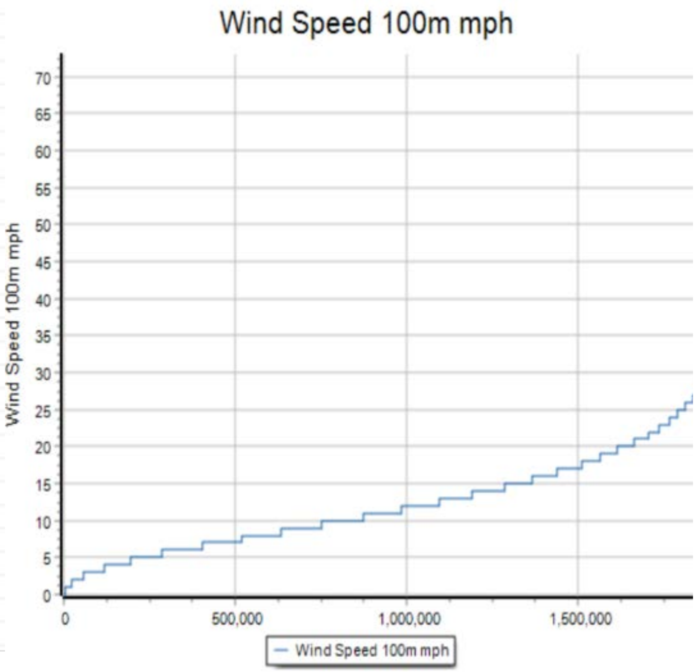
Right-click to see weather station dialog

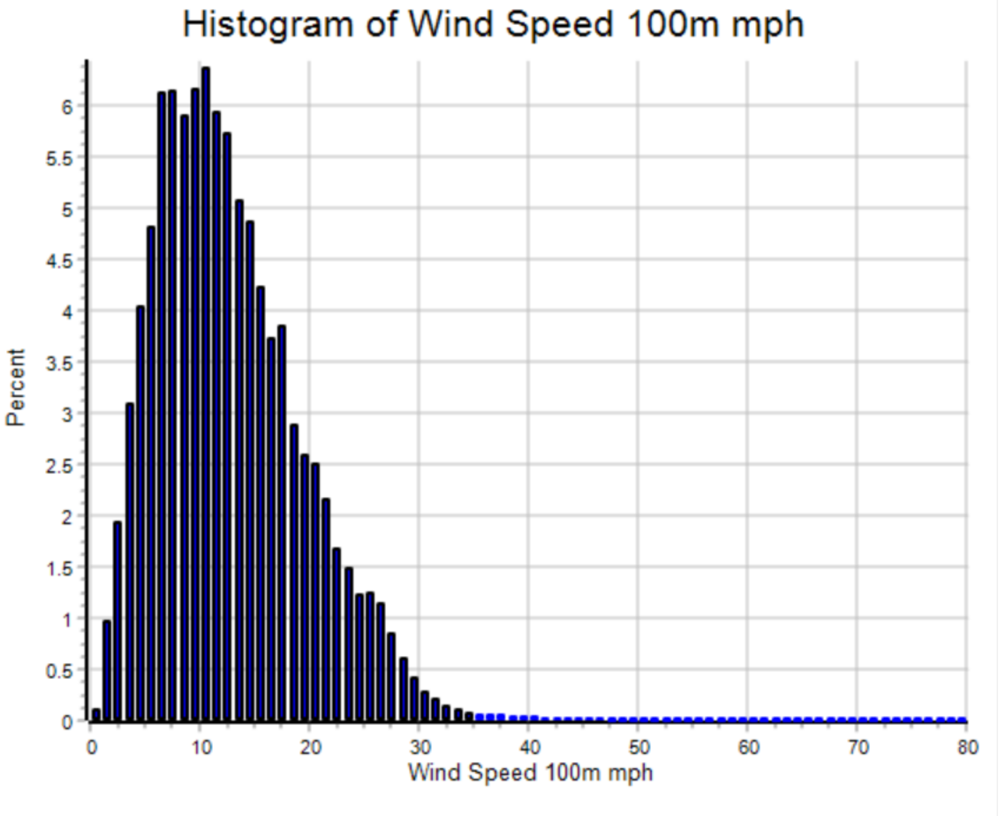
Viewing Weather for an Hour, HRRR

- Even the full HRRR data can be viewed this way (1.9 million weather stations!); it can also be sorted or plotted
  - In contrast Excel 2024 maxes out at about 1 million rows and 16,000 columns

Name. This is the unique identifier (Key Field) for the WeatherStation

1905112	+26.88-094.			8	YES	81.0
1905113	+26.80-094.			8	YES	80.0
1905114	+26.61-095.			8	YES	81.0
1905115	+26.59-095.76/	-95.761499	26.587168	98	YES	81.0
1905116	+26.56-095.94/	-95.939282	26.563589	98	YES	80.0
1905117	+26.56-095.82/	-95.821131	26.561729	98	YES	81.0
1905118	+26.54-095.91/	-95.910254	26.536718	98	YES	80.0
1905119	+27.20-094.74/	-94.735894	27.199874	98	YES	83.0
1905120	+26.86-094.84/	-94.836374	26.858313	98	YES	81.0
1905121	+26.86-094.75/	-94.747467	26.855979	98	YES	82.0
1905122	+26.83-094.84/	-94.837232	26.831875	98	YES	80.0
1905123	+26.83-094.75/	-94.748353	26.829542	98	YES	81.0
1905124	+26.61-095.79/	-95.790496	26.614086	98	YES	81.0
1905125	+26.59-095.88/	-95.879686	26.589097	98	YES	80.0
1905126	+26.59-095.79/	-95.791045	26.587663	98	YES	81.0
1905127	+26.56-095.85/	-95.850668	26.562207	98	YES	81.0
1905128	+26.51-094.82/	-94.817968	26.514034	98	YES	81.0
1905129	+26.49-094.82/	-94.818828	26.487626	98	YES	81.0
1905130	+26.59-095.85/	-95.850139	26.588628	98	YES	81.0
1905131	+26.59-095.82/	-95.820592	26.588150	98	YES	81.0
1905132	+26.56-095.91/	-95.909744	26.563137	98	YES	80.0
1905133	+26.56-095.88/	-95.880206	26.562676	98	YES	80.0
1905134	+26.83-094.78/	-94.777979	26.830328	98	YES	81.0
1905135	+26.86-094.78/	-94.777102	26.856766	98	YES	82.0
1905136	+26.83-094.81/	-94.807605	26.831106	98	YES	81.0
1905137	+26.86-094.81/	-94.806738	26.857544	98	YES	81.0
1905138	+26.51-094.85/	-94.847480	26.514799	98	YES	81.0
1905139	+26.49-094.88/	-94.877835	26.489148	98	YES	82.0
1905140	+28.14-108.49/	108.494895	28.144409	98	YES	71.0
1905141	+26.49-094.85/	-94.848331	26.488392	98	YES	81.0



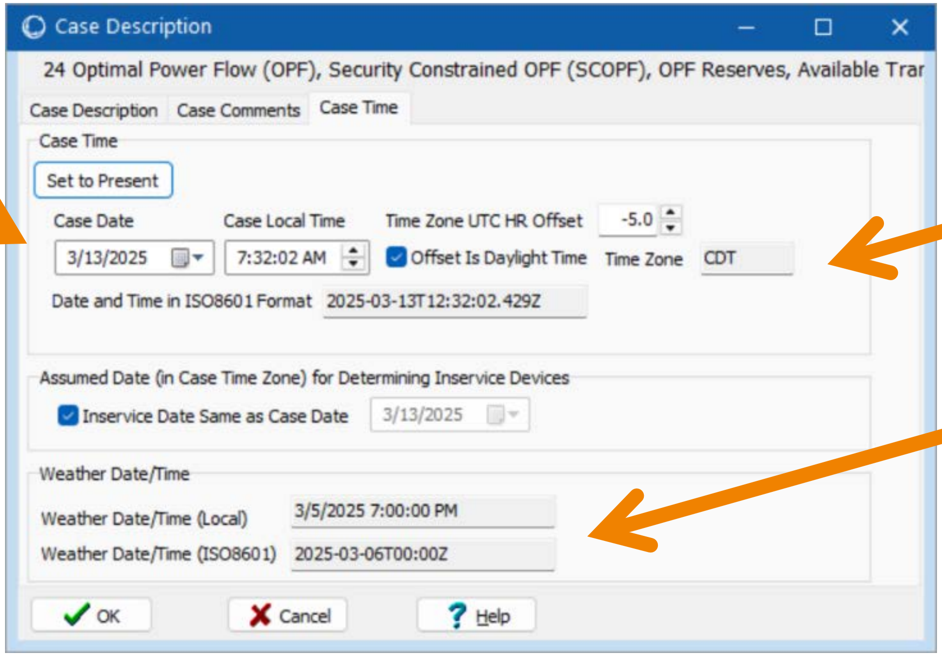


Date and Times in Simulator

- In general power flow cases do not need to have an associated date and time, however sometimes these values are useful
- When including weather almost always a date/time is needed, but it may be different from the case date/time
- Values can be seen with **Case Information, Case Description**

Case date/time

Weather date/time

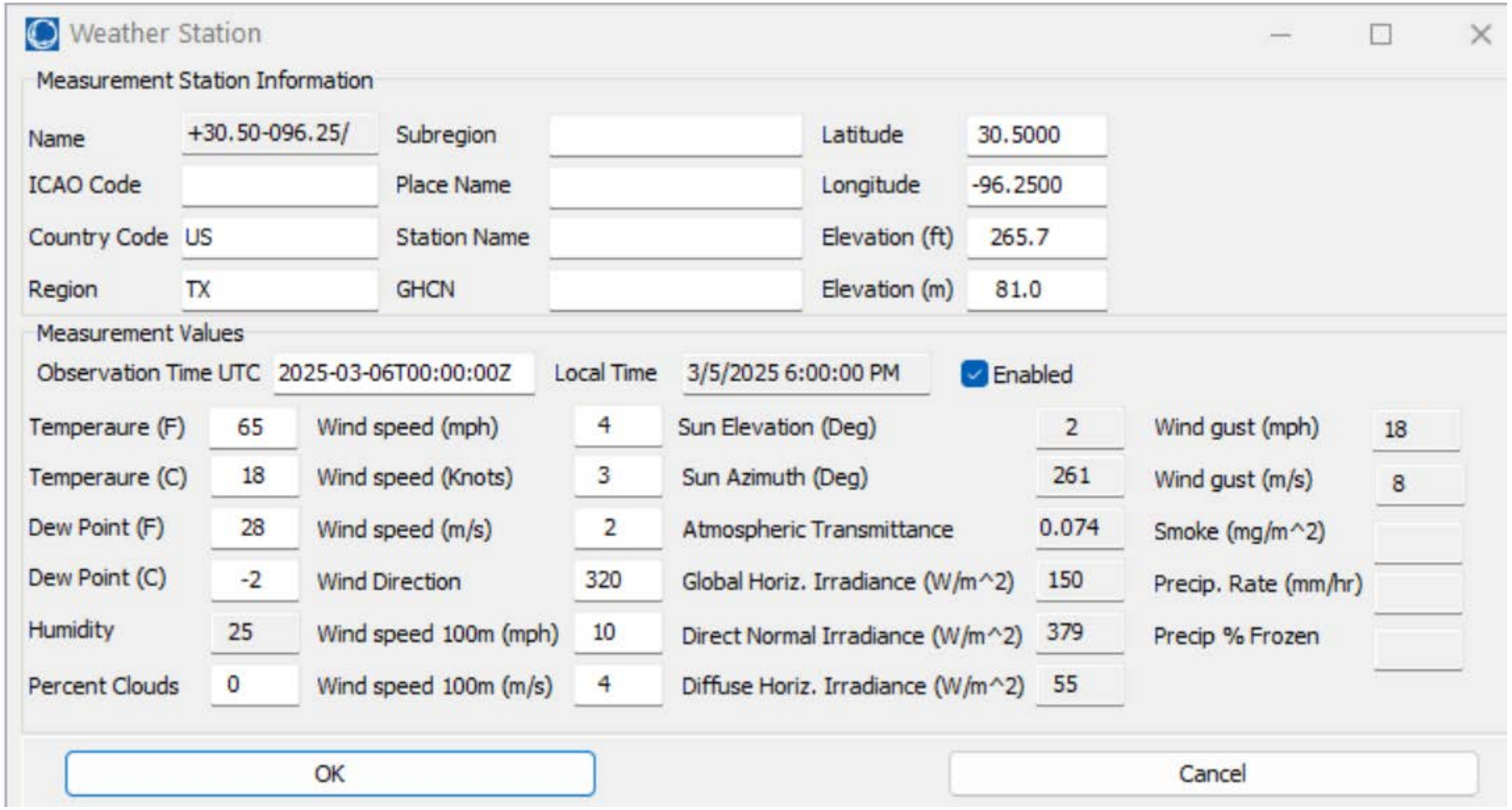


Assumed time zone

Weather date in ISO8601 format

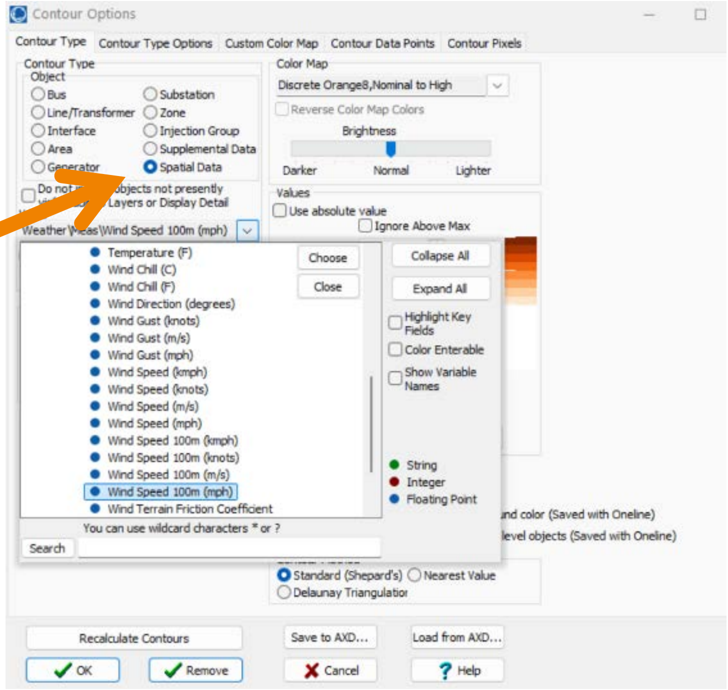
Simulator Weather Stations

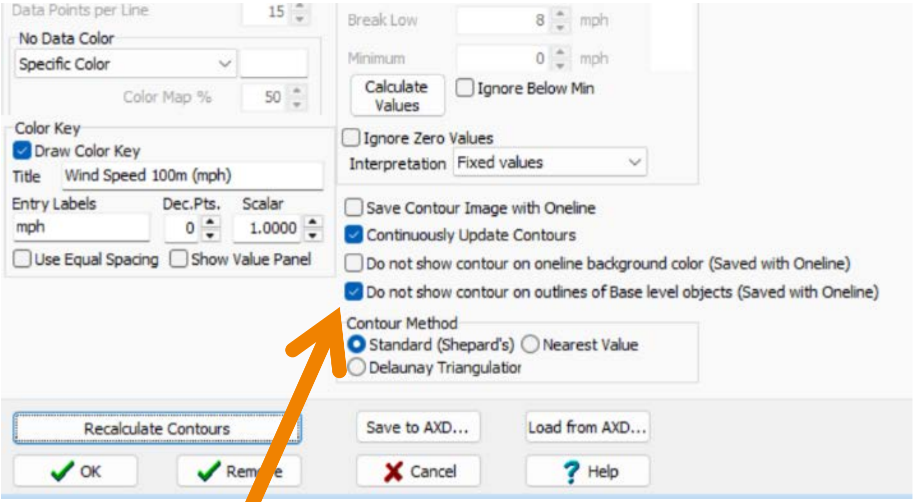
- Simulator uses weather station objects to store the weather data
- A weather station object must have a latitude and longitude; they usually have an elevation, and can have other identifiers
- A weather station may be an actual weather measuring location, but it could also just be a point in a weather model (e.g., ERA5 and HRRR)



Visualizing the Weather

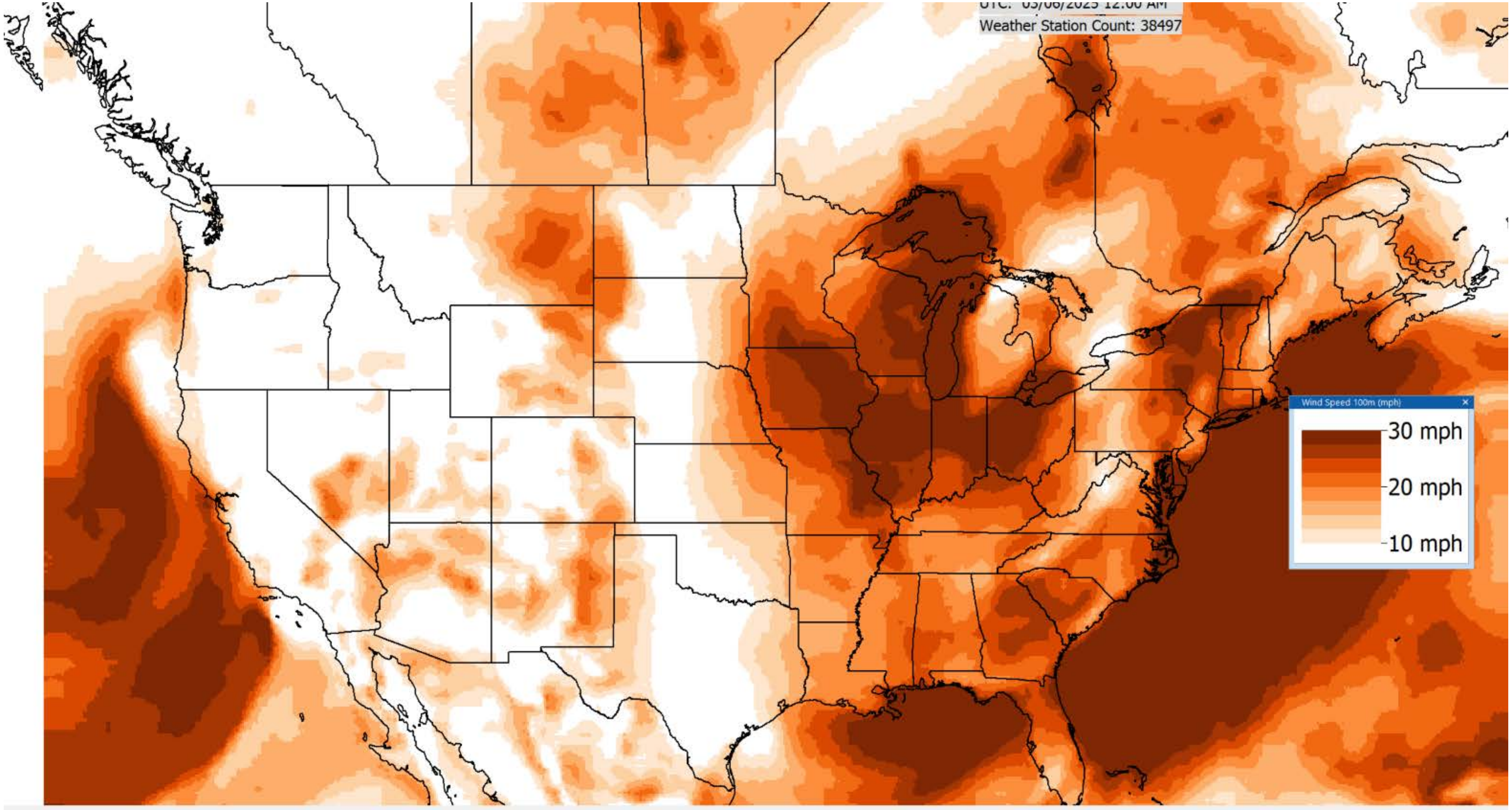
- Weather information can be contoured on a geographic oneline by right-clicking on the oneline background and selecting **Contouring…**
- The weather values can be contoured using the **Spatial Data** object, which does not require objects to actually be on the oneline





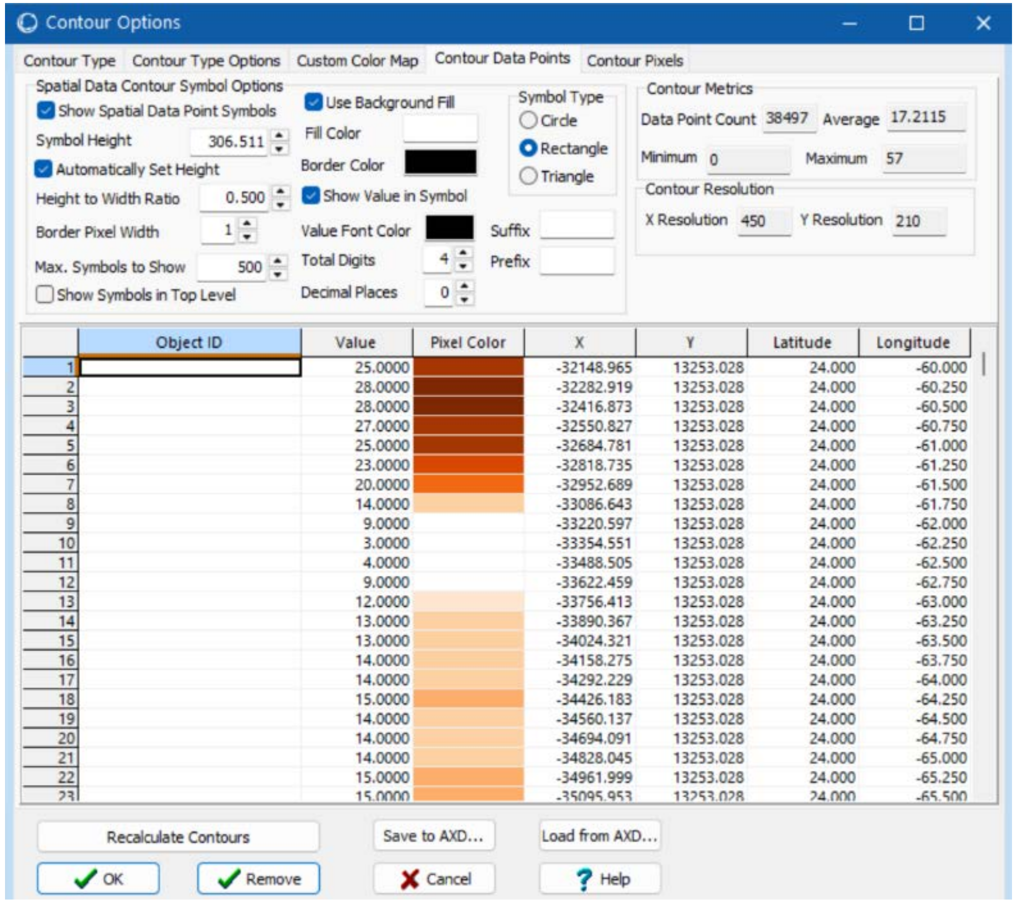
Use to select whether the contour is shown on the background, which is often ocean

Example Contour

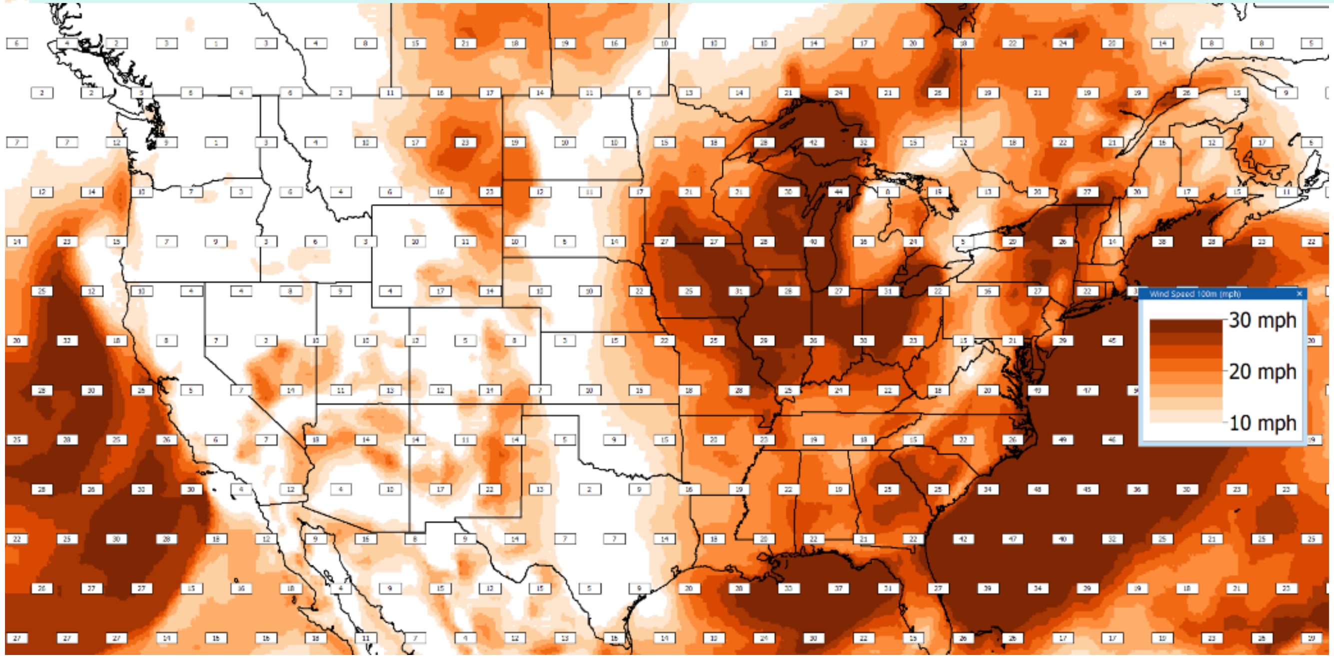


Showing Contour Data Symbols

- Data symbols can be easily added to the contour, and then also easily modified later by just right-clicking on one of them



In Version 24 they can be used with any contour type, not just spatial data ones



Available ERA5 Fields in Simulator

- The ERA5 dataset has hundreds of different values; currently we are using nine of them
  - Surface temperature, surface dew point
  - Wind speed at 10m, wind direction at 10m
  - Wind speed at 100m
  - Wind gusts
  - Total cloud cover (which takes into account all the layers)
  - Total sky direct short-wave (solar) radiation at surface (fdir); used to get the direct horizontal irradiance and the Direct Normal Irradiance (DNI)
  - Surface short-wave (solar) radiation downwards (ssrd); this is used with the direct horizontal irradiance to get the Diffuse Horizontal Irradiance
  - Derived values, like humidity and wind chill, are also available

Available HRRR Fields in Simulator

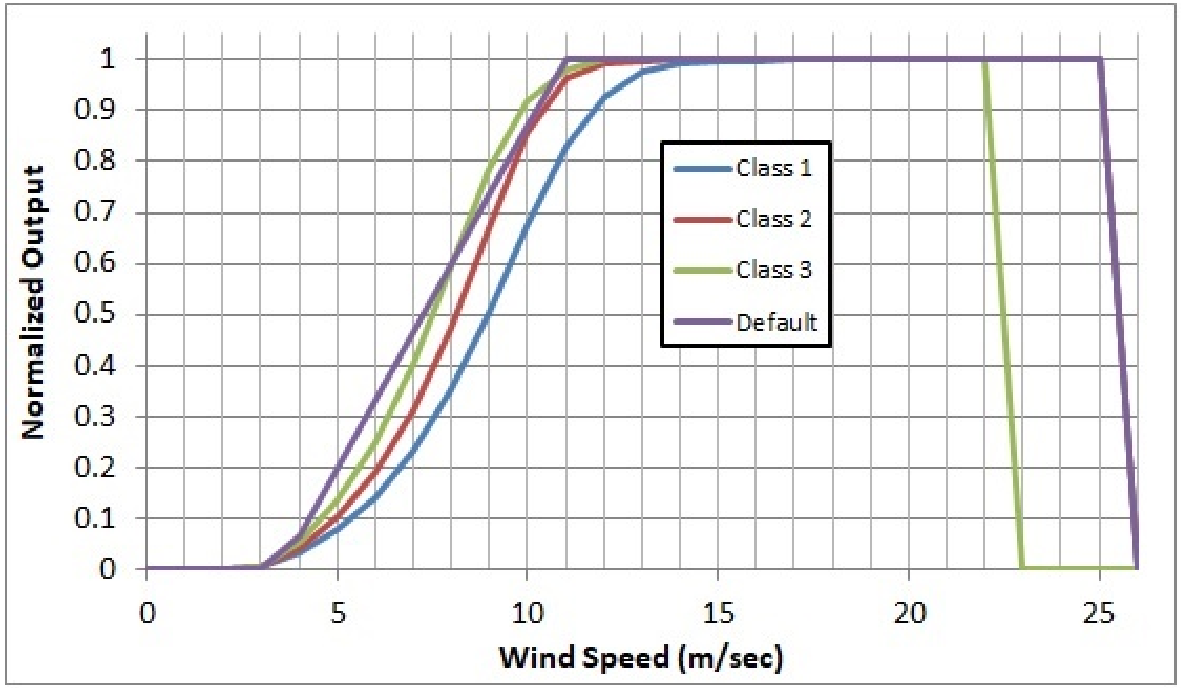
- Likewise, HRRR has many values; currently we are using 11 of them
  - Surface temperature, surface dew point
  - Wind speed at 10m, wind direction at 10m
  - Wind speed at 80m (converted to 100m when stored)
  - Total cloud cover (which takes into account all the layers)
  - Total sky direct short-wave (solar) radiation at surface (fdir); used to get the direct horizontal irradiance and the Direct Normal Irradiance (DNI)
  - Wind gusts
  - Hourly precipitation (mm/hr)
  - Percent frozen precipitation
  - Vertically-integrated total smoke (mg/m^2)
  - Derived values like humidity are also available

Models of Grid Weather Impacts

- Key focus here isn't weather per se, but modeling the impacts of weather on electric grid components (e.g., generators, lines)
- Certainly, a number of models already exist, and undoubtedly more will be created given that weather data is now conveniently available
- The approach used here for handling a growing list of models is to mimic what has been done with power system stability – start small and expand
  - Early (1960) stability codes just had a handful of models, whereas current codes support many hundreds of different model types
- PowerWorld implements this using PFW Models
  - PFW = Power Flow Weather or Power Flow Whatever models

Example: Gen MaxMW Wind and Solar

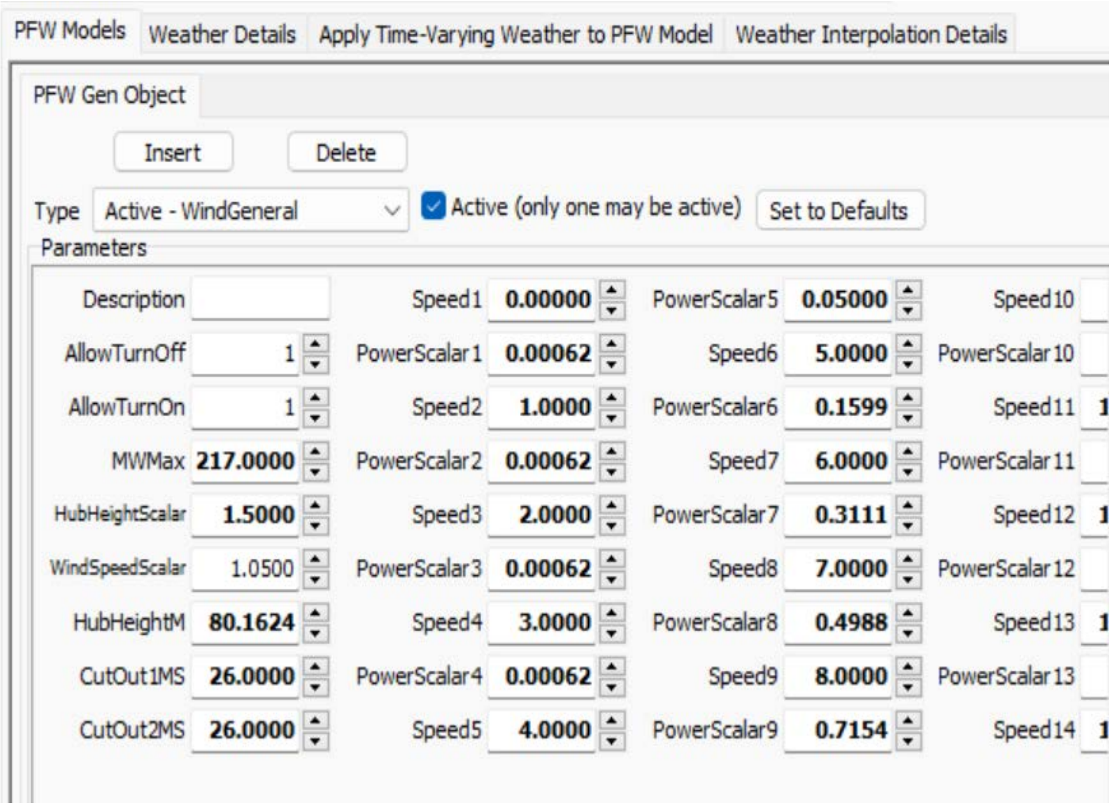
- An example is modeling the impact of wind speed on wind turbine output, or solar irradiation on PV output
  - The image on the right shows several of the generic wind turbine models are based on the turbine classes using data from [a]
  - A simple solar PV model uses either provided solar irradiation or the standard equations for insolation based on location and time of day including cloud cover; this is combined with whether the solar has tracking and, if needed, its tilt and azimuth

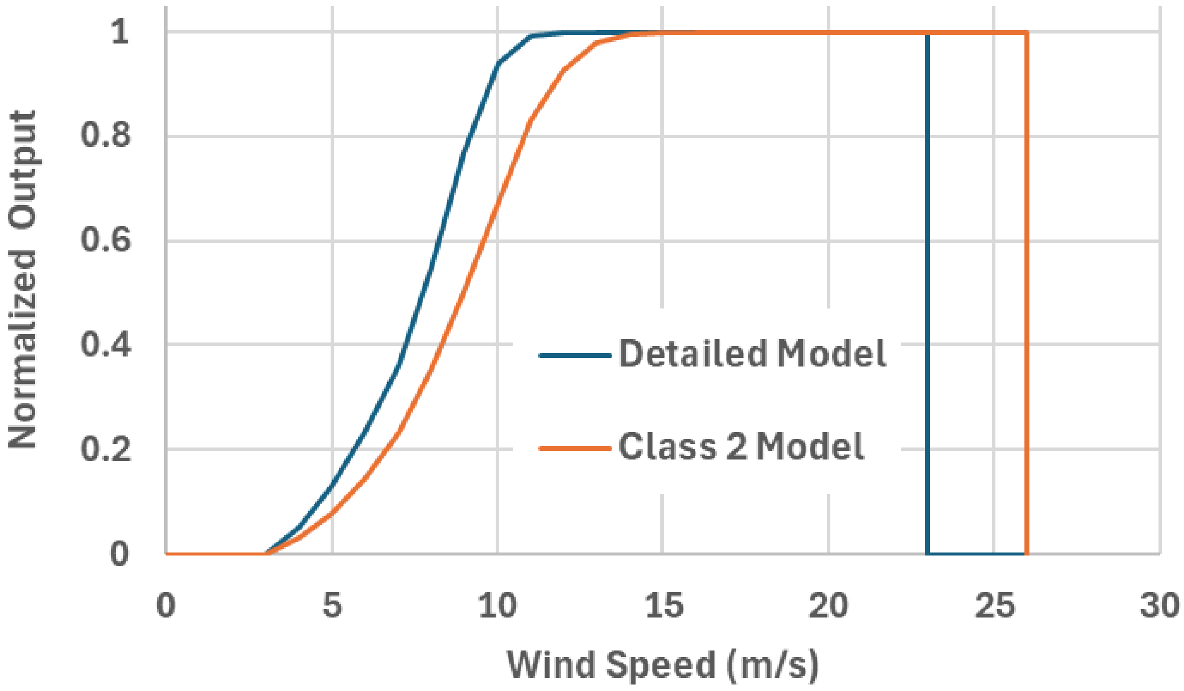


[a] C. Draxl, A. Clifton, B. Hodge, J. McCaa, "The Wind Integration National Dataset (WIND) Toolkit," *Applied Energy*, vol. 151, pp. 355-366, 2015.

Example: Customized Wind Power Curve Model

- Customized wind power curve models can also be defined; this only needs to be done once per wind generator





Additional PFWs, Including Stochastic Models

- Many different PFW models are possible, and they could certainly be stochastic
- Examples include ambient-adjusted line ratings, dynamic line ratings, thermal generator output variation with temperature, line outage due to wind gusts, asset failure during earthquakes (see figure with pga=Peak Ground Acceleration), incremental impacts of temperature on load, etc.
- Many such models exist in the literature, with others needing to be developed;

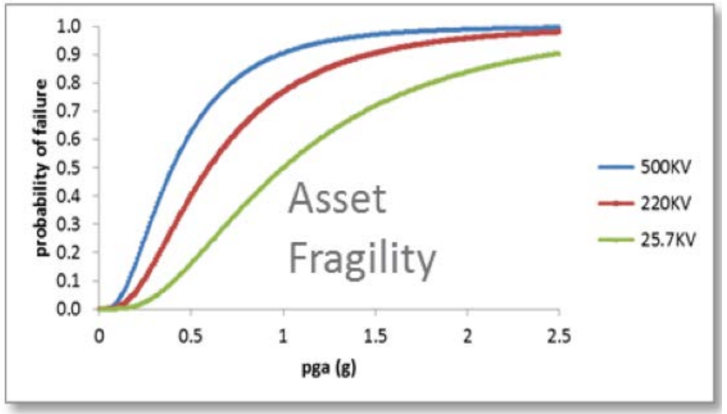
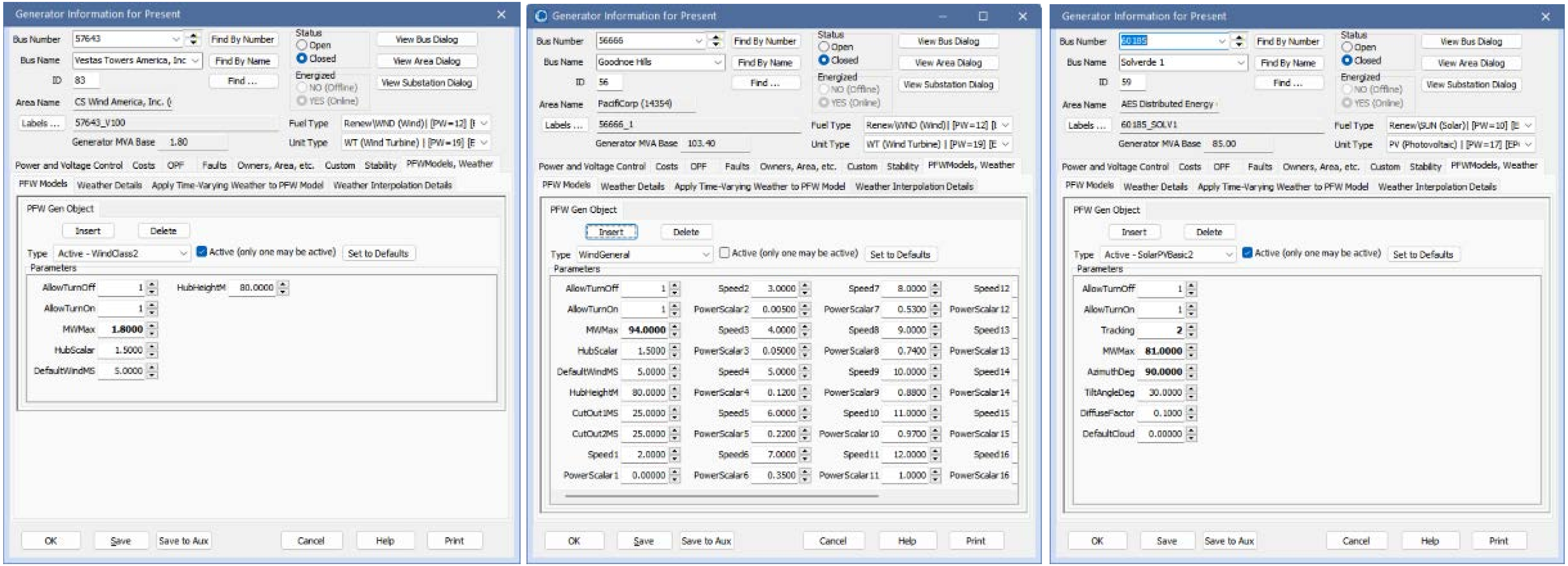


Image source: Figure 2.1 of A. Veeramany, G.A. Coles, S.D. Unwin, T.B. Nguyen, J.E Dagle, “Trial Implementation of the High Impact, Low-Frequency Power Grid Event Risk Framework to Support Informed Decision-Making,” PNNL-25667, October 2016.

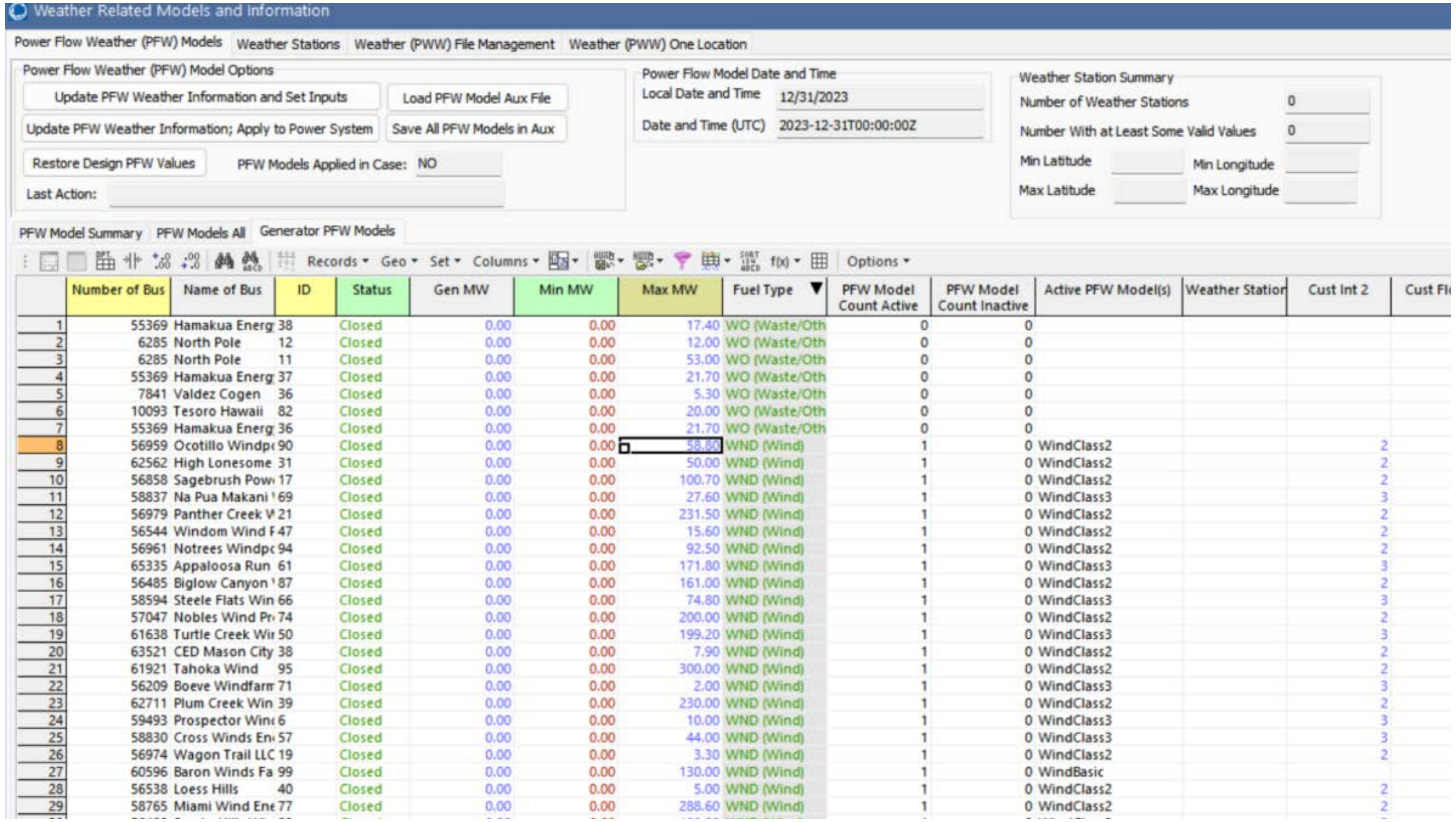
Example: Gen MaxMW PFW Model

- Individual generator PFW models can be entered or viewed using the generator dialog



Entering Large Number of PFW Models

- A large number of PFW models can be entered by going to the **Weather, Weather Models and Information, PFW Models** page
  - The Generator PFW Models list shows all the generators in the case
  - Select the desired ones, right-click and select **Insert New PFW Models**
- They can also be added with aux files or by pasting them in



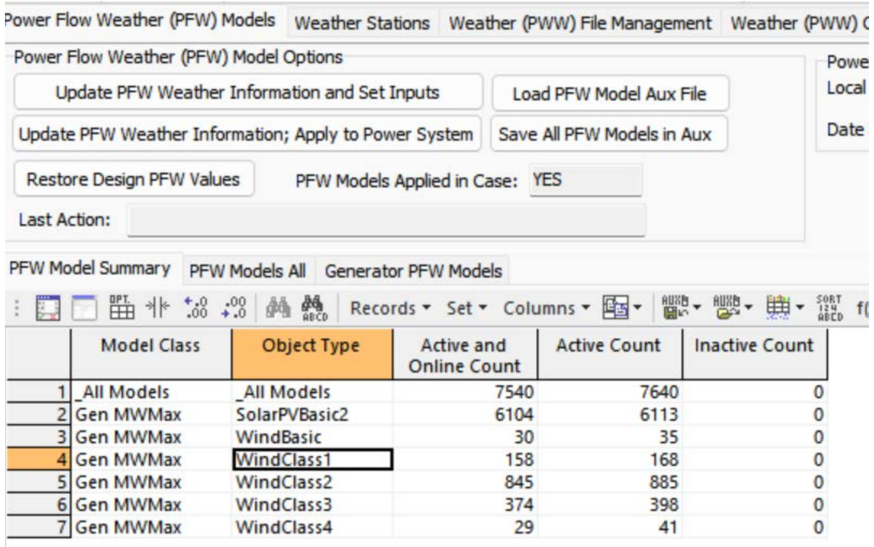
	Number of Bus	Name of Bus	ID	Status	Gen MW	Min MW	Max MW	Fuel Type	PFW Model Count Active	PFW Model Count Inactive	Active PFW Model(s)	Weather Station	Cust Int 2	Cust Fl
1	55369	Hamakua Energ	38	Closed	0.00	0.00	17.40	WO (Waste/Oth	0	0				
2	6285	North Pole	12	Closed	0.00	0.00	12.00	WO (Waste/Oth	0	0				
3	6285	North Pole	11	Closed	0.00	0.00	53.00	WO (Waste/Oth	0	0				
4	55369	Hamakua Energ	37	Closed	0.00	0.00	21.70	WO (Waste/Oth	0	0				
5	7841	Valdez Cogen	36	Closed	0.00	0.00	5.30	WO (Waste/Oth	0	0				
6	10093	Tesoro Hawaii	82	Closed	0.00	0.00	20.00	WO (Waste/Oth	0	0				
7	55369	Hamakua Energ	36	Closed	0.00	0.00	21.70	WO (Waste/Oth	0	0				
8	56959	Ocotillo Windp	90	Closed	0.00	0.00	58.80	WND (Wind)	1	0	WindClass2		2	
9	62562	High Lonesome	31	Closed	0.00	0.00	50.00	WND (Wind)	1	0	WindClass2		2	
10	56858	Sagebrush Pow	17	Closed	0.00	0.00	100.70	WND (Wind)	1	0	WindClass2		2	
11	58837	Na Pua Makani	69	Closed	0.00	0.00	27.60	WND (Wind)	1	0	WindClass3		3	
12	56979	Panther Creek W	21	Closed	0.00	0.00	231.50	WND (Wind)	1	0	WindClass2		2	
13	56544	Windom Wind F	47	Closed	0.00	0.00	15.60	WND (Wind)	1	0	WindClass2		2	
14	56961	Notrees Windp	94	Closed	0.00	0.00	92.50	WND (Wind)	1	0	WindClass2		2	
15	65335	Appaloosa Run	61	Closed	0.00	0.00	171.80	WND (Wind)	1	0	WindClass3		3	
16	56485	Biglow Canyon	87	Closed	0.00	0.00	161.00	WND (Wind)	1	0	WindClass2		2	
17	58594	Steele Flats Win	66	Closed	0.00	0.00	74.80	WND (Wind)	1	0	WindClass3		3	
18	57047	Nobles Wind Pr	74	Closed	0.00	0.00	200.00	WND (Wind)	1	0	WindClass2		2	
19	61638	Turtle Creek Wi	50	Closed	0.00	0.00	199.20	WND (Wind)	1	0	WindClass3		3	
20	63521	CED Mason City	38	Closed	0.00	0.00	7.90	WND (Wind)	1	0	WindClass2		2	
21	61921	Tahoka Wind	95	Closed	0.00	0.00	300.00	WND (Wind)	1	0	WindClass2		2	
22	56209	Boeve Windfarm	71	Closed	0.00	0.00	2.00	WND (Wind)	1	0	WindClass3		3	
23	62711	Plum Creek Win	39	Closed	0.00	0.00	230.00	WND (Wind)	1	0	WindClass2		2	
24	59493	Prospector Win	6	Closed	0.00	0.00	10.00	WND (Wind)	1	0	WindClass3		3	
25	58830	Cross Winds En	57	Closed	0.00	0.00	44.00	WND (Wind)	1	0	WindClass3		3	
26	56974	Wagon Trail LLC	19	Closed	0.00	0.00	3.30	WND (Wind)	1	0	WindClass2		2	
27	60596	Baron Winds Fa	99	Closed	0.00	0.00	130.00	WND (Wind)	1	0	WindBasic			
28	56538	Loess Hills	40	Closed	0.00	0.00	5.00	WND (Wind)	1	0	WindClass2		2	
29	58765	Miami Wind Ene	77	Closed	0.00	0.00	288.60	WND (Wind)	1	0	WindClass2		2	

Making it Easy to Get Started: Using EIA-860 Data

- To make it easy to get started we've setup copper plate (i.e., no transmission) power flow cases with PFW models based the data provided by the US Energy Information Administration (EIA) in their Form EIA-860 datasets
  - EIA-860 provides data on every generator in the US with 1 MW or more capacity
  - Available at www.eia.gov/electricity/data/eia860/; it is released yearly with monthly updates available
- We take this data and convert it into a copper plate power flow model, with the resultant cases publicly available at
  - electricgrids.engr.tamu.edu/eia-860-generator-data-cases/
  - Details on this process are in a 2024 TPEC paper (available as a 2024 paper at **overbye.engr.tamu.edu/publications**/)

Example EIA-860 Wind Generator Data

- Right image shows the PFW models to map weather (wind speed) to MW Max
  - From the **Weather, Weather Models and Information** display
- Bottom image shows some EIA-860 wind generators with turbine information



Power Flow Weather (PFW) Models | Weather Stations | Weather (PWW) File Management | Weather (PWW) C

Power Flow Weather (PFW) Model Options

Update PFW Weather Information and Set Inputs | Load PFW Model Aux File

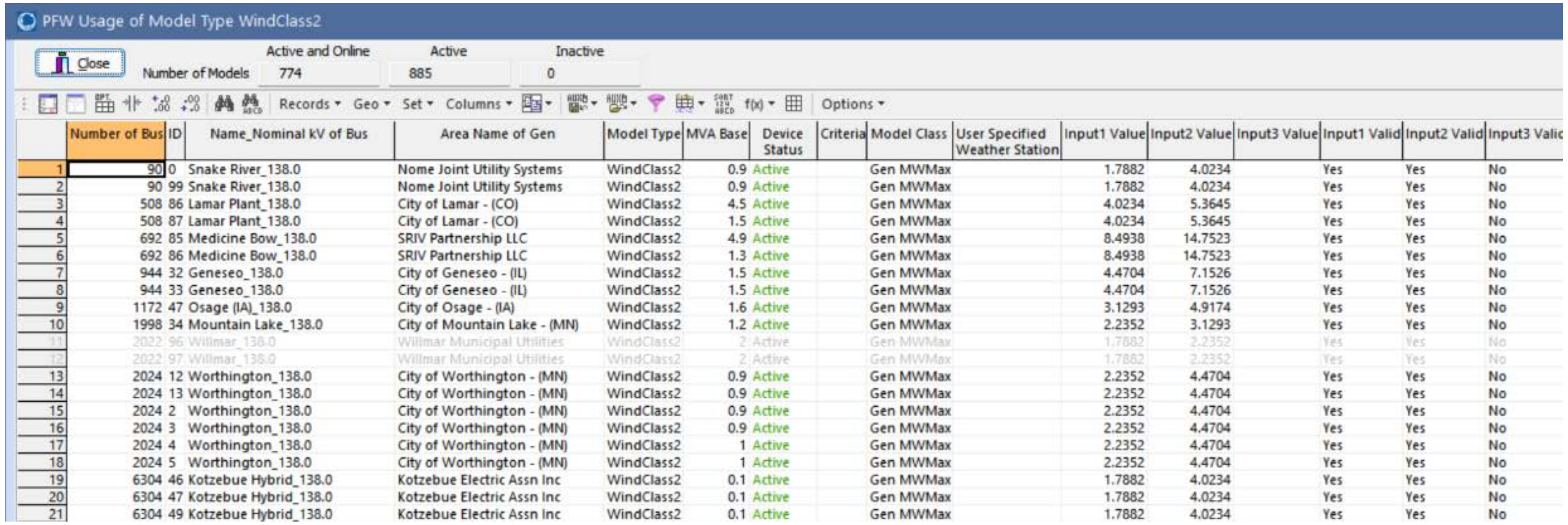
Update PFW Weather Information; Apply to Power System | Save All PFW Models in Aux

Restore Design PFW Values | PFW Models Applied in Case: YES

Last Action:

PFW Model Summary | PFW Models All | Generator PFW Models

	Model Class	Object Type	Active and Online Count	Active Count	Inactive Count
1	_All Models	_All Models	7540	7640	0
2	Gen MWMax	SolarPVBasic2	6104	6113	0
3	Gen MWMax	WindBasic	30	35	0
4	Gen MWMax	WindClass1	158	168	0
5	Gen MWMax	WindClass2	845	885	0
6	Gen MWMax	WindClass3	374	398	0
7	Gen MWMax	WindClass4	29	41	0



PFW Usage of Model Type WindClass2

Number of Models — Active and Online: 774 | Active: 885 | Inactive: 0

	Number of Bus	ID	Name_Nominal kV of Bus	Area Name of Gen	Model Type	MVA Base	Device Status	Criteria	Model Class	User Specified Weather Station	Input1 Value	Input2 Value	Input3 Value	Input1 Valid	Input2 Valid	Input3 Valid
1	90	0	Snake River_138.0	Nome Joint Utility Systems	WindClass2	0.9	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
2	90	99	Snake River_138.0	Nome Joint Utility Systems	WindClass2	0.9	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
3	508	86	Lamar Plant_138.0	City of Lamar - (CO)	WindClass2	4.5	Active		Gen MWMax		4.0234	5.3645		Yes	Yes	No
4	508	87	Lamar Plant_138.0	City of Lamar - (CO)	WindClass2	1.5	Active		Gen MWMax		4.0234	5.3645		Yes	Yes	No
5	692	85	Medicine Bow_138.0	SRIV Partnership LLC	WindClass2	4.9	Active		Gen MWMax		8.4938	14.7523		Yes	Yes	No
6	692	86	Medicine Bow_138.0	SRIV Partnership LLC	WindClass2	1.3	Active		Gen MWMax		8.4938	14.7523		Yes	Yes	No
7	944	32	Geneseo_138.0	City of Geneseo - (IL)	WindClass2	1.5	Active		Gen MWMax		4.4704	7.1526		Yes	Yes	No
8	944	33	Geneseo_138.0	City of Geneseo - (IL)	WindClass2	1.5	Active		Gen MWMax		4.4704	7.1526		Yes	Yes	No
9	1172	47	Osage (IA)_138.0	City of Osage - (IA)	WindClass2	1.6	Active		Gen MWMax		3.1293	4.9174		Yes	Yes	No
10	1998	34	Mountain Lake_138.0	City of Mountain Lake - (MN)	WindClass2	1.2	Active		Gen MWMax		2.2352	3.1293		Yes	Yes	No
11	2022	96	Willmar_138.0	Willmar Municipal Utilities	WindClass2	2	Active		Gen MWMax		1.7882	2.2352		Yes	Yes	No
12	2022	97	Willmar_138.0	Willmar Municipal Utilities	WindClass2	2	Active		Gen MWMax		1.7882	2.2352		Yes	Yes	No
13	2024	12	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
14	2024	13	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
15	2024	2	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
16	2024	3	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
17	2024	4	Worthington_138.0	City of Worthington - (MN)	WindClass2	1	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
18	2024	5	Worthington_138.0	City of Worthington - (MN)	WindClass2	1	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
19	6304	46	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
20	6304	47	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
21	6304	49	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No

For the CEII grids we have bus mapping for more than 95% of the generator capacity

Convenient Access to Wind Turbine Power Curves

- Reference [a], from PNNL, provides good access to power curves for all the wind turbines in CONUS as of end of 2020
- The data they provide can be directly pasted into Simulator

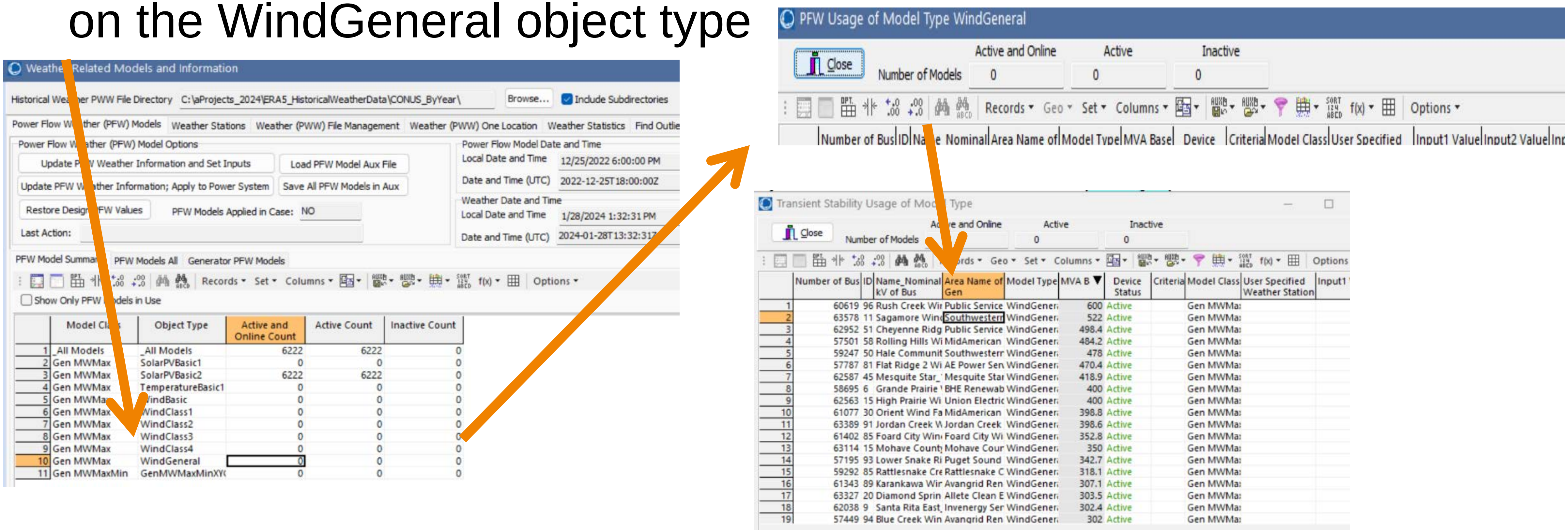
GenMWMax_WindGeneral

Label (for use in input	AllowTurn(	AllowTurn(	Device Sta	MWMax	HubHeight	Power-Speed Curve	plant_code	plant_code	generator_	lat	lon	ba	nerc_regio	state	system_ca	wind_farm	wind_farm	wind_turbi	wind_turbi	wind_turbi	wind_turbi	wind_reso	wind_reso	wind_reso	wind_farm	turb_gener	adjus
508_T4	1	1	Active	1.5	79.97952	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	508	508_1	T4	38.03333	-102.538	PSCO	WECC	CO	1500	[0]	[0]	79.97952	[0.0, 0.0, 0	[0.0, 0.25,	82.5	0.14	0.1	0	0	15	
508_T1-T3	1	1	Active	4.5	79.97952	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	508	508	T1-T3	38.03333	-102.538	PSCO	WECC	CO	4500	[0, 660.0,	[0, 0, 660.0	79.97952	[0.0, 0.0, 0	[0.0, 0.25,	82.5	0.14	0.1	0	0	15	
692_10	1	1	Active	4.9	49.9872	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	692	692	10	41.83528	-106.243	WAUW	WECC	WY	4900	[0, 376.0,	[0, 0, 0, 0,	49.9872	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	
692_11	1	1	Active	1.3	49.9872	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	692	692_1	11	41.83528	-106.243	WAUW	WECC	WY	1300	[0, 336.0]	[0, 0]	49.9872	[0, 0, 0, 0,	[0.0, 0.506	42	0.14	0.1	0	0	15	
944_10	1	1	Active	1.5	60.96	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	944	944	10	41.45149	-90.1485	MISO	MRO	IL	1500	[0]	[0]	60.96	[0, 0, 0, 0,	[0.0, 0.506	77	0.14	0.1	0	0	15	
944_11	1	1	Active	1.5	60.96	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	944	944_1	11	41.45149	-90.1485	MISO	MRO	IL	1500	[0]	[0]	60.96	[0, 0, 0, 0,	[0.0, 0.506	77	0.14	0.1	0	0	15	
1172_W1	1	1	Active	1.6	79.248	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	1172	1172	W1	43.27972	-92.8106	MISO	MRO	IA	1600	[0]	[0]	79.248	[0.0, 0.0, 0	[0.0, 0.25,	77	0.14	0.1	0	0	15	
1998_8	1	1	Active	1.2	74.9808	[3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5	1998	1998	8	43.9405	-94.9434	MISO	MRO	MN	1200	[0]	[0]	74.9808	[0.0, 0.0, 3	[3.0, 3.5, 4	64	0.14	0.1	0	0	15	
2022_WTG4	1	1	Active	2	79.97952	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	2022	2022_1	WTG4	45.12171	-95.0532	MISO	MRO	MN	2000	[0]	[0]	79.97952	[0, 0, 0, 0,	[0.0, 0.506	80	0.14	0.1	0	0	15	
2022_WTG3	1	1	Active	2	79.97952	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	2022	2022	WTG3	45.12171	-95.0532	MISO	MRO	MN	2000	[0]	[0]	79.97952	[0, 0, 0, 0,	[0.0, 0.506	80	0.14	0.1	0	0	15	
2024_9	1	1	Active	0.9	73.152	[2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0,	2024	2024_5	9	43.63349	-95.6092	MISO	MRO	MN	900	[0]	[0]	73.152	[2.96, 4.49	[2.5, 3.0, 3	52.2	0.14	0.1	0	0	15	
2024_8	1	1	Active	0.9	73.152	[2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0,	2024	2024_4	8	43.63349	-95.6092	MISO	MRO	MN	900	[0]	[0]	73.152	[2.96, 4.49	[2.5, 3.0, 3	52.2	0.14	0.1	0	0	15	
2024_12	1	1	Active	1	73.152	[3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5	2024	2024_2	12	43.63349	-95.6092	MISO	MRO	MN	1000	[0]	[0]	73.152	[0.0, 0.0, 2	[3.0, 3.5, 4	54	0.14	0.1	0	0	15	
2024_10	1	1	Active	0.9	73.152	[2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0,	2024	2024	10	43.63349	-95.6092	MISO	MRO	MN	900	[0]	[0]	73.152	[2.96, 4.49	[2.5, 3.0, 3	52.2	0.14	0.1	0	0	15	
2024_11	1	1	Active	0.9	73.152	[2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0,	2024	2024_1	11	43.63349	-95.6092	MISO	MRO	MN	900	[0]	[0]	73.152	[2.96, 4.49	[2.5, 3.0, 3	52.2	0.14	0.1	0	0	15	
2024_13	1	1	Active	1	73.152	[3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5	2024	2024_3	13	43.63349	-95.6092	MISO	MRO	MN	1000	[0]	[0]	73.152	[0.0, 0.0, 2	[3.0, 3.5, 4	54	0.14	0.1	0	0	15	
2240_CTNWD	1	1	Active	40.9	89.916	[3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5	2240	2240	CTNWD	41.4281	-96.4623	SWPP	MRO	NE	40900	[0, 564.0,	[0, 0, 0, 0,	89.916	[0.0, 0.0, 3	[3.0, 3.5, 4	70.5	0.14	0.1	0	0	15	
7381_1	1	1	Active	6	40.2336	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	7381	7381	1	42.8625	-72.9628	ISNE	NPCC	VT	6000	[0, 320.0,	[0, 0, 0, 0,	40.2336	[0.0, 0.0, 0	[0.0, 0.25,	40	0.14	0.1	0	0	15	
7501_2	1	1	Active	3	70.104	[4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0,	7501	7501	2	42.4789	-71.9	ISNE	NPCC	MA	3000	[0, 616.0]	[0, 0]	70.104	[54.0, 141.	[4.0, 5.0, 6	77	0.14	0.1	0	0	15	
7526_2	1	1	Active	24	79.97952	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	7526	7526	2	38.11642	-121.769	CISO	WECC	CA	24000	[0, 720.0,	[0, 0, 0, 0,	79.97952	[0.0, 0.0, 0	[0.0, 0.25,	90	0.14	0.1	0	0	15	
7526_2B	1	1	Active	63	79.97952	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	7526	7526_1	2B	38.11642	-121.769	CISO	WECC	CA	63000	[0, 720.0,	[0, 0, 0, 0,	79.97952	[0.0, 0.0, 0	[0.0, 0.25,	90	0.14	0.1	0	0	15	
7526_3	1	1	Active	128	79.97952	[0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3	7526	7526_2	3	38.11642	-121.769	CISO	WECC	CA	128000	[0, 720.0,	[0, 0, 0, 0,	79.97952	[0.0, 0.0, 0	[0.0, 0.25,	90	0.14	0.1	0	0	15	
7526_1	1	1	Active	13.2	54.864	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7526	7526_3	1	38.11642	-121.769	CISO	WECC	CA	13200	[0, 376.0,	[0, 0, 0, 0,	54.864	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	
7771_3	1	1	Active	1.5	61.47816	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7771	7771	3	42.82579	-99.7775	SWPP	MRO	NE	1500	[0]	[0]	61.47816	[0, 0, 0, 0,	[0.0, 0.506	77	0.14	0.1	0	0	15	
7771_4	1	1	Active	1.5	61.47816	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7771	7771_1	4	42.82579	-99.7775	SWPP	MRO	NE	1500	[0]	[0]	61.47816	[0, 0, 0, 0,	[0.0, 0.506	77	0.14	0.1	0	0	15	
7855_8	1	1	Active	0.7	54.864	[3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5, 11.	7855	7855	8	46.895	-96.7347	SWPP	MRO	MN	700	[0]	[0]	54.864	[4.4, 16.68	[3.5, 4.0, 4	48.2	0.14	0.1	0	0	15	
7855_9	1	1	Active	0.7	54.864	[3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, 10.5, 11.	7855	7855_1	9	46.895	-96.7347	SWPP	MRO	MN	700	[0]	[0]	54.864	[4.4, 16.68	[3.5, 4.0, 4	48.2	0.14	0.1	0	0	15	
7886_1	1	1	Active	11	64.9224	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7886	7886	1	44.6694	-87.6333	MISO	MRO	WI	11000	[0, 376.0,	[0, 0, 0, 0,	64.9224	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	
7927_1	1	1	Active	0.6	64.9224	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7927	7927	1	36.12099	-84.3387	TVA	SERC	TN	600	[0]	[0]	64.9224	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	
7927_2	1	1	Active	0.6	64.9224	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7927	7927_1	2	36.12099	-84.3387	TVA	SERC	TN	600	[0]	[0]	64.9224	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	
7927_3	1	1	Active	0.6	64.9224	[0.0, 0.5063291139240507, 1.0126582278481013, 1.51898734177215	7927	7927_2	3	36.12099	-84.3387	TVA	SERC	TN	600	[0]	[0]	64.9224	[0, 0, 0, 0,	[0.0, 0.506	47	0.14	0.1	0	0	15	

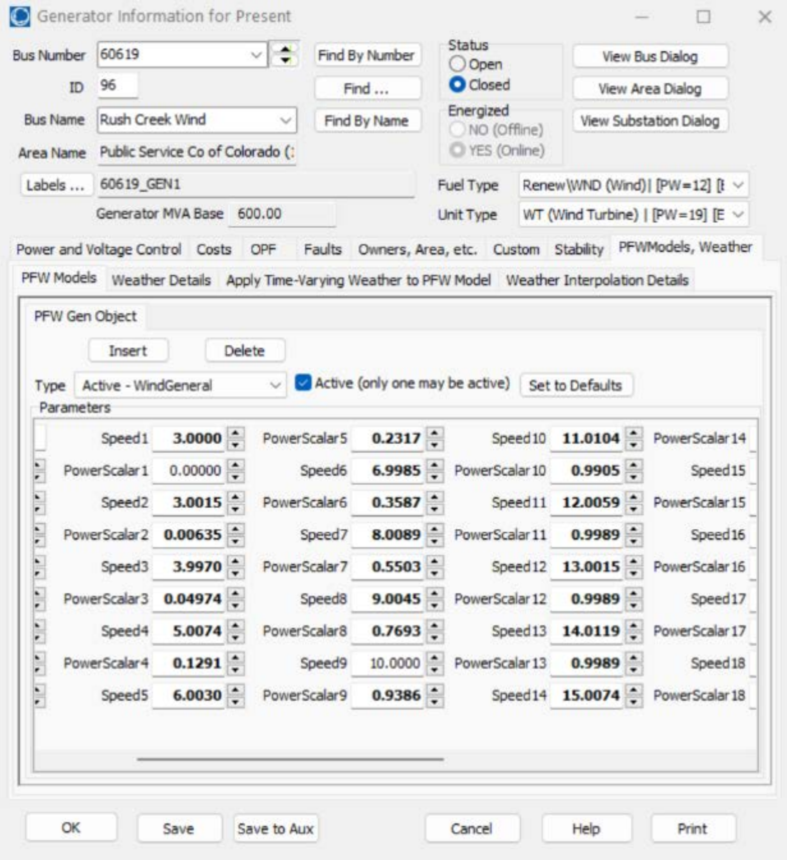
[a] C. Bracken, S. Underwood, A. Campbell, T.B. Thurber, N. Voisin, Hourly wind and solar generation profiles for every EIA 2020 plant in the CONUS, 2023, dx.doi.org/10.5281/zenodo.7901615

Pasting in the Wind Power Curves

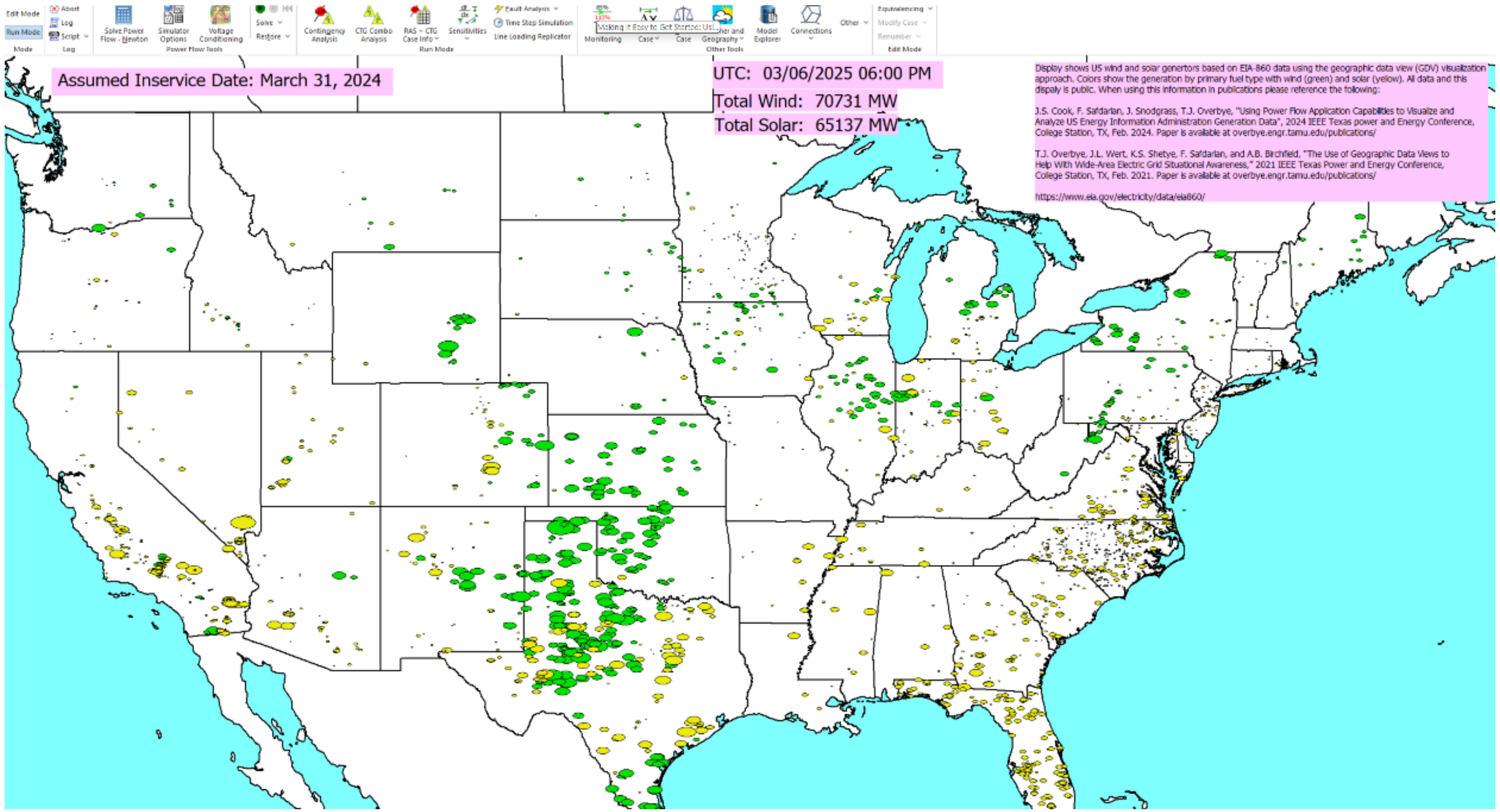
- Select all the data on the previous slide data in Excel, and copy it
- In Simulator open **Tools, Weather, Weather Models and Information**; select the PFW Model Summary page, and right-click on the WindGeneral object type



One Wind Turbine Example, Full CONUS Wind/Solar

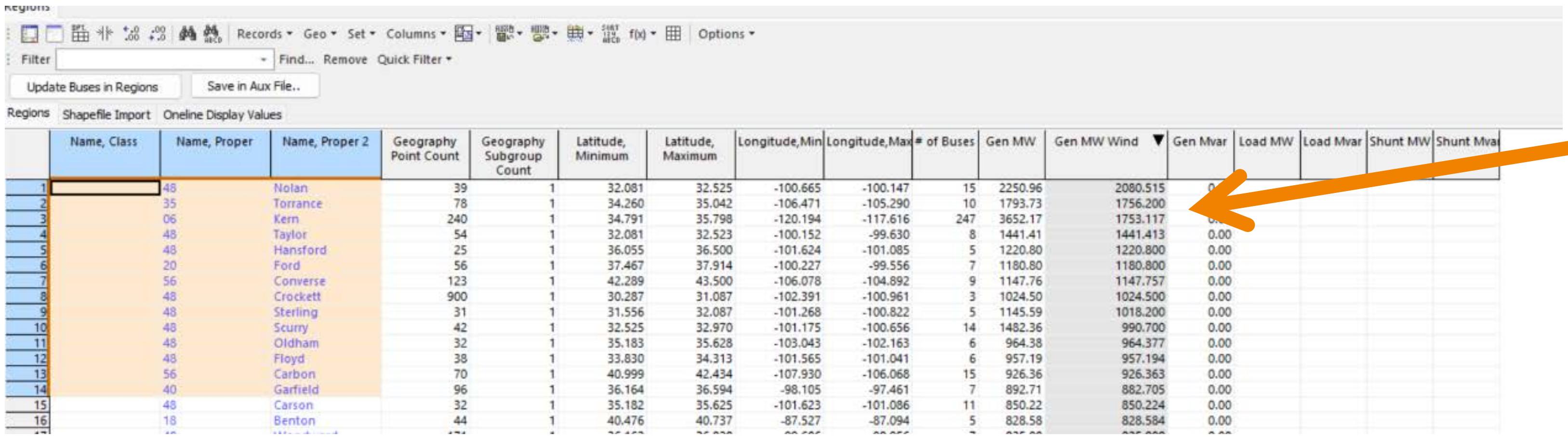


The below display shows the wind (green) and solar (yellow) installed capacity; applying the weather modifies these



Aside: Geographic Regions in Simulator Version 24

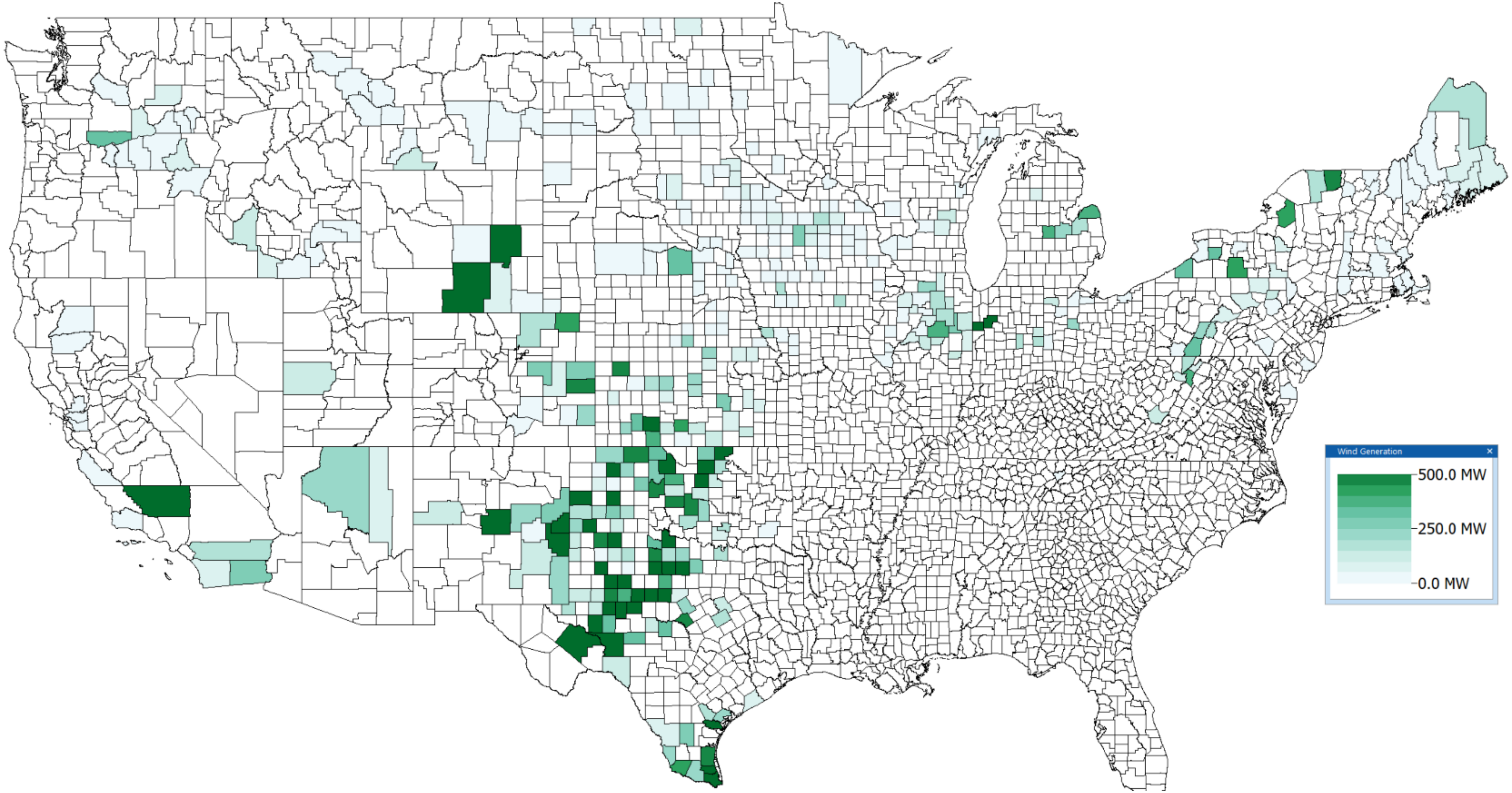
- New with version 24, Simulator can directly model geographic regions, including showing a summary and details on the buses in regions; results can also be visualized
- The functionality is available by selecting **Tools, Weather and Geography, Regions**
- Regions can be either stored in aux files, imported using shape files, or setup manually



	Name, Class	Name, Proper	Name, Proper 2	Geography Point Count	Geography Subgroup Count	Latitude, Minimum	Latitude, Maximum	Longitude,Min	Longitude,Max	# of Buses	Gen MW	Gen MW Wind	Gen Mvar	Load MW	Load Mvar	Shunt MW	Shunt Mvar
1		48	Nolan	39	1	32.081	32.525	-100.665	-100.147	15	2250.96	2080.515	[illegible]				
2		35	Torrance	78	1	34.260	35.042	-106.471	-105.290	10	1793.73	1756.200	[illegible]				
3		06	Kern	240	1	34.791	35.798	-120.194	-117.616	247	3652.17	1753.117	[illegible]				
4		48	Taylor	54	1	32.081	32.523	-100.152	-99.630	8	1441.41	1441.413	0.00				
5		48	Hansford	25	1	36.055	36.500	-101.624	-101.085	5	1220.80	1220.800	0.00				
6		20	Ford	56	1	37.467	37.914	-100.227	-99.556	7	1180.80	1180.800	0.00				
7		56	Converse	123	1	42.289	43.500	-106.078	-104.892	9	1147.76	1147.757	0.00				
8		48	Crockett	900	1	30.287	31.087	-102.391	-100.961	3	1024.50	1024.500	0.00				
9		48	Sterling	31	1	31.556	32.087	-101.268	-100.822	5	1145.59	1018.200	0.00				
10		48	Scurry	42	1	32.525	32.970	-101.175	-100.656	14	1482.36	990.700	0.00				
11		48	Oldham	32	1	35.183	35.628	-103.043	-102.163	6	964.38	964.377	0.00				
12		48	Floyd	38	1	33.830	34.313	-101.565	-101.041	6	957.19	957.194	0.00				
13		56	Carbon	70	1	40.999	42.434	-107.930	-106.068	15	926.36	926.363	0.00				
14		40	Garfield	96	1	36.164	36.594	-98.105	-97.461	7	892.71	882.705	0.00				
15		48	Carson	32	1	35.182	35.625	-101.623	-101.086	11	850.22	850.224	0.00				
16		18	Benton	44	1	40.476	40.737	-87.527	-87.094	5	828.58	828.584	0.00				

Shows the wind generation by county

Aside: Geographic Regions Showing Wind Generation by County



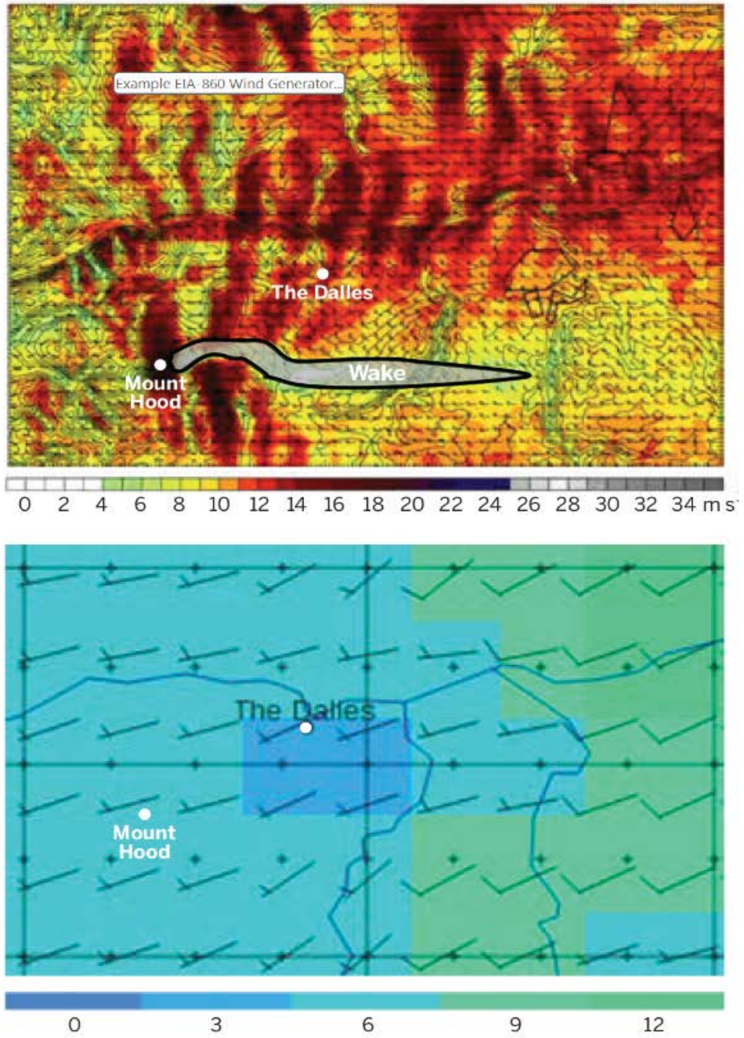
Mapping Weather to the Electric Grid Components

- While the newer weather datasets have lots of points, there is still usually at least some distance between power grid components and the nearest weather measurement, requiring interpolation
- There is no single best algorithm for doing the needed 2D scattered data interpolation, but there are a number of good and fast algorithms (grid-based, closest neighbor, Delaunay Triangulation, Shepherd's)
  - Since the weather values have an associated elevation, if the power grid component's elevation (or profile for a line) is known this could be considered
- If high resolution is needed, then HRRR data can be quite useful

Dealing with Local Terrain

- In some situations, particularly wind, the local terrain variation can be significant, meaning that by themselves datasets like ERA5 may not be sufficient
  - High resolution datasets like HRRR can certainly help in these situations
- It is important to keep in mind the ultimate goal of using weather in planning; often quite acceptable results can be obtained including compensation terms in the PFW models that only need to be set once

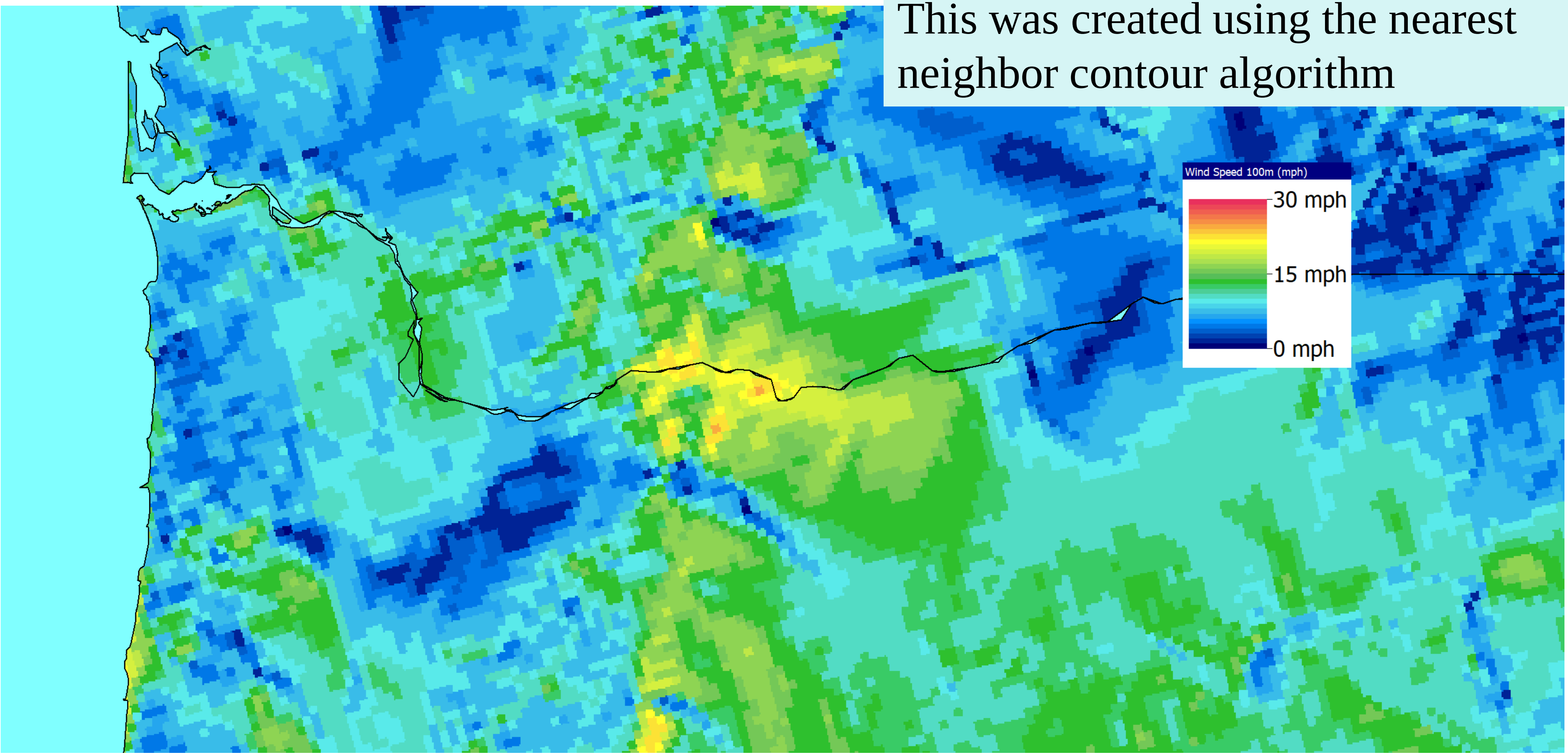
FIGURE 5
Wakes and Waves Observable in a 1 km, But Not 30 km, Simulation of the Columbia Gorge in the U.S. Pacific Northwest



The output from a 1 km Weather Research and Forecasting (WRF) simulation (top) clearly shows mountain wake and wave activity to the east of Mount Hood, whereas the output from the 30 km ERA5 dataset (bottom) for the same hour in April 2010 does not show this activity.

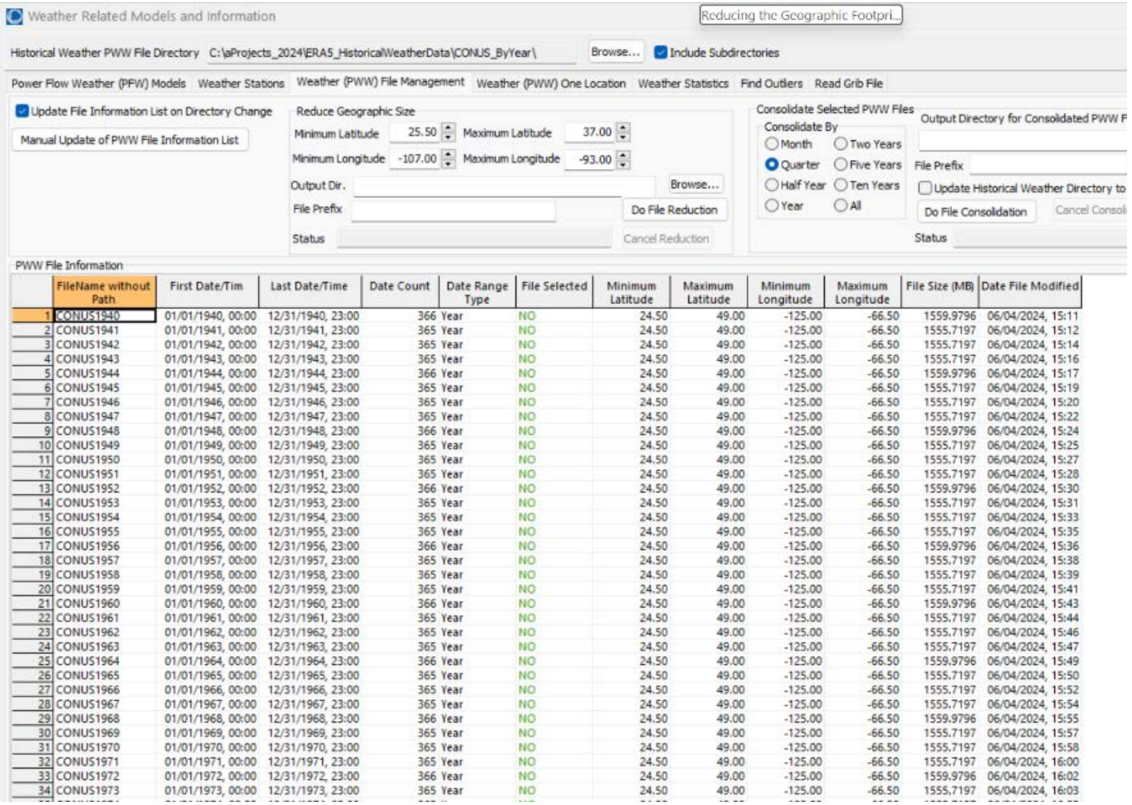
Simulator HRRR 100m Wind Contour Columbia River

This was created using the nearest neighbor contour algorithm



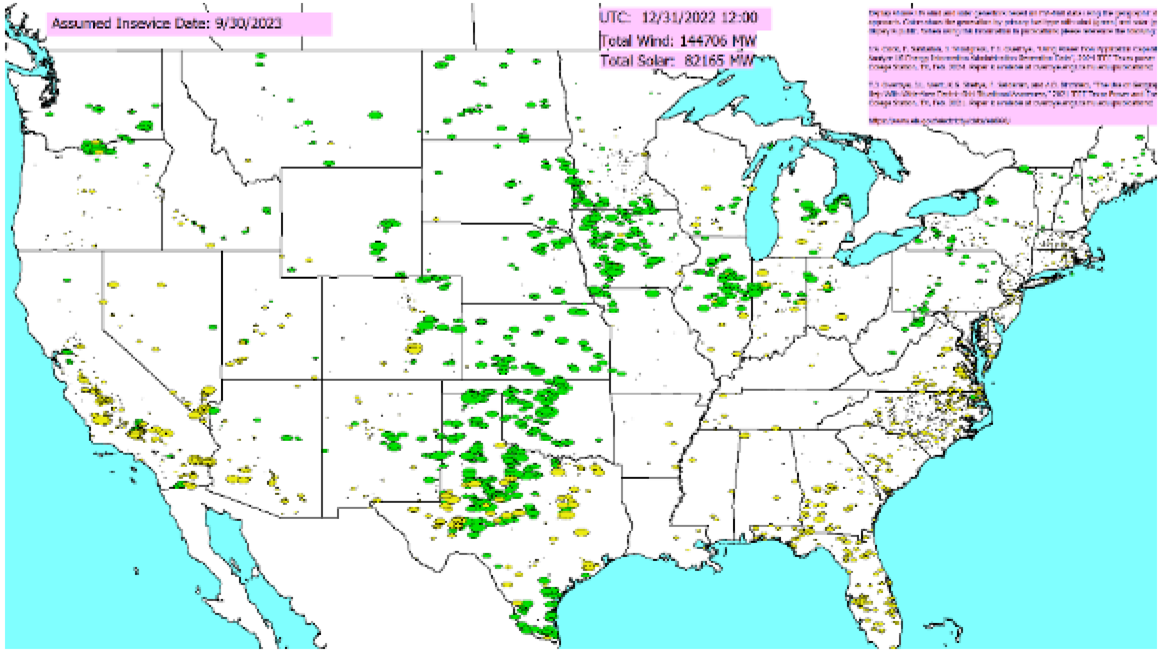
Reducing the Geographic Footprint

- Using data for all of North America is not usually recommended
  - Smaller footprints use less memory, down quicker and require less computation
  - We are supplying data more most of North America to make sure all data is available for subsequent reduction
- PowerWorld has a tool to make it easy to reduce the footprint by specifying a new geographic rectangle
- At **Tools, Weather, Weather Models and Information** on the Weather PWW File Management page



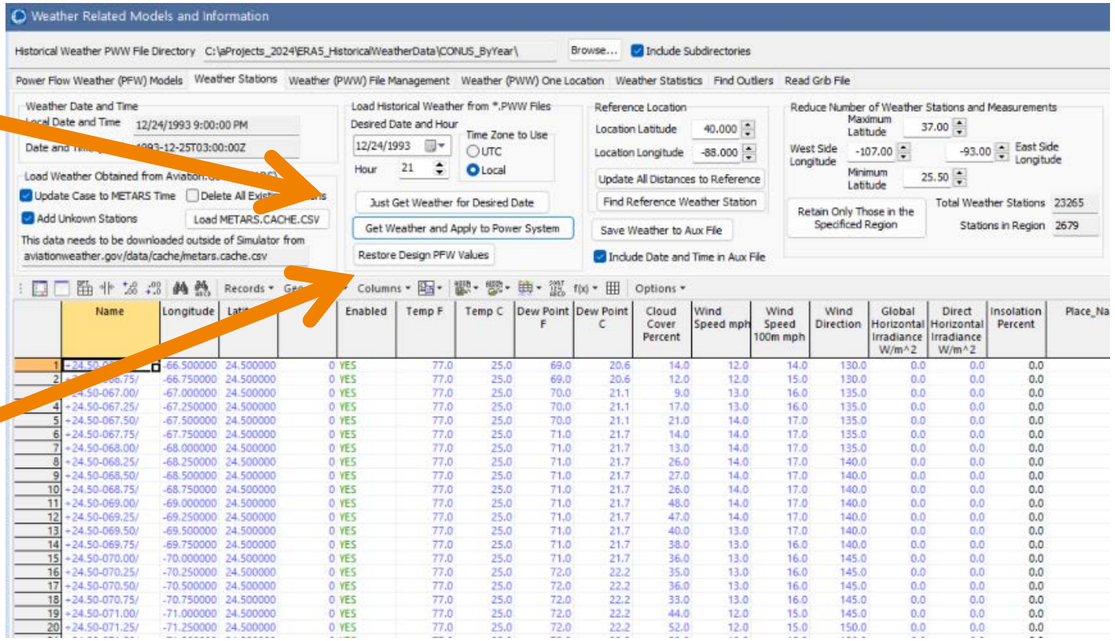
Applying the Weather

- Weather can be applied to a power flow case using the pww files in multiple ways
  - At a specified point in time
  - As a summary of a large amount of weather at a single location (e.g., a generator) or at a few locations (a transmission line)
  - As a time series, sequentially solving lots of different time points
- The next few slides give an overview of these, showing the changes in the wind and solar outputs



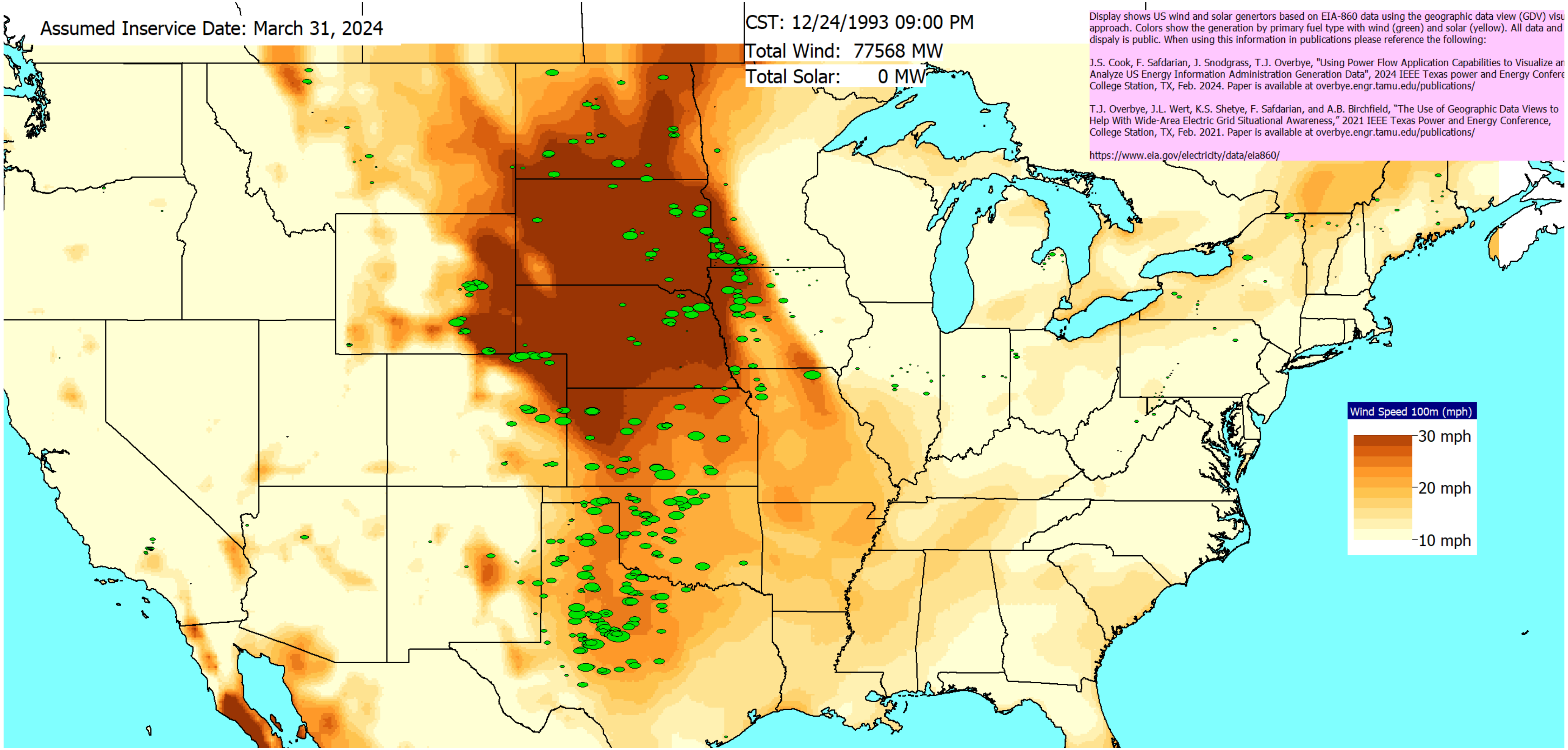
Applying Weather for a Single Time Point

- With the provided pww files, any time going back to 1940 can be simulated. The pww files are designed for quick searching, and for providing direct access to all the data for a particular time.
- Getting the access to the weather for all of North America with ERA5 takes about a second; optionally the weather can also be applied to the power flow
- Once applied the power flow (and other applications) can be solved as normal
- Restore values at the end



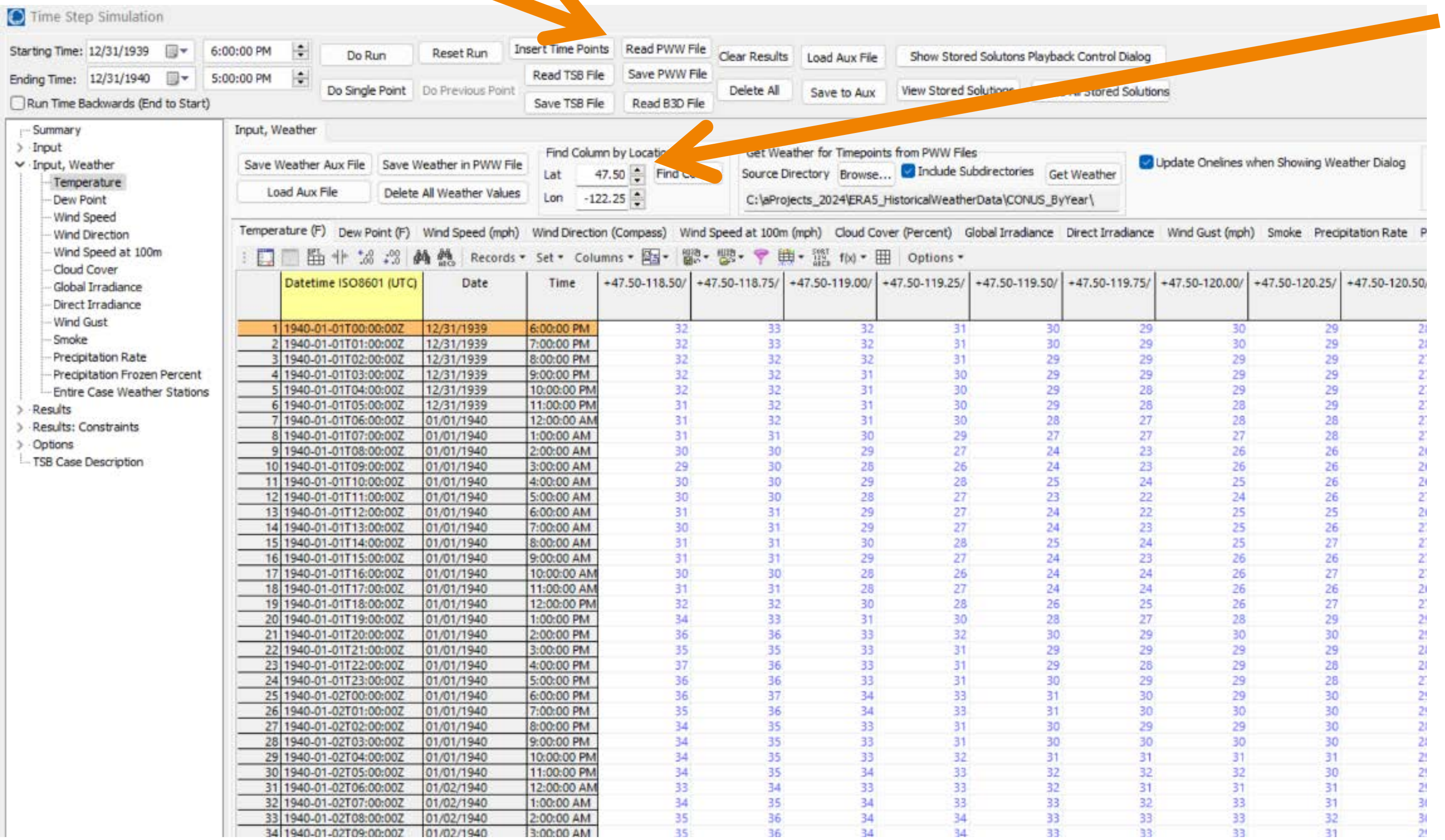
Visualization of Weather from 12/24/1993

Historical weather is being applied to 2024 wind and solar generation



Simulating Large Amounts of Weather Information

- To easily view and simulate many time values, the pww files can be loaded into the Time Step simulation (**Tools, Time Step Simulation**)
  - Select **Read PWW File** to load the desired file

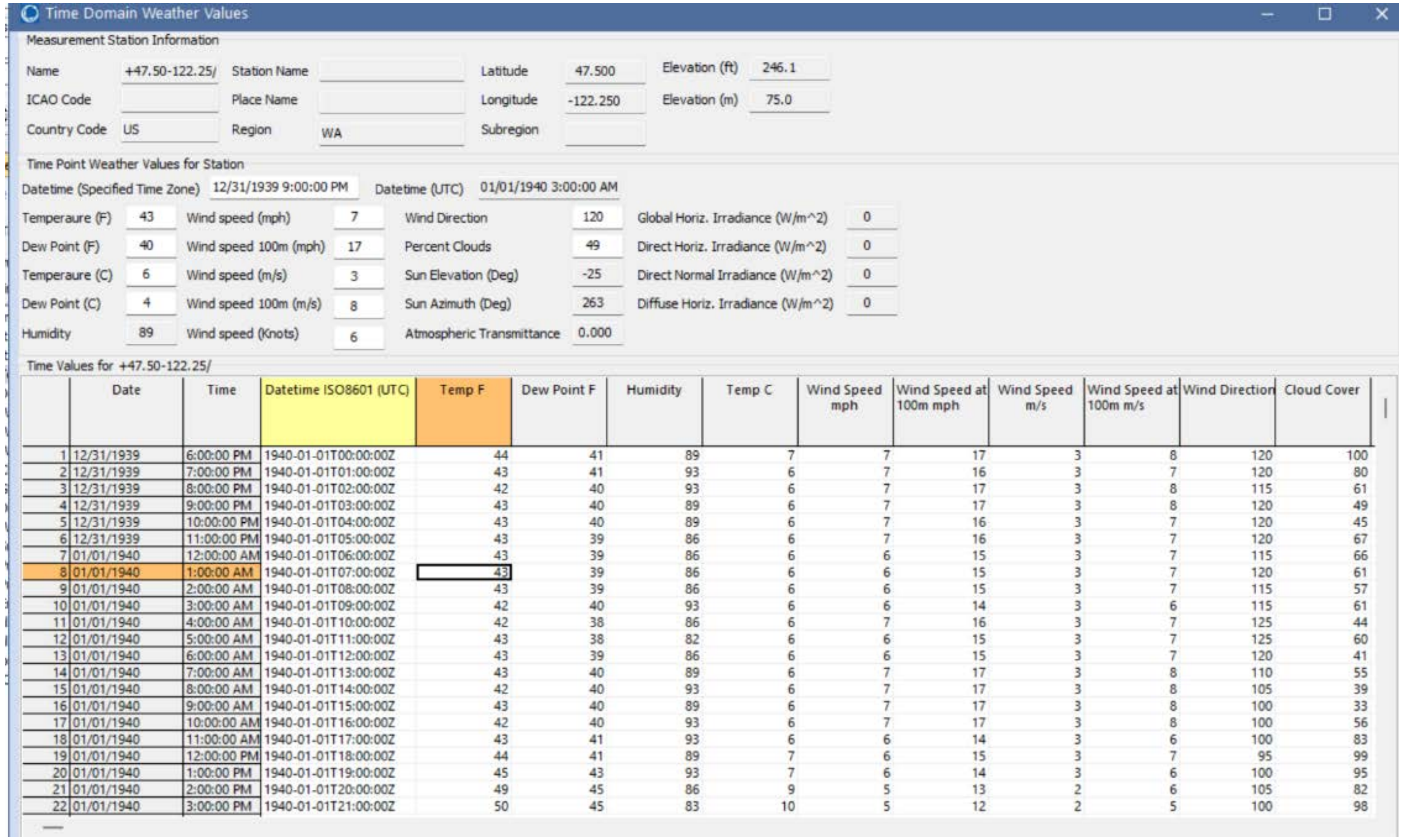


Allows a weather location to be easily located (Seattle here)

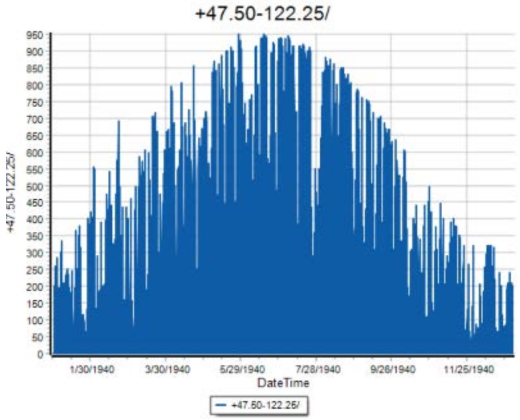
Like any Simulator case information grid, the data can be easily plotted and exported

Seeing All Weather Data for a Location

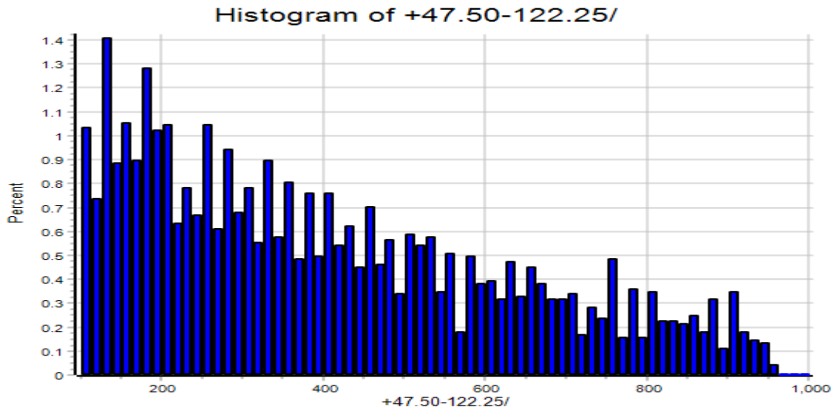
- To see all the weather data for a location, just right-click on the column and select **Show Dialog with All Times for Location**



	Date	Time	Datetime ISO8601 (UTC)	Temp F	Dew Point F	Humidity	Temp C	Wind Speed mph	Wind Speed at 100m mph	Wind Speed m/s	Wind Speed at 100m m/s	Wind Direction	Cloud Cover
1	12/31/1939	6:00:00 PM	1940-01-01T00:00:00Z	44	41	89	7	7	17	3	8	120	100
2	12/31/1939	7:00:00 PM	1940-01-01T01:00:00Z	43	41	93	6	7	16	3	7	120	80
3	12/31/1939	8:00:00 PM	1940-01-01T02:00:00Z	42	40	93	6	7	17	3	8	115	61
4	12/31/1939	9:00:00 PM	1940-01-01T03:00:00Z	43	40	89	6	7	17	3	8	120	49
5	12/31/1939	10:00:00 PM	1940-01-01T04:00:00Z	43	40	89	6	7	16	3	7	120	45
6	12/31/1939	11:00:00 PM	1940-01-01T05:00:00Z	43	39	86	6	7	16	3	7	120	67
7	01/01/1940	12:00:00 AM	1940-01-01T06:00:00Z	43	39	86	6	6	15	3	7	115	66
8	01/01/1940	1:00:00 AM	1940-01-01T07:00:00Z	43	39	86	6	6	15	3	7	120	61
9	01/01/1940	2:00:00 AM	1940-01-01T08:00:00Z	43	39	86	6	6	15	3	7	115	57
10	01/01/1940	3:00:00 AM	1940-01-01T09:00:00Z	42	40	93	6	6	14	3	6	115	61
11	01/01/1940	4:00:00 AM	1940-01-01T10:00:00Z	42	38	86	6	7	16	3	7	125	44
12	01/01/1940	5:00:00 AM	1940-01-01T11:00:00Z	43	38	82	6	6	15	3	7	125	60
13	01/01/1940	6:00:00 AM	1940-01-01T12:00:00Z	43	39	86	6	6	15	3	7	120	41
14	01/01/1940	7:00:00 AM	1940-01-01T13:00:00Z	43	40	89	6	7	17	3	8	110	55
15	01/01/1940	8:00:00 AM	1940-01-01T14:00:00Z	42	40	93	6	7	17	3	8	105	39
16	01/01/1940	9:00:00 AM	1940-01-01T15:00:00Z	43	40	89	6	7	17	3	8	100	33
17	01/01/1940	10:00:00 AM	1940-01-01T16:00:00Z	42	40	93	6	7	17	3	8	100	56
18	01/01/1940	11:00:00 AM	1940-01-01T17:00:00Z	43	41	93	6	6	14	3	6	100	83
19	01/01/1940	12:00:00 PM	1940-01-01T18:00:00Z	44	41	89	7	6	15	3	7	95	99
20	01/01/1940	1:00:00 PM	1940-01-01T19:00:00Z	45	43	93	7	6	14	3	6	100	95
21	01/01/1940	2:00:00 PM	1940-01-01T20:00:00Z	49	45	86	9	5	13	2	6	105	82
22	01/01/1940	3:00:00 PM	1940-01-01T21:00:00Z	50	45	83	10	5	12	2	5	100	98



Global irradiance values (histogram neglects 0)



Availability of Forecasted Weather Information

- Forecasted weather information is also available from a variety of sources; here we use the free forecasts provided by US National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) NCEP Central Operations
  - nco.ncep.noaa.gov/pmb/products/gfs/
  - Specifically we're using the 0.25 degree resolution GFS results, which provide four global forecasts per day going out for 16 days (hourly for the first five days, then every three hours)
  - Forecasts are also pww files, so all of the existing tools can be used, though the forecasts to not have the solar irradiance values
- We hope to soon get access to longer-term forecasts

Some Potential Additional Models

- With weather information a part of the power flow a wide variety of additional power flow model enhancements become possible. Some examples are given below, recognizing that many are already done using external analysis
  - Transmission line limits that depend on temperature, wind and insolation along the right-of-way; working with industry we already have some quite sophisticated models
  - Transformer limits
  - Load models (recognizing that the load depends on many factors, initial models could be linearizations about a specified value)
  - Line resistance (though this would be more complex since it is operating point dependent
  - Etc.

Future Directions

- There are many future directions to pursue
  - A number of models that relate weather to electric grid values already exist, but many more certainly need to be developed
  - Integration of weather into tools such as contingency analysis; better tools for dealing with stochastic models
  - Support for more weather types, greater integration of reading primary sources such as GRIB and GRIB2 files
  - Determining the required level of weather details; higher resolution datasets are available; also other potentially severe resiliency events
  - More validation!!
  - Increased automation of the updating process; maybe more footprints
  - Machine learning applications given lots of potential operating points

Thank You! Questions?

Recent papers are at overbye.engr.tamu.edu/publications/ For questions afterwards email at overbye@tamu.edu or overbye@powerworld.com