Quick Start Guide to Using Historical and Forecasted Weather Information in PowerWorld Simulator

Thomas J. Overbye
O'Donnell Foundation Chair III
Texas A&M University
overbye@tamu.edu, Overbye@powerworld.com

February 14, 2024

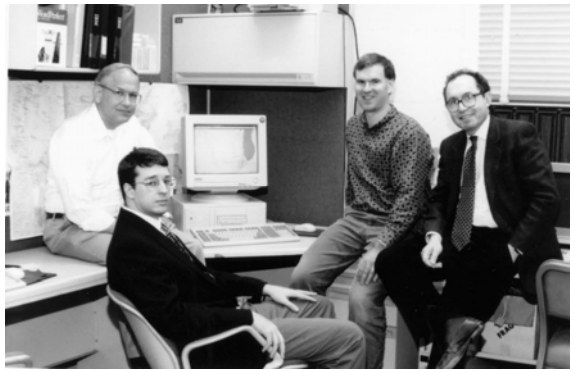
Overview

- 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
- All the weather data in the presentation (hourly data for North America) going back to January 1940 is available for immediate download
- This presentation builds on the one I gave on 1/24/24, with more of a PowerWorld Simulator focus here
  - Slides from January are at **smartgridcenter.tamu.edu/webinars/**

About Tom Overbye

- Since 2017 been a professor in the Electrical and Computer Engineering Department at Texas A&M (TAMU) working in the power systems area
- Also the director of the Texas A&M Smart Grid Center
- From 1991 to 2016 was with University of Illinois (UIUC)
- Got all degrees from University of Wisconsin-Madison, and worked eight years as an engineer with Madison
- Taught many power systems classes over last 33 years and worked on a wide variety of research projects

About Tom Overbye



- Started the development of the code that became PowerWorld during graduate school
- Co-founder of PowerWorld Corporation in 1996
  - Goal is to make grid analysis as easy as possible
- Since both UIUC and TAMU encourage faculty to do consulting and/or have external business relationships, I have continued to work with the PowerWorld code including OPF, stability, visualization, GMD, HEMP, and now weather
- As was the case at UIUC, at TAMU my relationship with PowerWorld is covered by a management plan

Using Weather with PowerWorld Simulator

- Over the last 18 months 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 can impact the power system devices 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

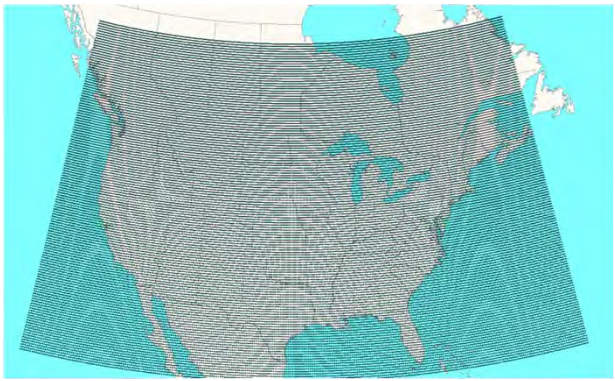
- The weather functionality is only available in Version 23, and is currently available as an add-on included in the base package
- Much of the weather does not require cases with geographic values, but more can be done when available
- What is available depends on the build date
- The Simulator version and build date are available by selecting **Window, About**
- We desire your suggestions on what should be included moving forward

Availability of Historical Weather Information

- When this effort started we were 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 are very useful (e.g., at electrical substations)
- We are also now using ERA5 data, 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

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, and direct horizontal irradiance
  - The North America pww files have 38,497 data points; with 8 values per hour, this is about 220 MB per month, or about 225 GB for the total set
- This data is public so it can be freely used and shared



Eelectricgrids.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

References

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

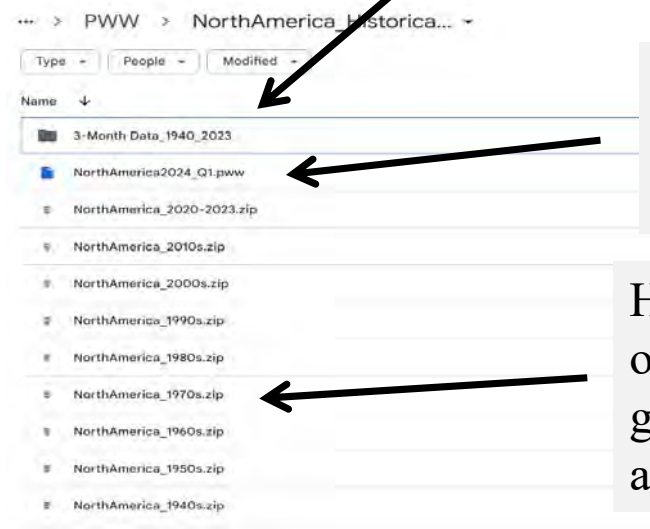
T. J. Overbye, F. Safdarian, W. Trinh, Z. Mao, J. Snodgrass, and J. Yeo, "An Approach for the Direct Inclusion of Weather Information in the Power Flow," *Proc. 56th Hawaii International Conference on System Sciences (HICSS)*, January 2023.

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 3-month data is your download speed is slow

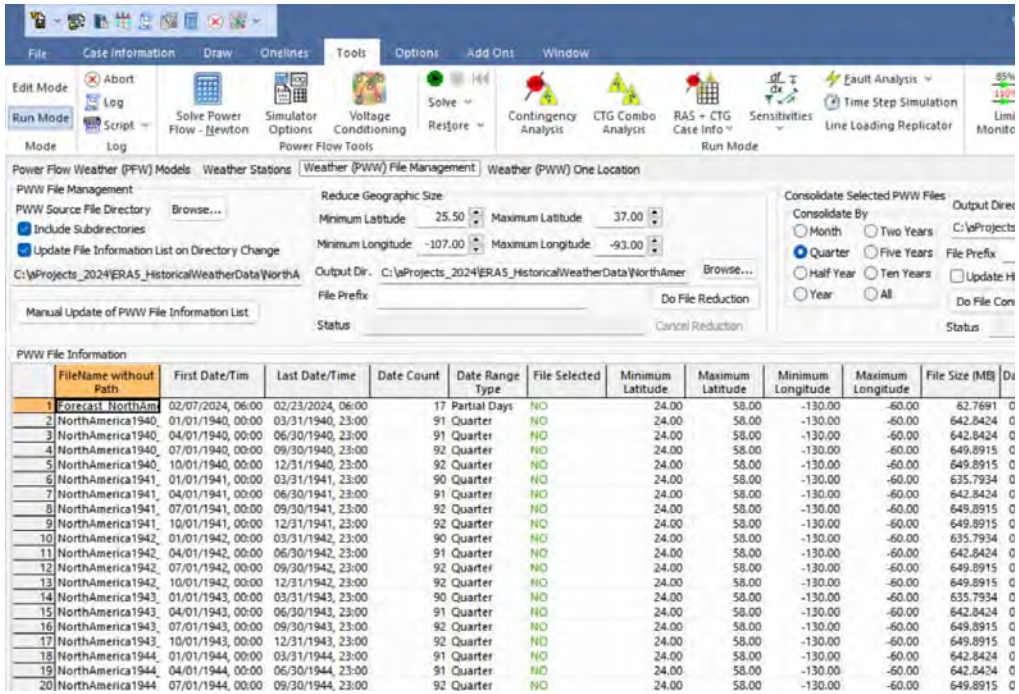


Data for current year, updated daily

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

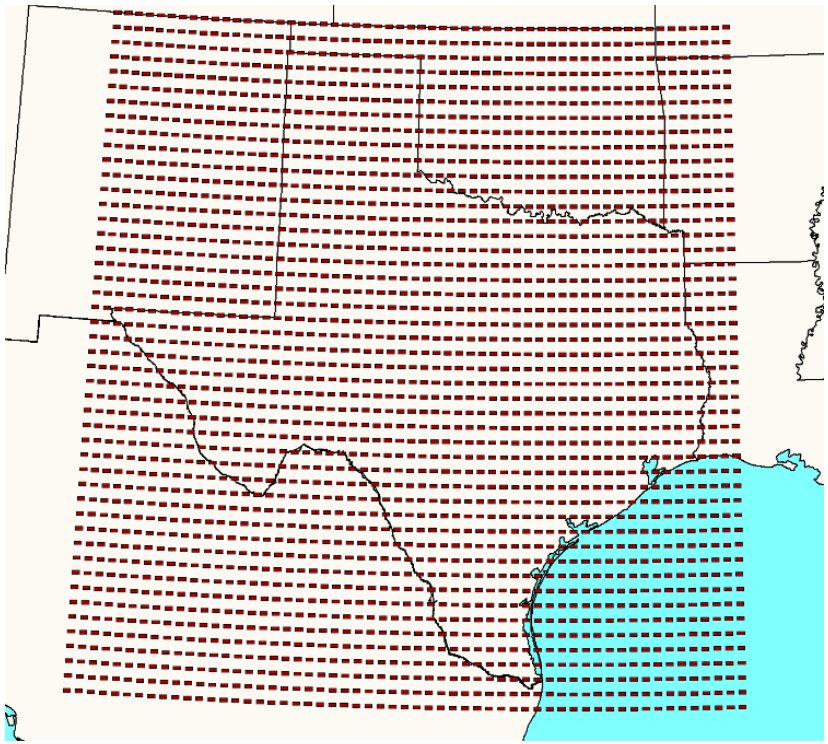
Reducing the Geographic Footprint

- 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



Example: Texas PWW Files, Stored Every Two Years

- The Texas pww files have 2679 grid points; each file stores two years of data with a size of 367 MB; total set (1940-2024) is 15 GB



WW) File Management | Weather (PWW) One Location

Geographic Size
Latitude 25.50 Maximum Latitude 37.00
Longitude -107.00 Maximum Longitude -93.00
ir. C:\aProjects_2024\ERA5_HistoricalWeatherData\NorthAmer Browse...
x
Do File Reduction
Cancel Reduction

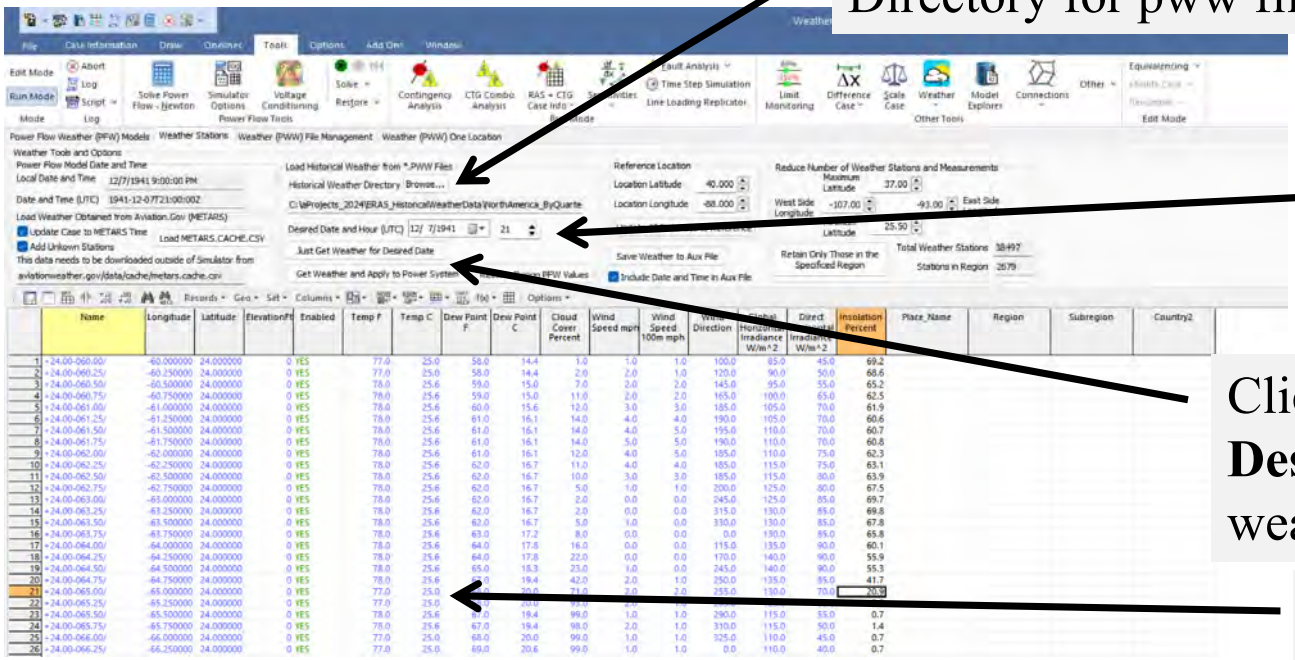
Consolidate Selected PWW Files
Consolidate By
Month Two Years
Quarter Five Years
Half Year Ten Years
Year All
Output Directory for Consolidated PWW Files Browse...
C:\aProjects_2024\ERA5_HistoricalWeatherData\Texas_ByTwoYears'
File Prefix
Delete Source Files
Update Historical Weather Directory to Output Directory
Do File Consolidation
Cancel Consolidation
Status

	Date Count	Date Range Type	File Selected	Minimum Latitude	Maximum Latitude	Minimum Longitude	Maximum Longitude	File Size (MB)	Date File Modified
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:29
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:30
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:30
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:30
0	90	Quarter	NO	25.50	37.00	-107.00	-93.00	44.2479	01/25/2024, 09:30
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:31
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:31
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:31
0	90	Quarter	NO	25.50	37.00	-107.00	-93.00	44.2479	01/25/2024, 09:31
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:32
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:32
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:32
0	90	Quarter	NO	25.50	37.00	-107.00	-93.00	44.2479	01/25/2024, 09:33
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:33
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:33
0	92	Quarter	NO	25.50	37.00	-107.00	-93.00	45.2289	01/25/2024, 09:33
0	91	Quarter	NO	25.50	37.00	-107.00	-93.00	44.7384	01/25/2024, 09:34

Tool for reducing or consolidating pww files

Viewing Weather for an Hour

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



Directory for pww files

Enter the day and hour; note, all times are Coordinated Universal Time (UTC)

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

Results; value can be shown in metric if desired

Available ERA5 Fields in PowerWorld

- The ERA5 dataset has hundreds of different values; currently we are using eight of them
  - Surface temperature, surface dew point
  - Wind speed at 10m, wind direction at 10m
  - Wind speed at 100m
  - 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 are also available
  - Other values could be used, like 10m wind gusts and icing estimates

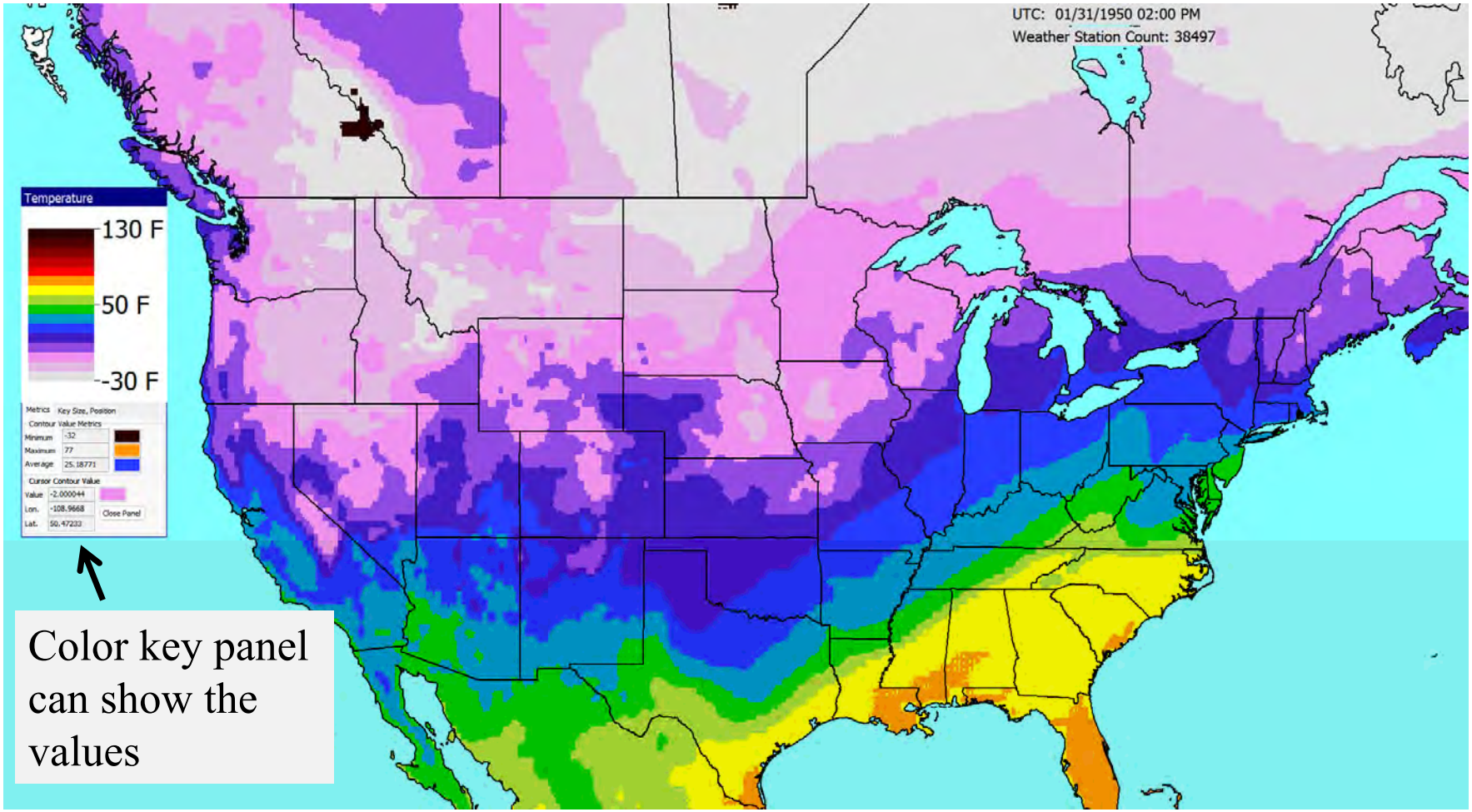
PWW File Format

- The Power Weather (*.pww) files use a binary format to store weather information for a set of time points and a set of 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
  - The data (e.g., the weather measurements) can be stored as either bytes or words (two bytes)
- Header information gives the file's time range and geographic range
- Format will be public, though currently just available by request to Overbye@tamu.edu

Visualizing the Weather

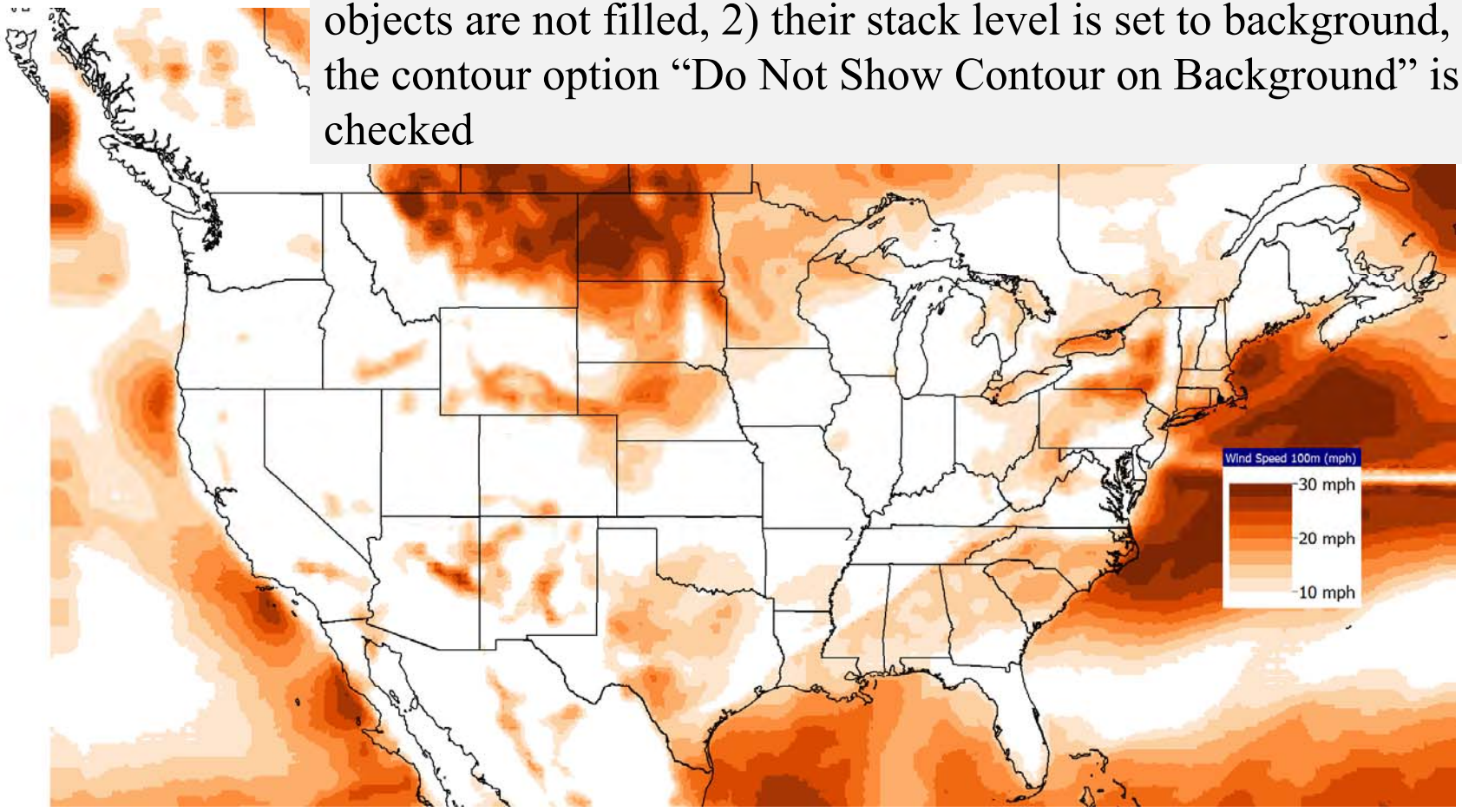
- With its relatively new “Spatial Data” contours, PowerWorld makes it very easy to visualize the weather
  - Spatial data contours visualize geographically specified data that does not have a corresponding power grid component; added initially for geomagnetically induced current (GIC) electric fields, but also used with weather
  - Spatial data contours do not require that the electric grid have geographic information; **so weather can be visualized with any PowerWorld case!**
- To make this very easy PowerWorld has example *.pwd files that have predefined contours
  - Available at www.powerworld.com/knowledge-base/simple-weather-example
- The pww files include off-shore values; they are just not contoured

Coldest Recorded Day in Seattle: Jan 31, 1950



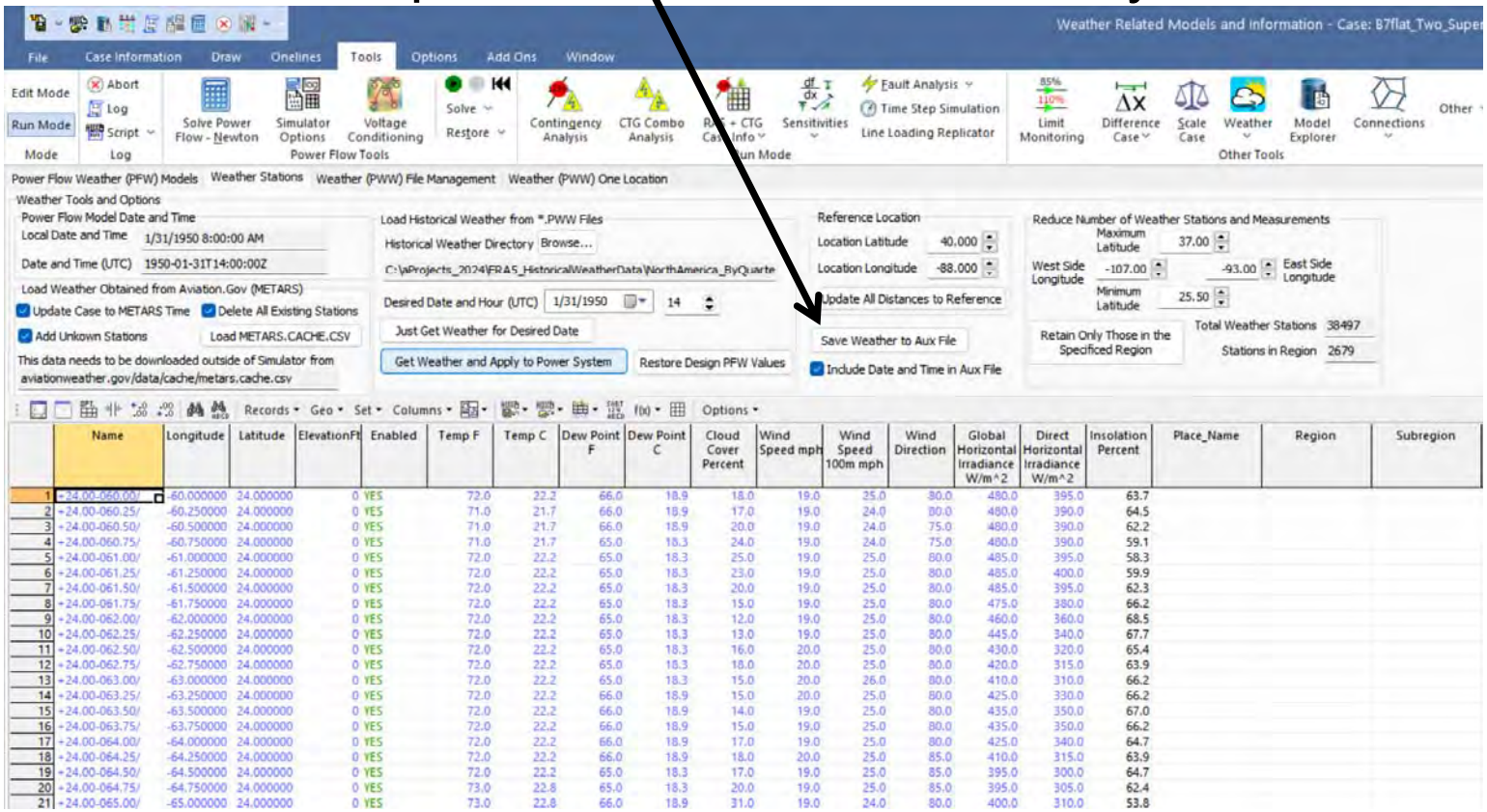
Contour Example Including Oceans (1/31/50)

To show the ocean values, redefine the display so 1) background objects are not filled, 2) their stack level is set to background, and 3) the contour option “Do Not Show Contour on Background” is not checked



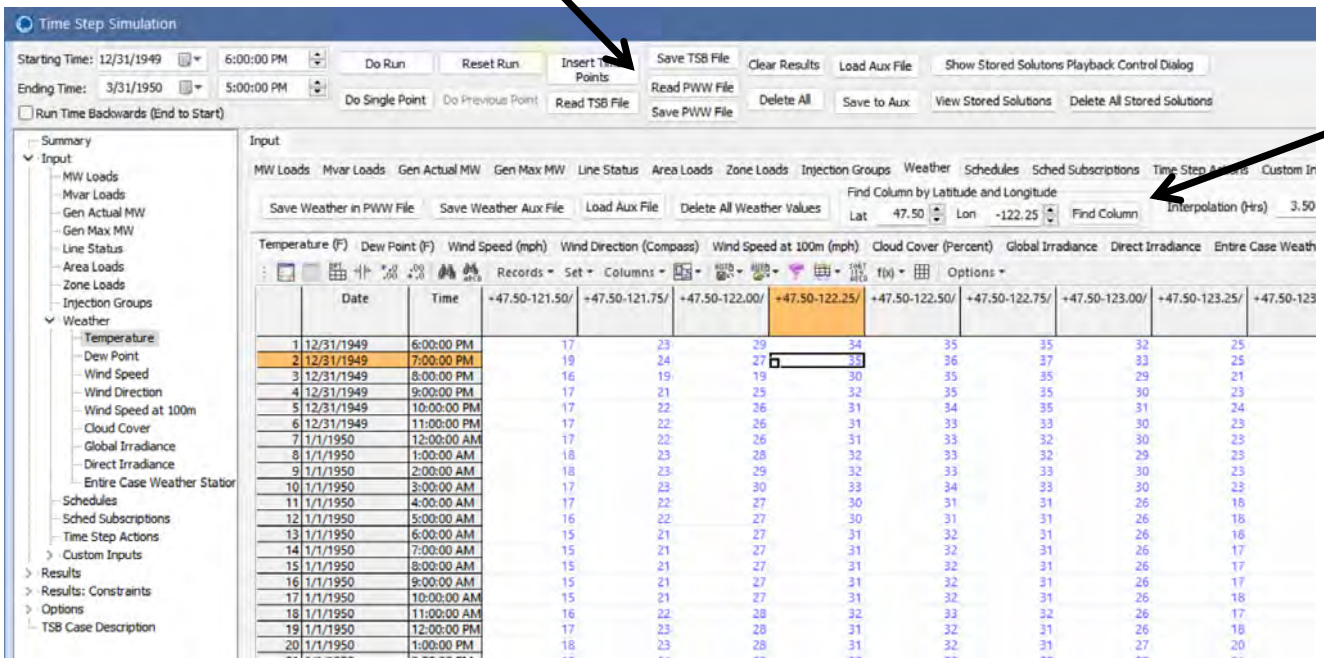
Saving Snapshot Weather in an Aux File

- Weather for a particular hour can be easily saved in an aux file



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

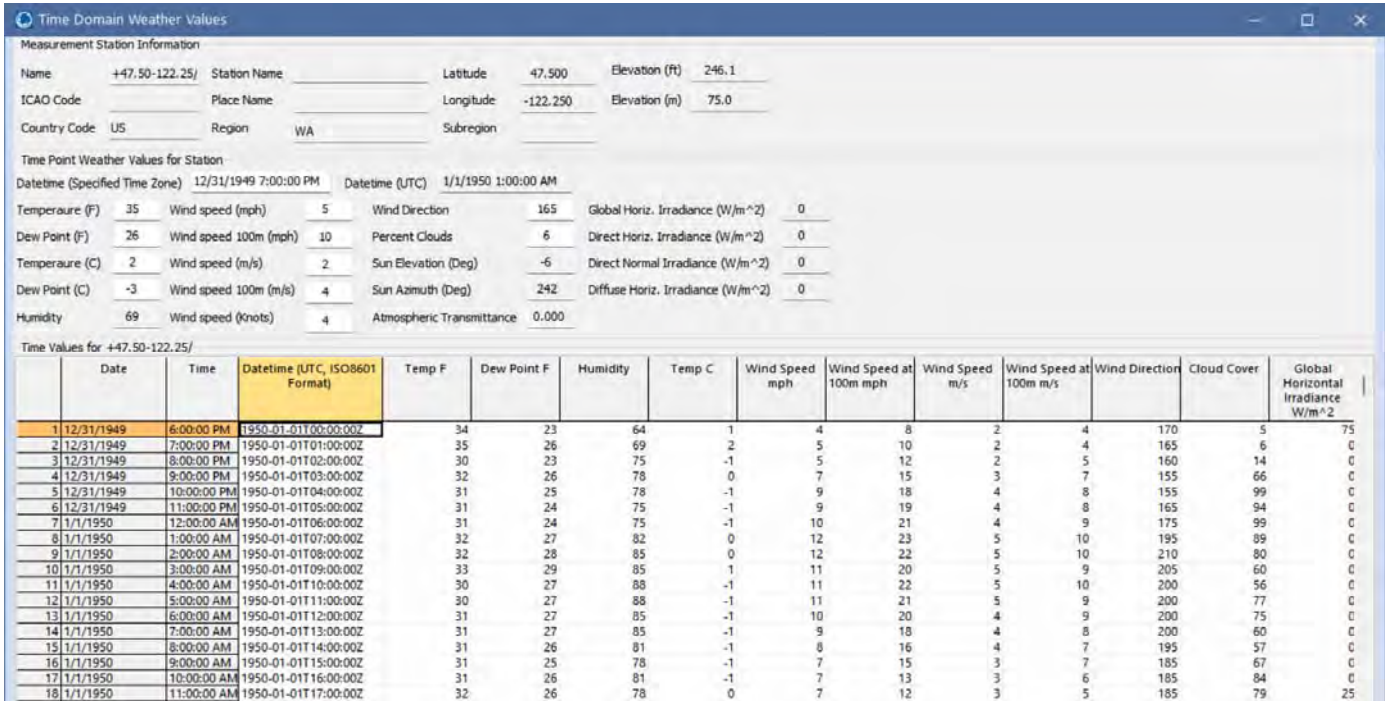


Allows a weather location to be easily located (Seattle here)

Like any PowerWorld 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**



Time Domain Weather Values

Measurement Station Information

Name	+47.50-122.25/	Station Name		Latitude	47.500	Elevation (ft)	246.1
ICAO Code		Place Name		Longitude	-122.250	Elevation (m)	75.0
Country Code	US	Region	WA	Subregion			

Time Point Weather Values for Station

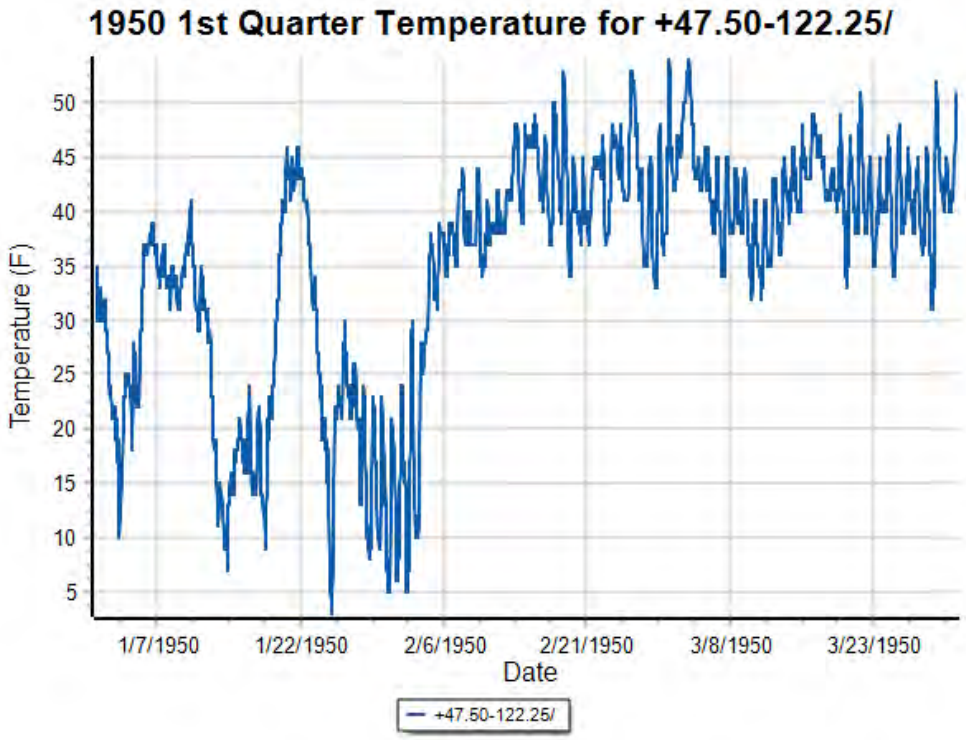
Datetime (Specified Time Zone)	12/31/1949 7:00:00 PM			Datetime (UTC)	1/1/1950 1:00:00 AM		
Temperaure (F)	35	Wind speed (mph)	5	Wind Direction	165	Global Horiz. Irradiance (W/m^2)	0
Dew Point (F)	26	Wind speed 100m (mph)	10	Percent Clouds	6	Direct Horiz. Irradiance (W/m^2)	0
Temperaure (C)	2	Wind speed (m/s)	2	Sun Elevation (Deg)	-6	Direct Normal Irradiance (W/m^2)	0
Dew Point (C)	-3	Wind speed 100m (m/s)	4	Sun Azimuth (Deg)	242	Diffuse Horiz. Irradiance (W/m^2)	0
Humidity	69	Wind speed (Knots)	4	Atmospheric Transmittance	0.000		

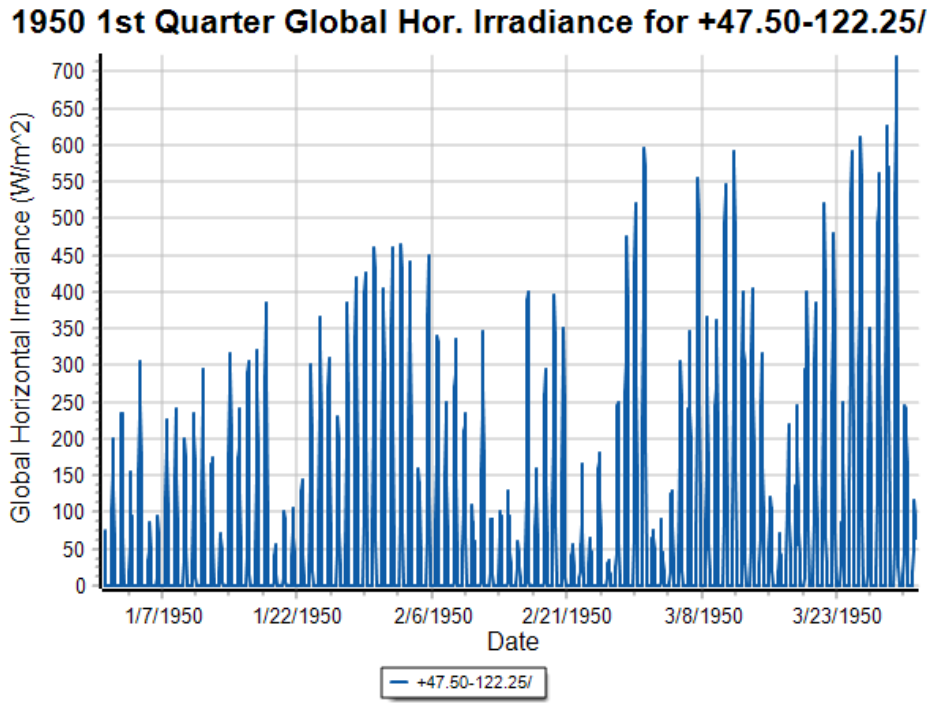
Time Values for +47.50-122.25/

	Date	Time	Datetime (UTC, ISO8601 Format)	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	Global Horizontal Irradiance W/m^2
1	12/31/1949	6:00:00 PM	1950-01-01T00:00:00Z	34	23	64	1	4	8	2	4	170	5	75
2	12/31/1949	7:00:00 PM	1950-01-01T01:00:00Z	35	26	69	2	5	10	2	4	165	6	0
3	12/31/1949	8:00:00 PM	1950-01-01T02:00:00Z	30	23	75	-1	5	12	2	5	160	14	0
4	12/31/1949	9:00:00 PM	1950-01-01T03:00:00Z	32	26	78	0	7	15	3	7	155	66	0
5	12/31/1949	10:00:00 PM	1950-01-01T04:00:00Z	31	25	78	-1	9	18	4	8	155	99	0
6	12/31/1949	11:00:00 PM	1950-01-01T05:00:00Z	31	24	75	-1	9	19	4	8	165	94	0
7	1/1/1950	12:00:00 AM	1950-01-01T06:00:00Z	31	24	75	-1	10	21	4	9	175	99	0
8	1/1/1950	1:00:00 AM	1950-01-01T07:00:00Z	32	27	82	0	12	23	5	10	195	89	0
9	1/1/1950	2:00:00 AM	1950-01-01T08:00:00Z	32	28	85	0	12	22	5	10	210	80	0
10	1/1/1950	3:00:00 AM	1950-01-01T09:00:00Z	33	29	85	1	11	20	5	9	205	60	0
11	1/1/1950	4:00:00 AM	1950-01-01T10:00:00Z	30	27	88	-1	11	22	5	10	200	56	0
12	1/1/1950	5:00:00 AM	1950-01-01T11:00:00Z	30	27	88	-1	11	21	5	9	200	77	0
13	1/1/1950	6:00:00 AM	1950-01-01T12:00:00Z	31	27	85	-1	10	20	4	9	200	75	0
14	1/1/1950	7:00:00 AM	1950-01-01T13:00:00Z	31	27	85	-1	9	18	4	8	200	60	0
15	1/1/1950	8:00:00 AM	1950-01-01T14:00:00Z	31	26	81	-1	8	16	4	7	195	57	0
16	1/1/1950	9:00:00 AM	1950-01-01T15:00:00Z	31	25	78	-1	7	15	3	7	185	67	0
17	1/1/1950	10:00:00 AM	1950-01-01T16:00:00Z	31	26	81	-1	7	13	3	6	185	84	0
18	1/1/1950	11:00:00 AM	1950-01-01T17:00:00Z	32	26	78	0	7	12	3	5	185	79	25

First Quarter 1950 Data for Seattle

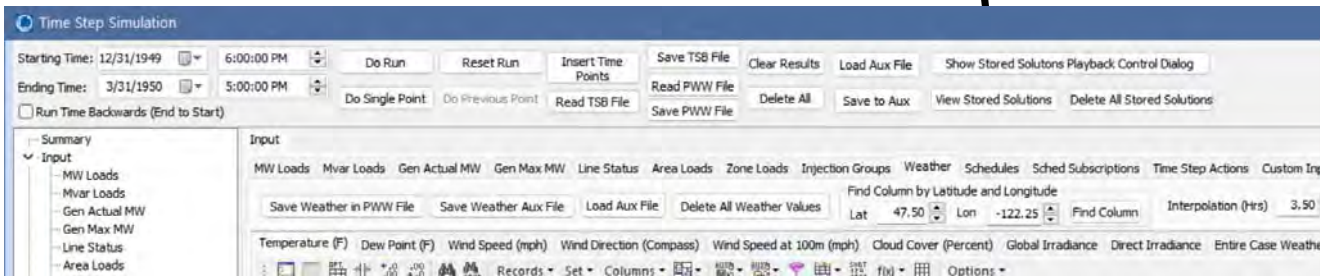
- Data for any range can be easily plotted

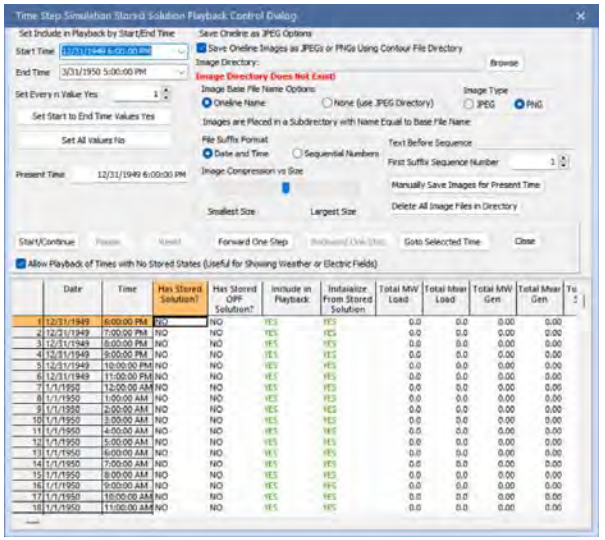




Visualizing Time-Varying Data

- In addition to graphs, in the Time Step Simulation the data for any time point can be easily visualized by right-clicking on the desired time and selecting **Time Point Records**, **Apply Time Point (with Weather Update)**
- Movies can be easily created by using the **Stored Solutions Playback Control Dialog** to create a series of jpg or png files, then using image software like Adobe Premiere Pro





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
  - File names include the run time in ISO 8601 format. Example is "Forecast_NorthAmerica_Run2024-02-07T06Z.pww"
    - The date tells when the forecast was run; they contain 16 days

Availability of Forecasted Weather Information

This is Forecast_NorthAmerica_Run2024-02-07T06Z; hence the first time value is on Feb 7, 2024 at 06:00 UTC

Time Step Simulation

Starting Time: 2/ 7/2024 12:00:00 AM
Ending Time: 2/23/2024 12:00:00 AM
Run Time Backwards (End to Start)

Do Run | Reset Run | Insert Time Points | Save TSB File | Do Single Point | Do Previous Point | Read TSB File | Read PWW File | Save PWW File | Delete All | Save to Aux | View Stored Solutions | Delete All Stored Solutions

- Summary
- Input
  - MW Loads
  - Mvar Loads
  - Gen Actual MW
  - Gen Max MW
  - Line Status
  - Area Loads
  - Zone Loads
  - Injection Groups
  - Weather
    - Temperature
    - Dew Point
    - Wind Speed
    - Wind Direction
    - Wind Speed at 100m
    - Cloud Cover
    - Global Irradiance
    - Direct Irradiance
    - Entire Case Weather Station
  - Schedules
  - Sched Subscriptions
  - Time Step Actions
  - Custom Inputs
- Results
- Results: Constraints
- Options
- TSB Case Description

Input

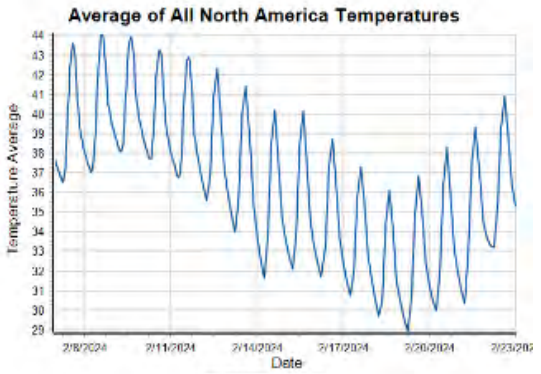
MW Loads | Mvar Loads | Gen Actual MW | Gen Max MW | Line Status | Area Loads | Zone Loads | Injection Groups | Weather | Schedules | Sched Subscriptions | Time Step Actions

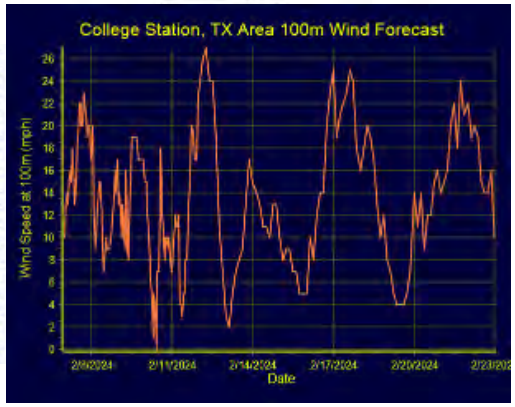
Save Weather in PWW File | Save Weather Aux File | Load Aux File | Delete All Weather Values | Find Column by Latitude and Longitude Lat 40.00 Lon -80.00 | Find Column | Interpolation

Temperature (F) | Dew Point (F) | Wind Speed (mph) | Wind Direction (Compass) | Wind Speed at 100m (mph) | Cloud Cover (Percent) | Global Irradiance | Direct Irradiance | Entire

Records | Columns | Options

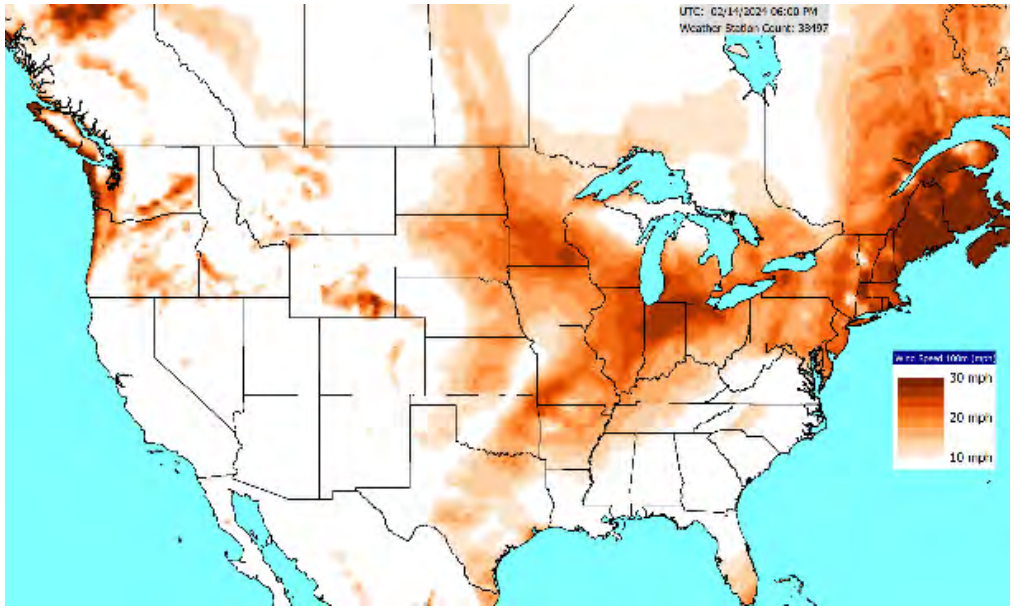
	Date	Time	Datetime (UTC ISO8601 Format)	Num Valid Temperatures	Save Timepoint in Aux or PWW File	Temperature Average	Temperature Minimum	Temperature Maximum	+24.00-060.00/	+24.00-
1	2/7/2024	12:00:00 AM	2024-02-07T06:00:00Z	38497	YES	37.60	-31	78	75	
2	2/7/2024	1:00:00 AM	2024-02-07T07:00:00Z	38497	YES	37.37	-31	78	73	
3	2/7/2024	2:00:00 AM	2024-02-07T08:00:00Z	38497	YES	37.16	-33	77	75	
4	2/7/2024	3:00:00 AM	2024-02-07T09:00:00Z	38497	YES	36.98	-34	77	75	
5	2/7/2024	4:00:00 AM	2024-02-07T10:00:00Z	38497	YES	36.81	-34	77	74	
6	2/7/2024	5:00:00 AM	2024-02-07T11:00:00Z	38497	YES	36.64	-34	77	74	
7	2/7/2024	6:00:00 AM	2024-02-07T12:00:00Z	38497	YES	36.50	-32	76	74	
8	2/7/2024	7:00:00 AM	2024-02-07T13:00:00Z	38497	YES	36.67	-30	76	74	
9	2/7/2024	8:00:00 AM	2024-02-07T14:00:00Z	38497	YES	37.33	-29	76	73	
10	2/7/2024	9:00:00 AM	2024-02-07T15:00:00Z	38497	YES	38.44	-26	76	75	
11	2/7/2024	10:00:00 AM	2024-02-07T16:00:00Z	38497	YES	39.81	-19	76	74	
12	2/7/2024	11:00:00 AM	2024-02-07T17:00:00Z	38497	YES	41.22	-16	77	74	
13	2/7/2024	12:00:00 PM	2024-02-07T18:00:00Z	38497	YES	42.38	-13	82	75	
14	2/7/2024	1:00:00 PM	2024-02-07T19:00:00Z	38497	YES	43.22	-13	85	74	
15	2/7/2024	2:00:00 PM	2024-02-07T20:00:00Z	38497	YES	43.62	-16	87	74	
16	2/7/2024	3:00:00 PM	2024-02-07T21:00:00Z	38497	YES	43.49	-20	89	74	
17	2/7/2024	4:00:00 PM	2024-02-07T22:00:00Z	38497	YES	42.85	-21	90	74	
18	2/7/2024	5:00:00 PM	2024-02-07T23:00:00Z	38497	YES	41.87	-23	90	74	
19	2/7/2024	6:00:00 PM	2024-02-08T00:00:00Z	38497	YES	40.88	-23	86	74	
20	2/7/2024	7:00:00 PM	2024-02-08T01:00:00Z	38497	YES	39.94	-23	79	75	
21	2/7/2024	8:00:00 PM	2024-02-08T02:00:00Z	38497	YES	39.34	-23	77	74	
22	2/7/2024	9:00:00 PM	2024-02-08T03:00:00Z	38497	YES	38.94	-23	76	74	
23	2/7/2024	10:00:00 PM	2024-02-08T04:00:00Z	38497	YES	38.62	-23	76	74	
24	2/7/2024	11:00:00 PM	2024-02-08T05:00:00Z	38497	YES	38.34	-23	76	74	
25	2/8/2024	12:00:00 AM	2024-02-08T06:00:00Z	38497	YES	38.09	-24	76	75	
26	2/8/2024	1:00:00 AM	2024-02-08T07:00:00Z	38497	YES	37.85	-24	76	74	
27	2/8/2024	2:00:00 AM	2024-02-08T08:00:00Z	38497	YES	37.63	-24	76	74	



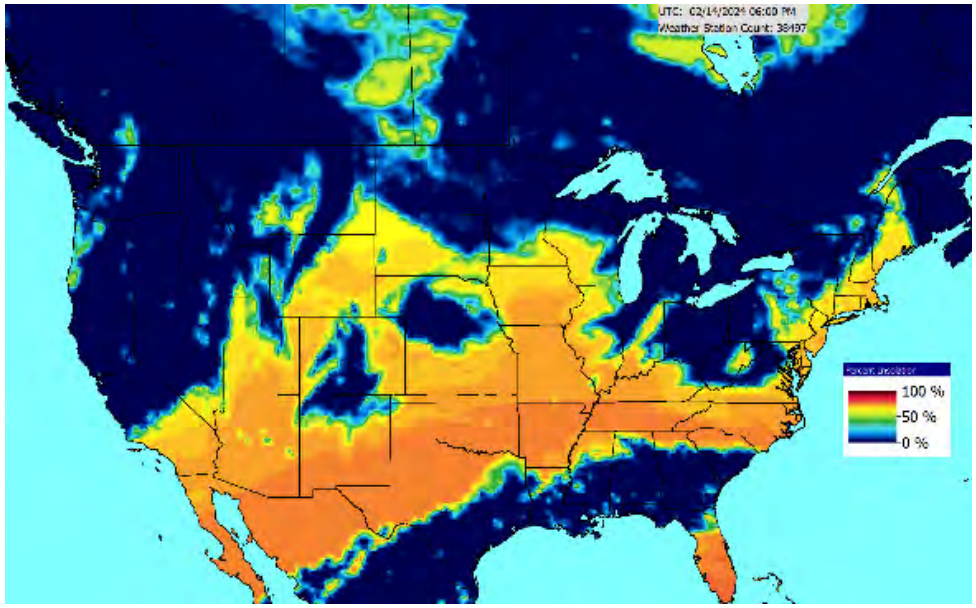


Estimated Feb 14 Wind and Solar at Noon Central from Feb 7 Forecast (i.e., a week ahead!)

Forecasted Wind Speed at 100m



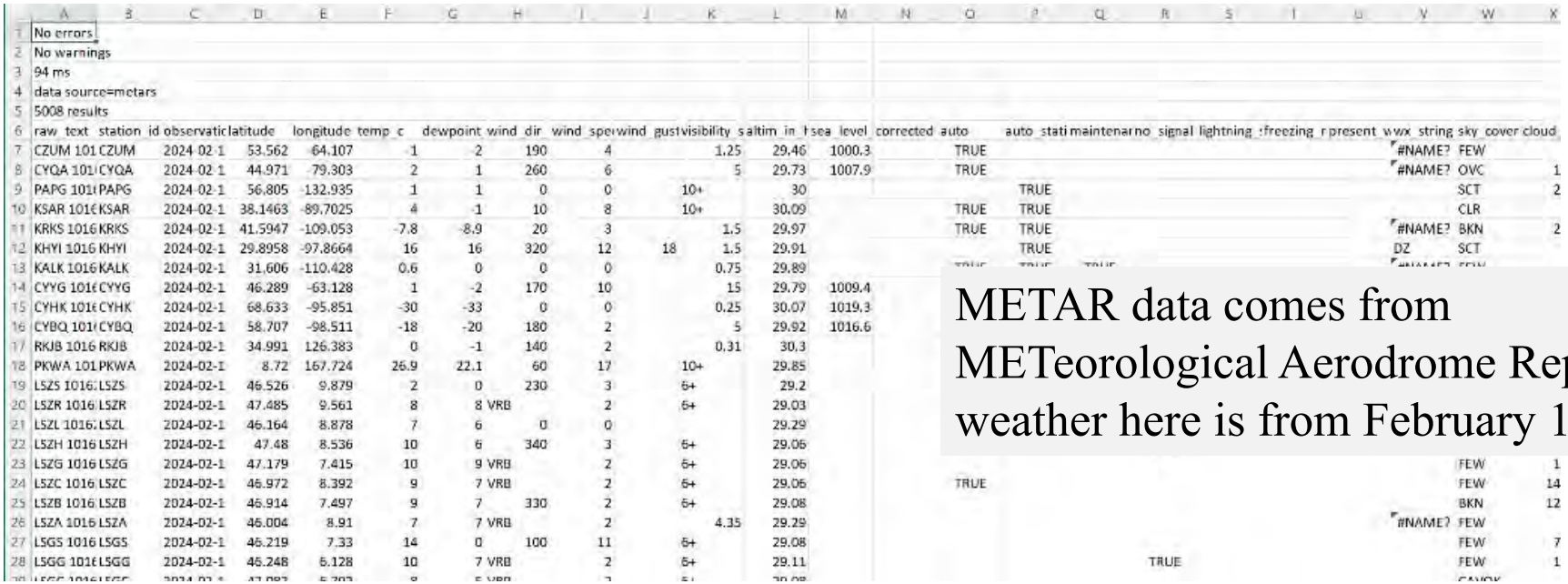
Estimated Percent Insolation



Currently these forecasts to not have irradiation values, so the percent insolation is estimated from the sun's position and the cloud cover percentage

Current Weather

- If desired, to supplement forecasted weather, current weather is available for download at https://aviationweather.gov/data/cache/metars.cache.csv

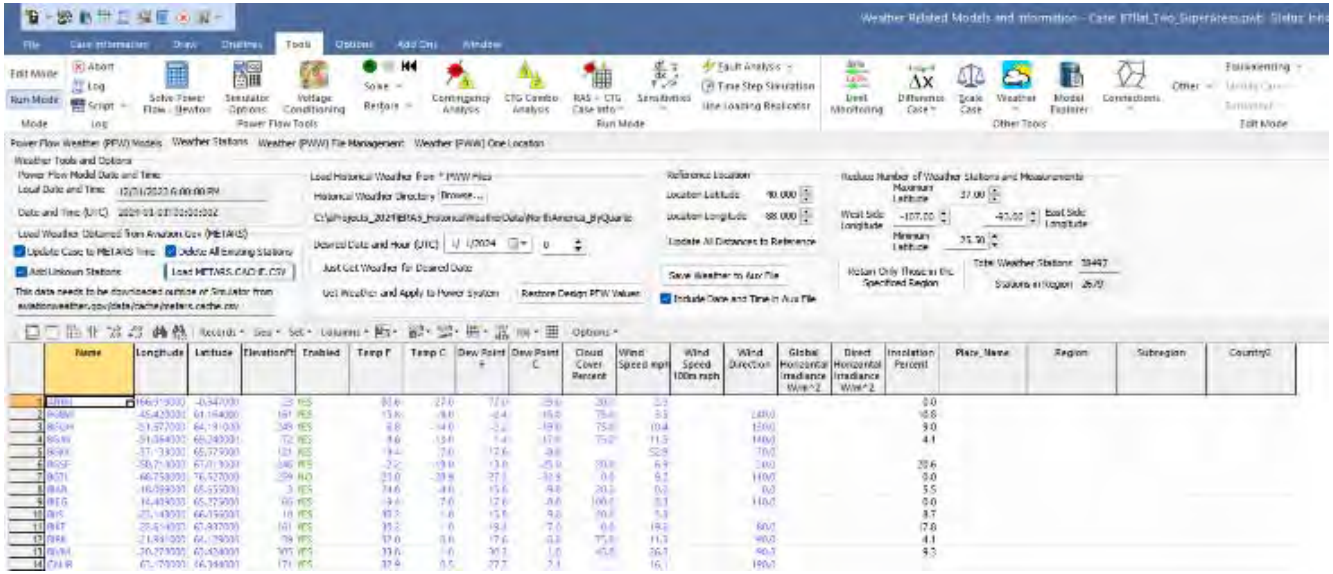


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	No errors																							
2	No warnings																							
3	94 ms																							
4	data source=metars																							
5	5008 results																							
6	raw_text	station_id	observatic	latitude	longitude	temp_c	dewpoint	wind_dir	wind_spe	wind_gust	visibility	altim_in_h	sea_level	corrected	auto	auto_stati	maintenan	no_signal	lightning	freezing_r	present_	wx_string	sky_cover	cloud_
7	CZUM 101	CZUM	2024-02-1	53.562	-64.107	1	2	190	4		1.25	29.46	1000.3		TRUE							#NAME?	FEW	
8	CYQA 101	CYQA	2024-02-1	44.971	-79.303	2	1	260	6		5	29.73	1007.9		TRUE							#NAME?	OVC	1
9	PAPG 101	PAPG	2024-02-1	56.805	-132.935	1	1	0	0	10+		30				TRUE							SCT	2
10	KSAR 101	KSAR	2024-02-1	38.1463	-89.7025	4	-1	10	8	10+		30.09			TRUE	TRUE							CLR	
11	KRKS 1016	KRKS	2024-02-1	41.5947	-109.053	-7.8	-8.9	20	3		1.5	29.97			TRUE	TRUE						#NAME?	BKN	2
12	KHYI 1016	KHYI	2024-02-1	29.8958	-97.8664	16	16	320	12	18	1.5	29.91				TRUE						DZ	SCT	
13	KALK 1016	KALK	2024-02-1	31.606	-110.428	0.6	0	0	0		0.75	29.89												
14	CYYG 101	CYYG	2024-02-1	46.289	-63.128	1	-2	170	10		15	29.79	1009.4											
15	CYHK 101	CYHK	2024-02-1	68.633	-95.851	-30	-33	0	0		0.25	30.07	1019.3											
16	CYBQ 101	CYBQ	2024-02-1	58.707	-98.511	-18	-20	180	2		5	29.92	1016.6											
17	RKJB 1016	RKJB	2024-02-1	34.991	126.383	0	-1	140	2		0.31	30.3												
18	PKWA 101	PKWA	2024-02-1	8.72	167.724	26.9	22.1	60	17	10+		29.85												
19	LSZS 1016	LSZS	2024-02-1	46.526	9.879	2	0	230	3	6+		29.2												
20	LSZR 1016	LSZR	2024-02-1	47.485	9.561	8	8	VRB	2	6+		29.03												
21	LSZL 1016	LSZL	2024-02-1	46.164	8.878	7	6	0	0			29.29												
22	LSZH 1016	LSZH	2024-02-1	47.48	8.536	10	6	340	3	6+		29.06												
23	LSZG 1016	LSZG	2024-02-1	47.179	7.415	10	9	VRB	2	6+		29.06											FEW	1
24	LSZC 1016	LSZC	2024-02-1	46.972	8.392	9	7	VRB	2	6+		29.06			TRUE								FEW	14
25	LSZB 1016	LSZB	2024-02-1	46.914	7.497	9	7	330	2	6+		29.08											BKN	12
26	LSZA 1016	LSZA	2024-02-1	46.004	8.91	7	7	VRB	2		4.35	29.29										#NAME?	FEW	
27	LSGS 1016	LSGS	2024-02-1	46.219	7.33	14	0	100	11	6+		29.08											FEW	7
28	LSGG 101	LSGG	2024-02-1	46.248	6.128	10	7	VRB	2	6+		29.11							TRUE				FEW	1

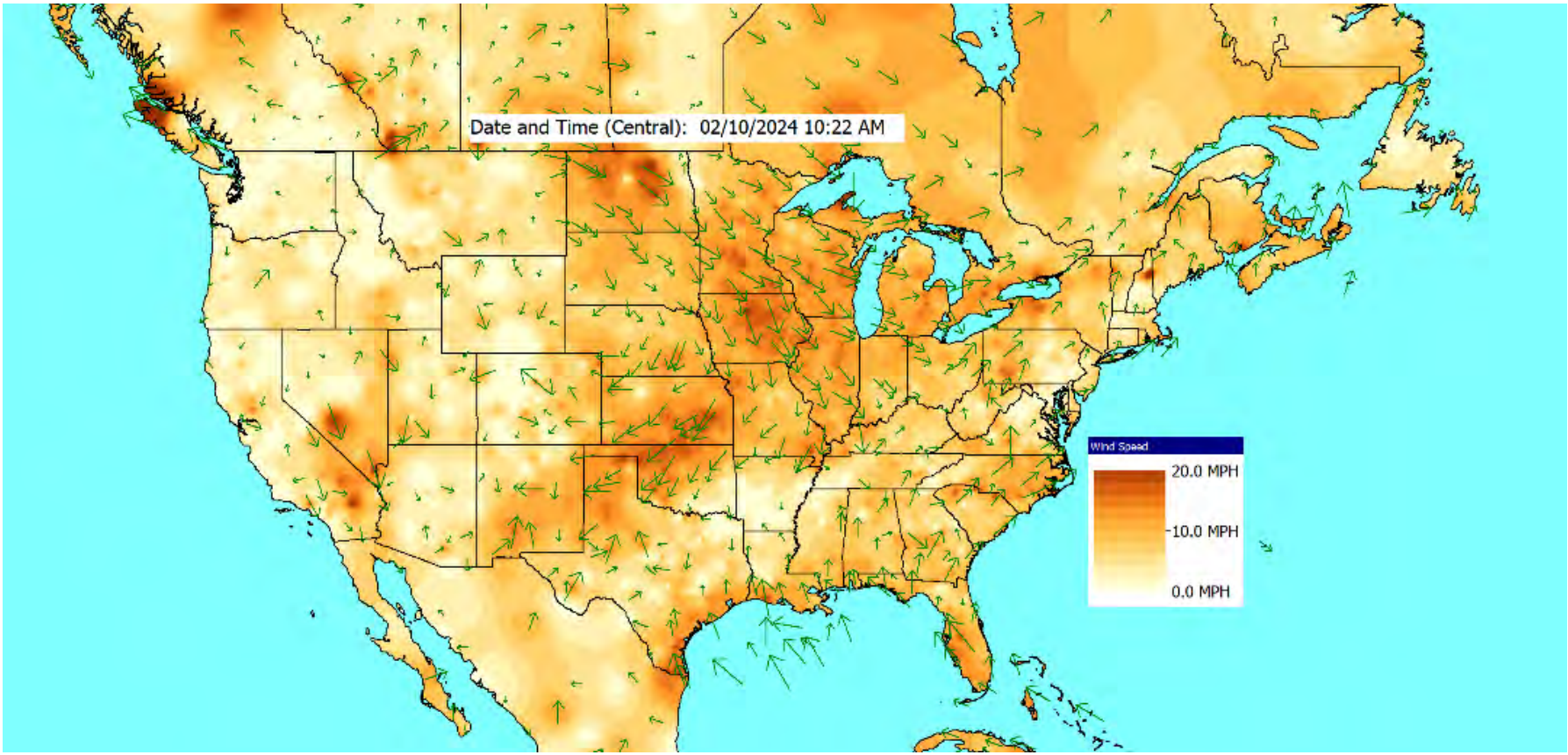
METAR data comes from METeorological Aerodrome Reports; the weather here is from February 10, 2024

Loading METAR data in PowerWorld

- The METAR *.csv file can be quickly loaded in PowerWorld, and if desired, the values visualized using auto-updating GDV displays
  - At **Tools, Weather, Weather Models and Information,** Weather Stations page
  - Previous slide *.csv has 4969 stations worldwide, though not all have full data



METAR Wind Speed Visualization with Directions

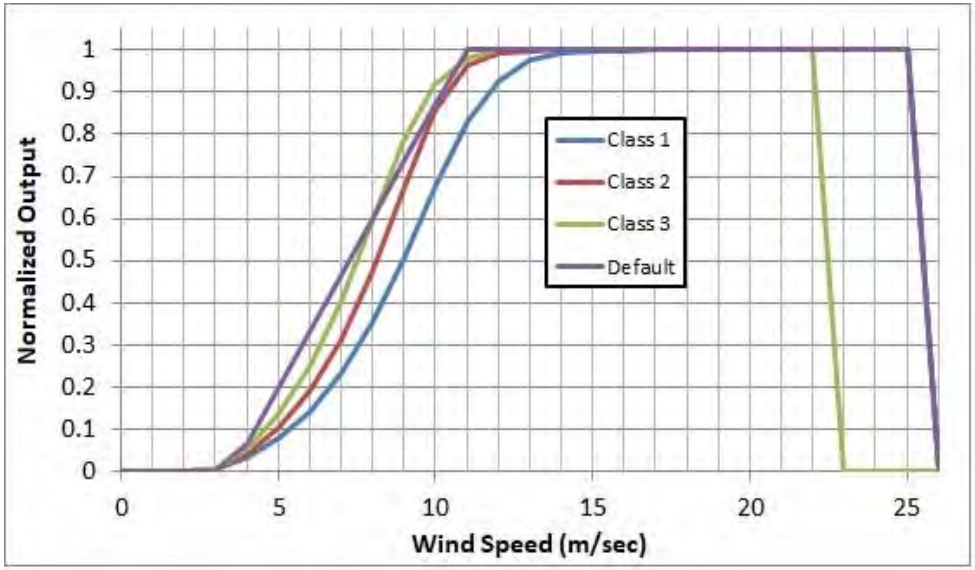


Models of Grid Weather Impacts

- 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

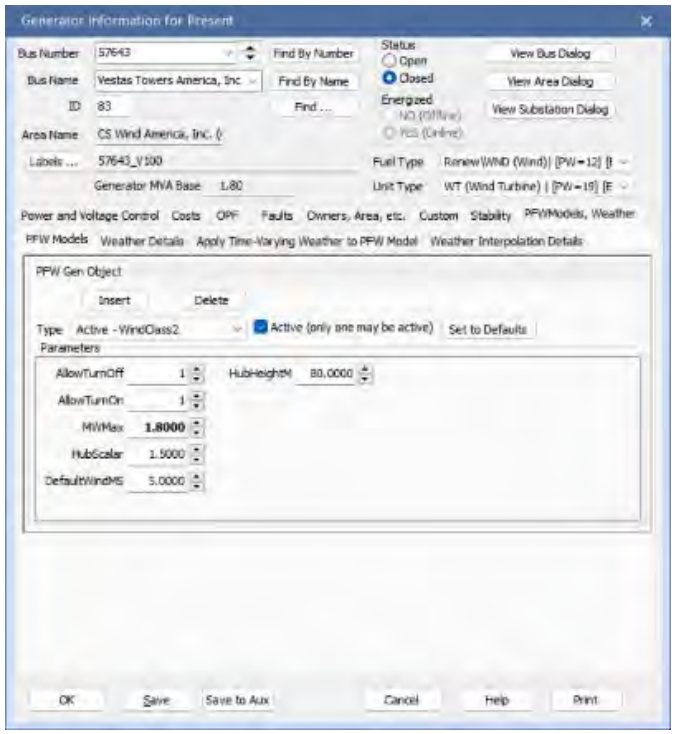
- An example is modeling the impact of wind speed on wind turbine output, or solar irradiation on PV output
  - The image on the right shows several of the generic wind turbine models are based on the turbine classes using data from [a]
  - A simple solar PV model uses either provided solar irradiation 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

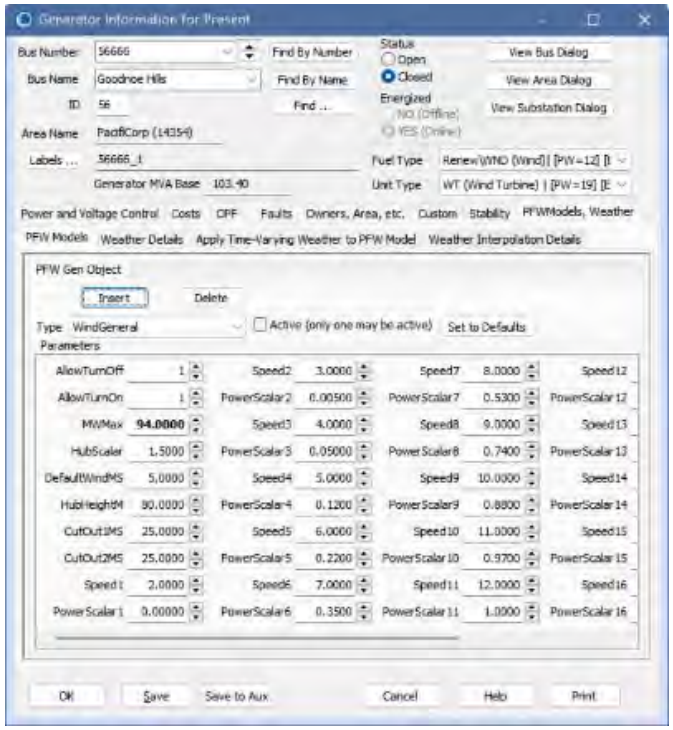


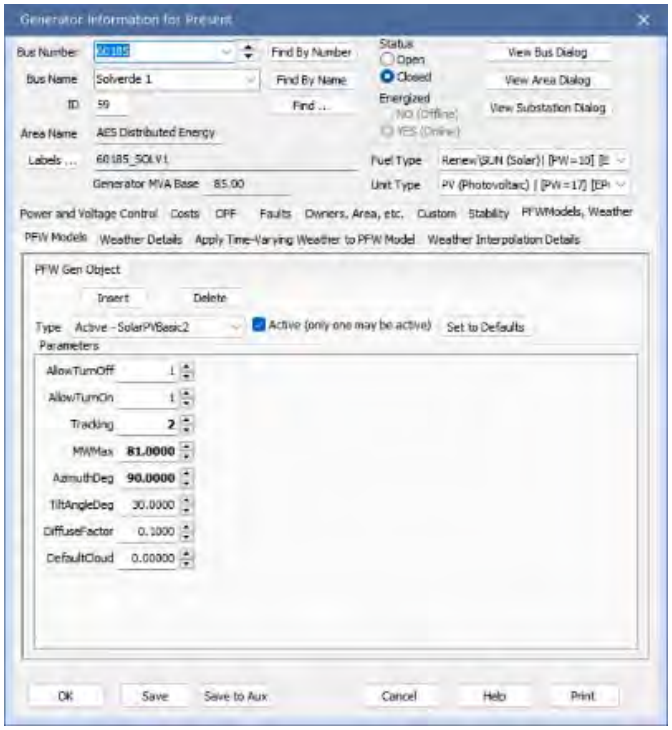
[a] C. Draxl, A. Clifton, B. Hodge, J. McCaa, "The Wind Integration National Dataset (WIND) Toolkit," *Applied Energy*, vol. 151, pp. 355-366, 2015.

Example: Gen MaxMW PFW Model

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

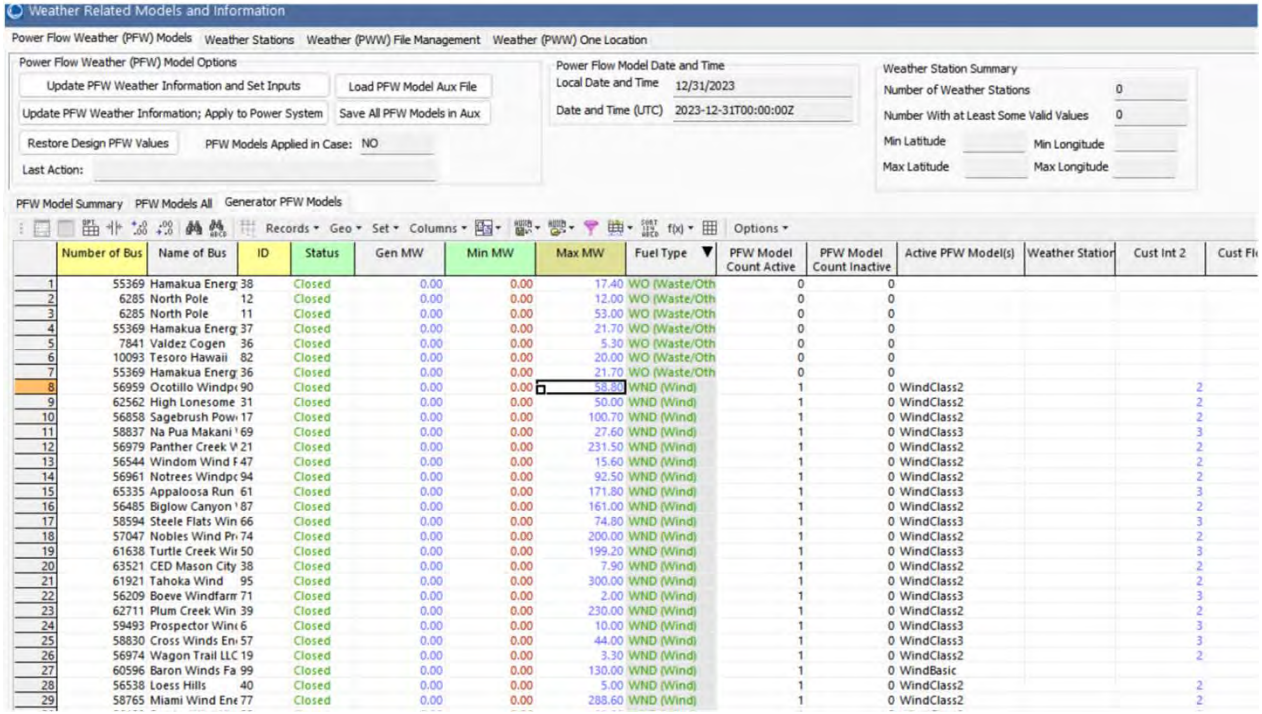






Entering Large Number of PFW Models

- 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**

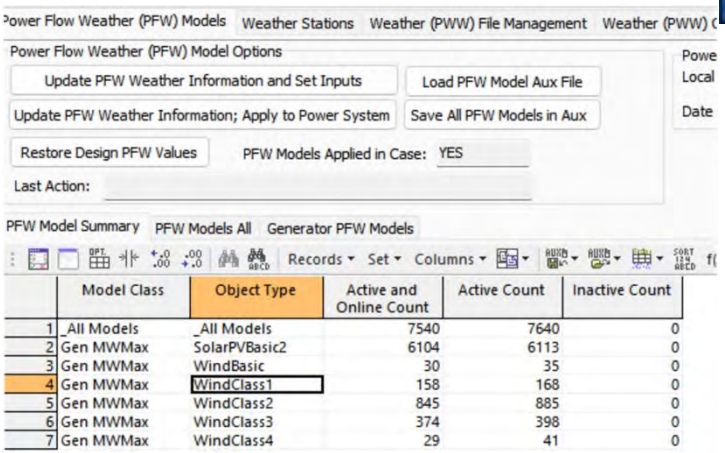


Making it Easy to Get Started: Using EIA-860 Data

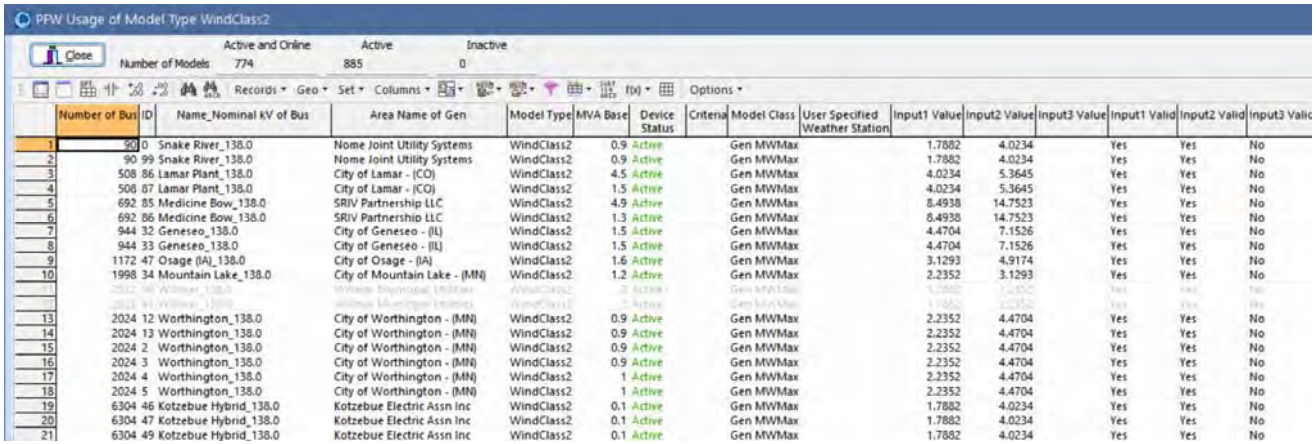
- To make it easy to get started we've setup copper plate (i.e., no transmission) power flow cases with PFW models based the data provided by the US Energy Information Administration (EIA) in their Form EIA-860 datasets
  - EIA-860 provides data on every generator in the US with 1 MW or more capacity
  - 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 2024 paper 3 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



	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



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
90	0	Snake River_138.0	Nome Joint Utility Systems	WindClass2	0.9	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
90	99	Snake River_138.0	Nome Joint Utility Systems	WindClass2	0.9	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
508	86	Lamar Plant_138.0	City of Lamar - (CO)	WindClass2	4.5	Active		Gen MWMax		4.0234	5.3645		Yes	Yes	No
508	87	Lamar Plant_138.0	City of Lamar - (CO)	WindClass2	1.5	Active		Gen MWMax		4.0234	5.3645		Yes	Yes	No
692	85	Medicine Bow_138.0	SRIV Partnership LLC	WindClass2	4.9	Active		Gen MWMax		8.4938	14.7523		Yes	Yes	No
692	86	Medicine Bow_138.0	SRIV Partnership LLC	WindClass2	1.3	Active		Gen MWMax		8.4938	14.7523		Yes	Yes	No
944	32	Geneseo_138.0	City of Geneseo - (IL)	WindClass2	1.5	Active		Gen MWMax		4.4704	7.1526		Yes	Yes	No
944	33	Geneseo_138.0	City of Geneseo - (IL)	WindClass2	1.5	Active		Gen MWMax		4.4704	7.1526		Yes	Yes	No
1172	47	Osage (IA)_138.0	City of Osage - (IA)	WindClass2	1.6	Active		Gen MWMax		3.1293	4.9174		Yes	Yes	No
1998	34	Mountain Lake_138.0	City of Mountain Lake - (MN)	WindClass2	1.2	Active		Gen MWMax		2.2352	3.1293		Yes	Yes	No
2024	12	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
2024	13	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
2024	2	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
2024	3	Worthington_138.0	City of Worthington - (MN)	WindClass2	0.9	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
2024	4	Worthington_138.0	City of Worthington - (MN)	WindClass2	1	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
2024	5	Worthington_138.0	City of Worthington - (MN)	WindClass2	1	Active		Gen MWMax		2.2352	4.4704		Yes	Yes	No
6304	46	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
6304	47	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No
6304	49	Kotzebue Hybrid_138.0	Kotzebue Electric Assn Inc	WindClass2	0.1	Active		Gen MWMax		1.7882	4.0234		Yes	Yes	No

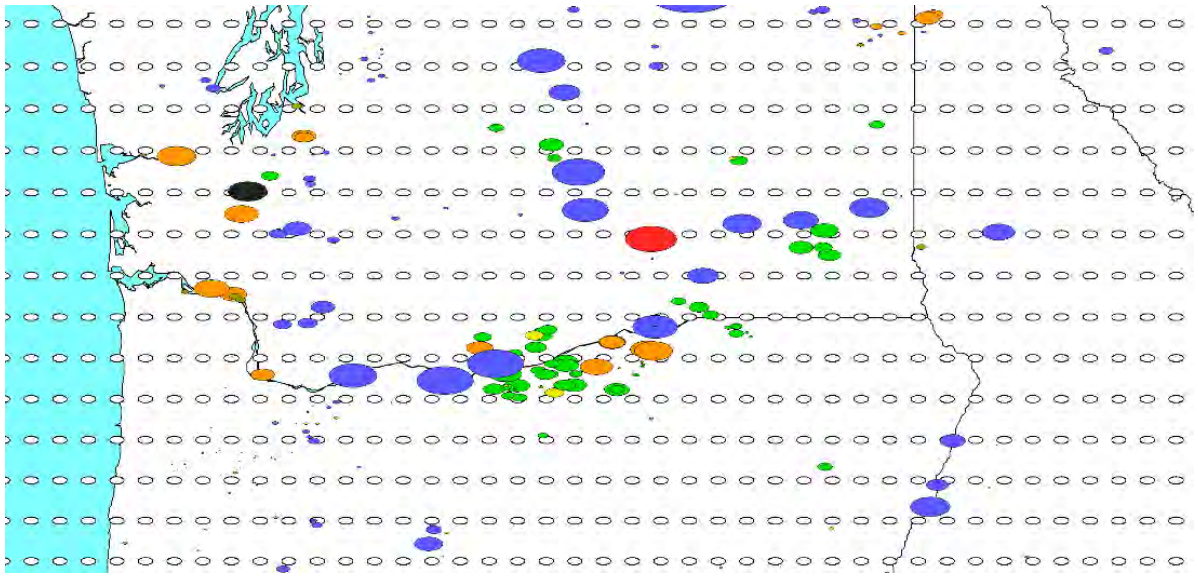
For the CEII grids we have bus mapping for more than 95% of the generator capacity

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
- Usually places in which the weather changes rapidly with geography (e.g., mountains) don't have much electric infrastructure (the exceptions are covered next)

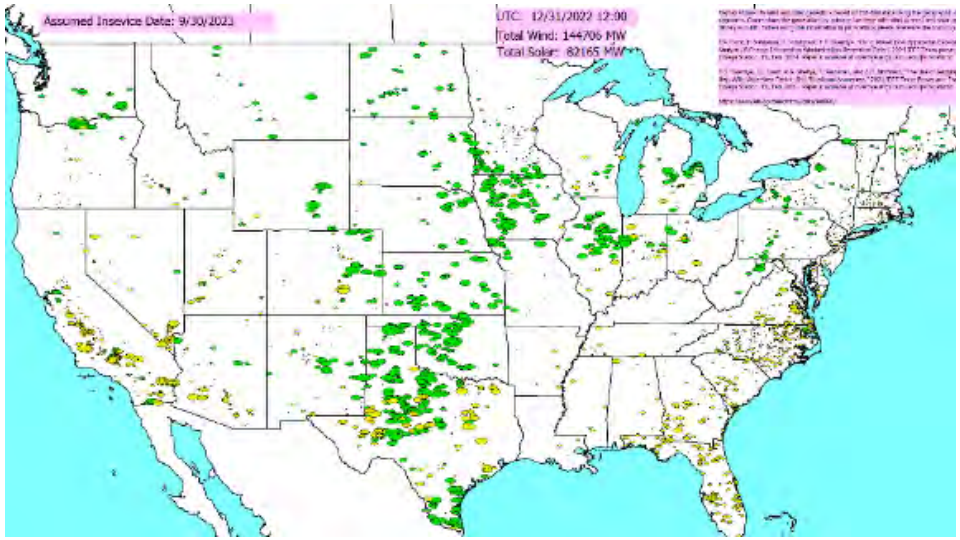
Mapping Weather to the Electric Grid Components

- In situations in which interpolation does not work well (e.g., valleys, mountains, some coastal regions), specific weather stations could be assigned to the electric grid devices (e.g., a wind farm)
  - An example is the Columbia River Gorge with a length of 190 km and an average width of 5 km; the gorge has a unique and complex climate often with high winds
  - Image shows the generation (ovals, with green for wind and blue for hydro) and the weather data points (as white ovals)



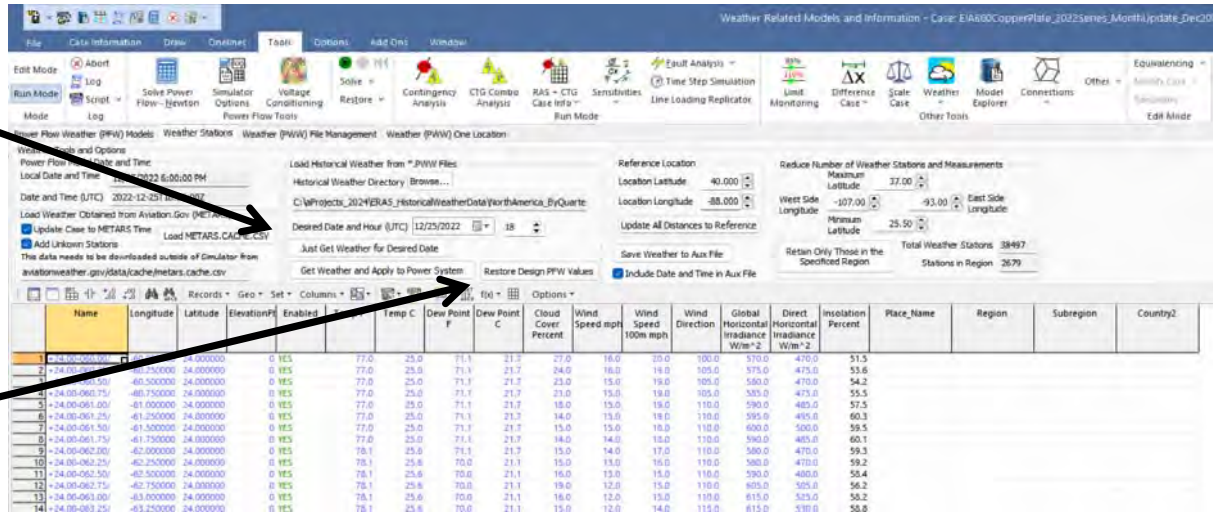
Applying the Weather

- 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 demonstrate each of these, showing the change in the wind and solar outputs



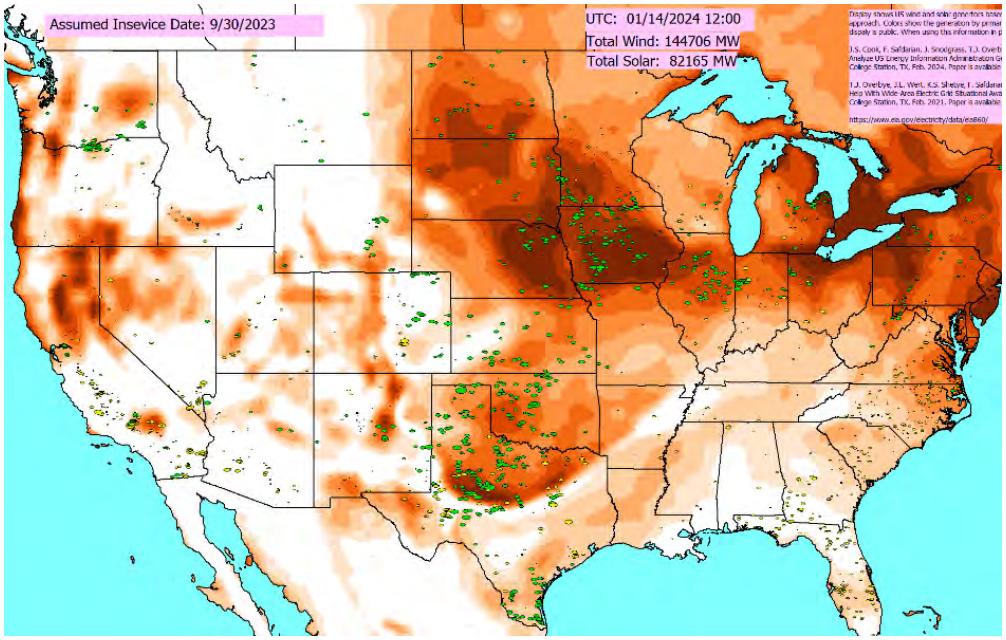
Applying Weather for a Single Time Point

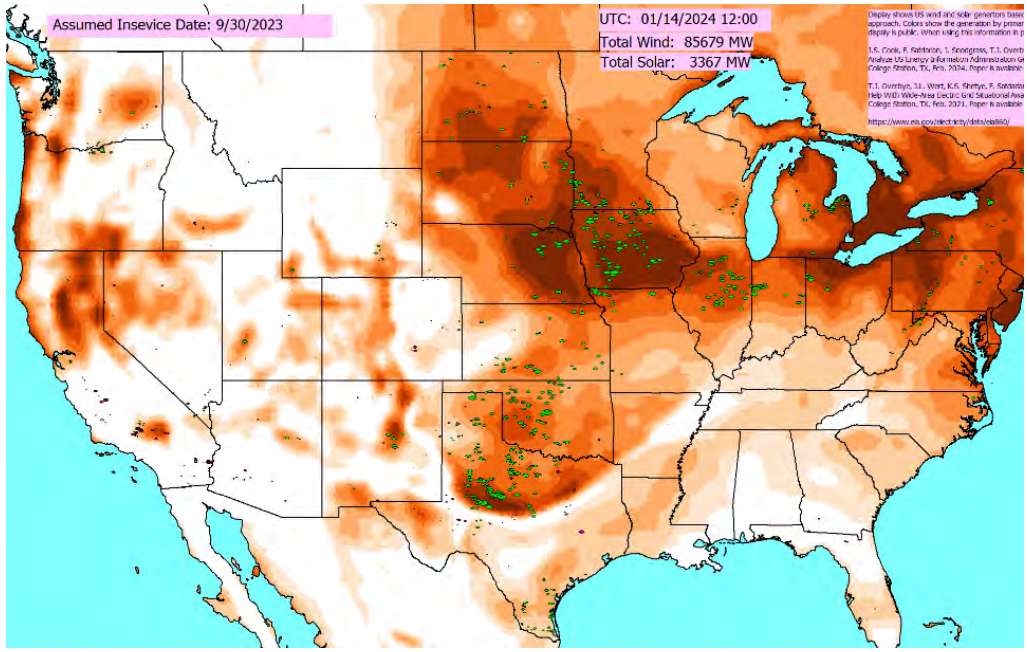
- With the provided pww files, any time going back to 1940 can be simulated. The pww files are designed for quick searching, and for providing direct access to all the data for a particular time.
- Getting the access to the weather for all of North America takes about a second; optionally the weather 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



Applying Weather Without and With Updating the PFW Models and the Power Flow

- Left image just shows the weather, without updating the PFW models (i.e., not changing the power flow values) whereas the right one also updates the PFW models (note the very low solar)

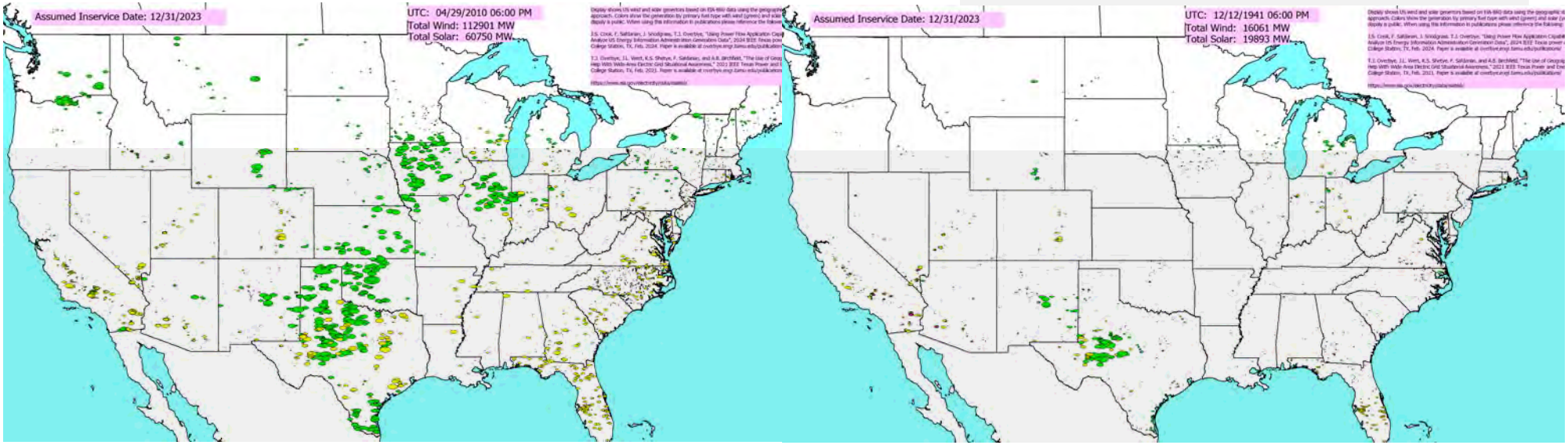




Contrasting Two Days: 4/29/2010 and 12/12/1941

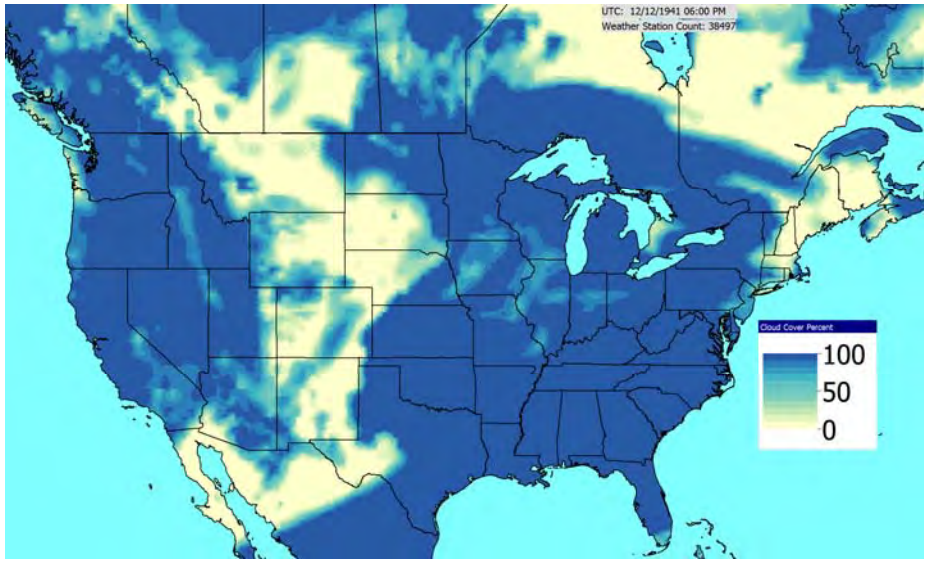
- Assuming the 12/31/2023 renewable generation (147 GW wind, 90 GW solar), we determined a few outlier days. At noon (Central) weather for 4/29/2010 would have an 73% available, while 12/12/1941 weather would have 15%

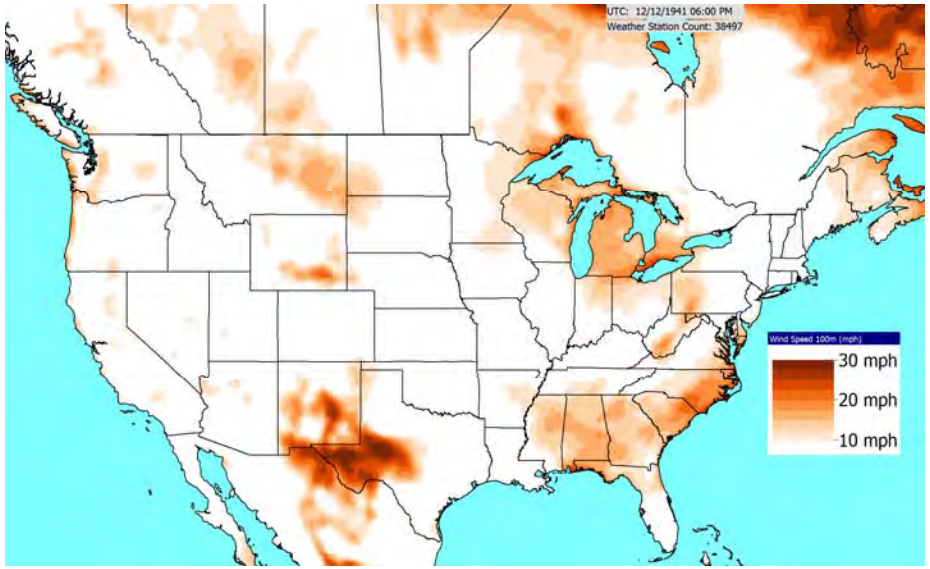
Applying the weather and getting the values is quick



December 12, 1941 Clouds and Wind

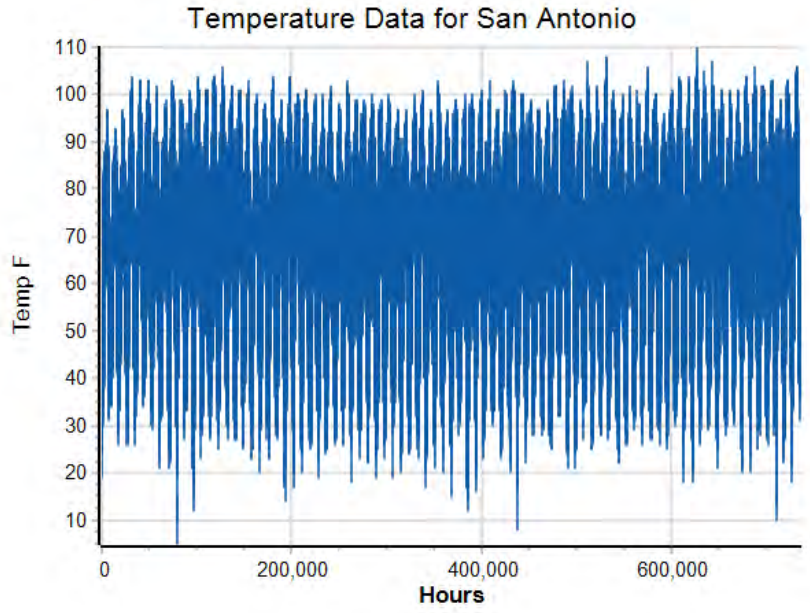
- Dec 12, 1941 was a cloudy, mostly windless day nationwide. But this needs to be considered on a regional basis. For example, it would not have been a particularly severe day in Texas.

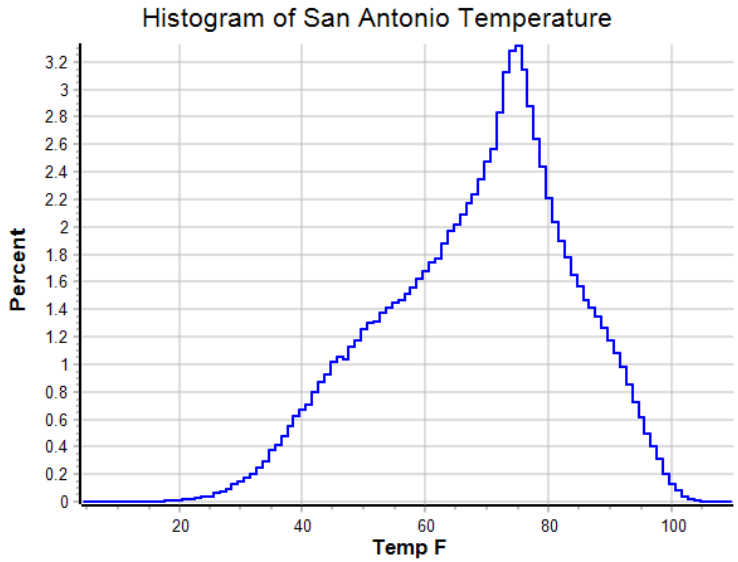




Getting Lots of Weather for a Single Location

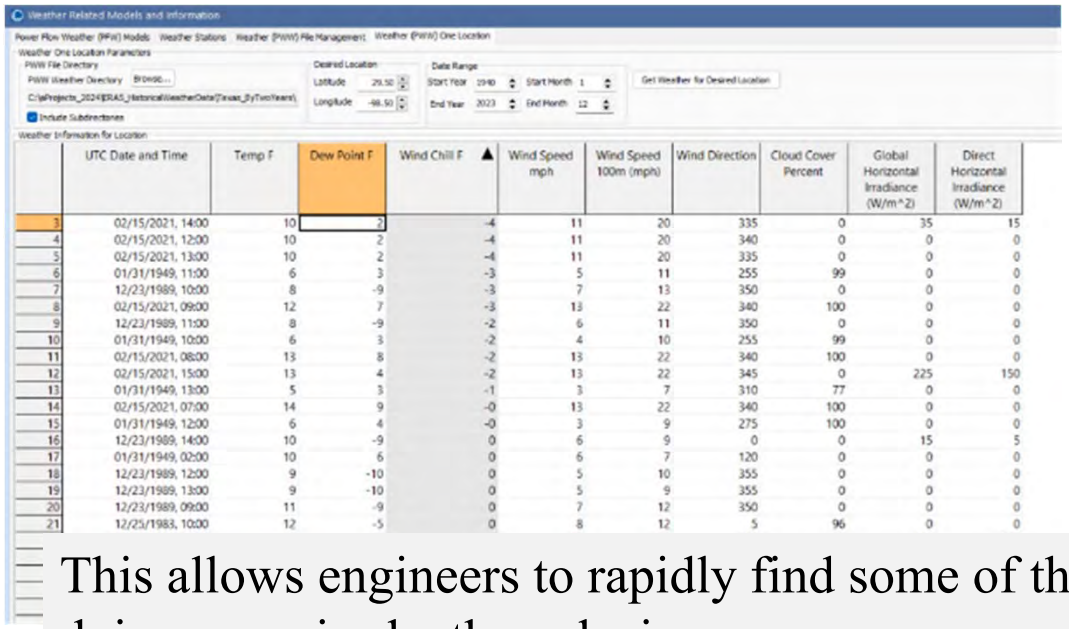
- By automatically parsing through the pww files, weather for a single location can be quickly determined
  - For the Texas cases this takes on the order of 4 seconds, returning data for more than 700,000 hours; below data is for San Antonio, TX



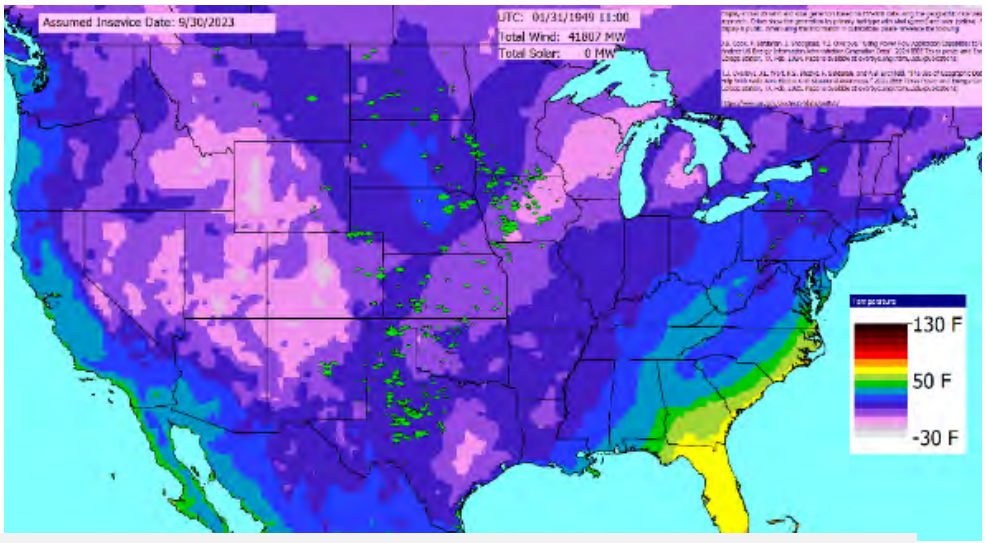


One Application is Looking for Outliers

- Lower left image shows lowest wind chills in San Antonio; the lower right contours temperatures for Jan 31, 1949 at 11am (UTC)



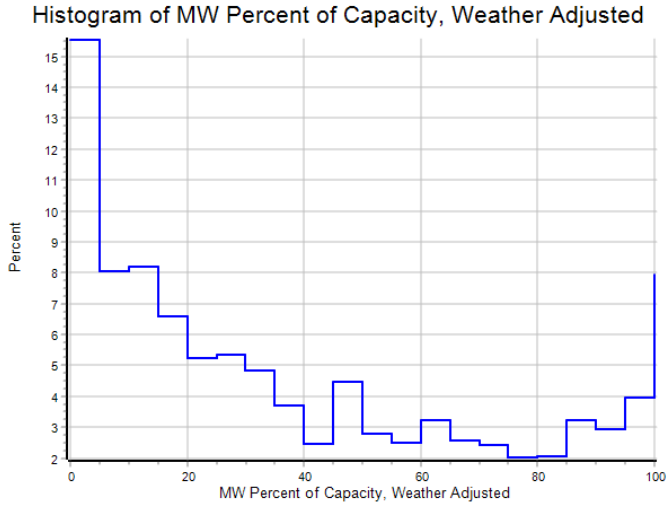
	UTC Date and Time	Temp F	Dew Point F	Wind Chill F ▲	Wind Speed mph	Wind Speed 100m (mph)	Wind Direction	Cloud Cover Percent	Global Horizontal Irradiance (W/m^2)	Direct Horizontal Irradiance (W/m^2)
3	02/15/2021, 14:00	10	2	-4	11	20	335	0	35	15
4	02/15/2021, 12:00	10	2	-4	11	20	340	0	0	0
5	02/15/2021, 13:00	10	2	-4	11	20	335	0	0	0
6	01/31/1949, 11:00	6	3	-3	5	11	255	99	0	0
7	12/23/1989, 10:00	8	-9	-3	7	13	350	0	0	0
8	02/15/2021, 09:00	12	7	-3	13	22	340	100	0	0
9	12/23/1989, 11:00	8	-9	-2	6	11	350	0	0	0
10	01/31/1949, 10:00	6	3	-2	4	10	255	99	0	0
11	02/15/2021, 08:00	13	8	-2	13	22	340	100	0	0
12	02/15/2021, 15:00	13	4	-2	13	22	345	0	225	150
13	01/31/1949, 13:00	5	3	-1	3	7	310	77	0	0
14	02/15/2021, 07:00	14	9	-0	13	22	340	100	0	0
15	01/31/1949, 12:00	6	4	-0	3	9	275	100	0	0
16	12/23/1989, 14:00	10	-9	0	6	9	0	0	15	5
17	01/31/1949, 02:00	10	6	0	6	7	120	0	0	0
18	12/23/1989, 12:00	9	-10	0	5	10	355	0	0	0
19	12/23/1989, 13:00	9	-10	0	5	9	355	0	0	0
20	12/23/1989, 09:00	11	-9	0	7	12	350	0	0	0
21	12/25/1983, 10:00	12	-5	0	8	12	5	96	0	0



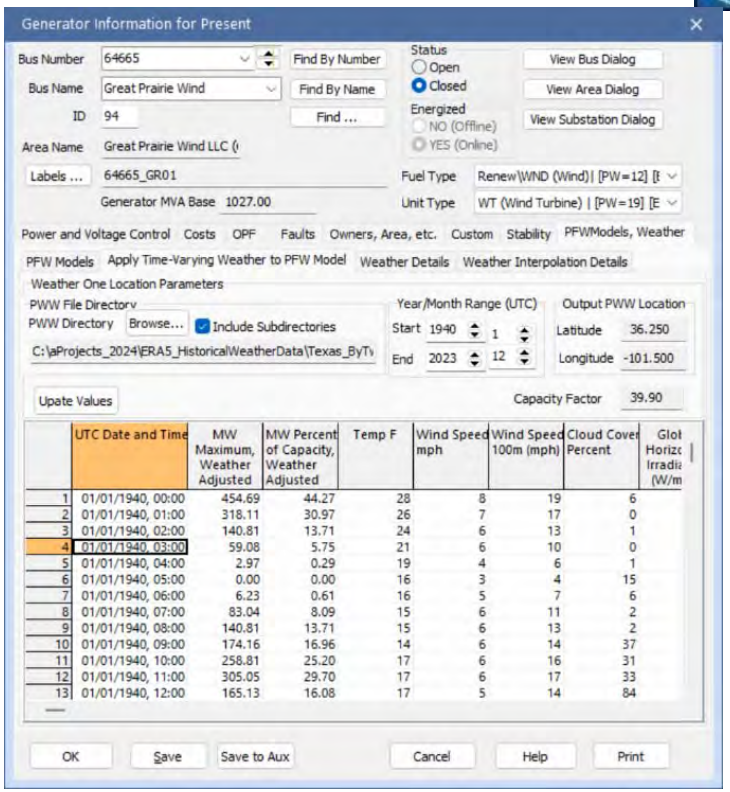
This allows engineers to rapidly find some of the worst conditions for a location and doing more in-depth analysis

Anticipated Performance of Wind or Solar Generation Can Also Be Determined

- Hourly weather data can also be repeated applied to individual devices, such as generators. This allows the capacity factor to be estimated for any location (existing or new)

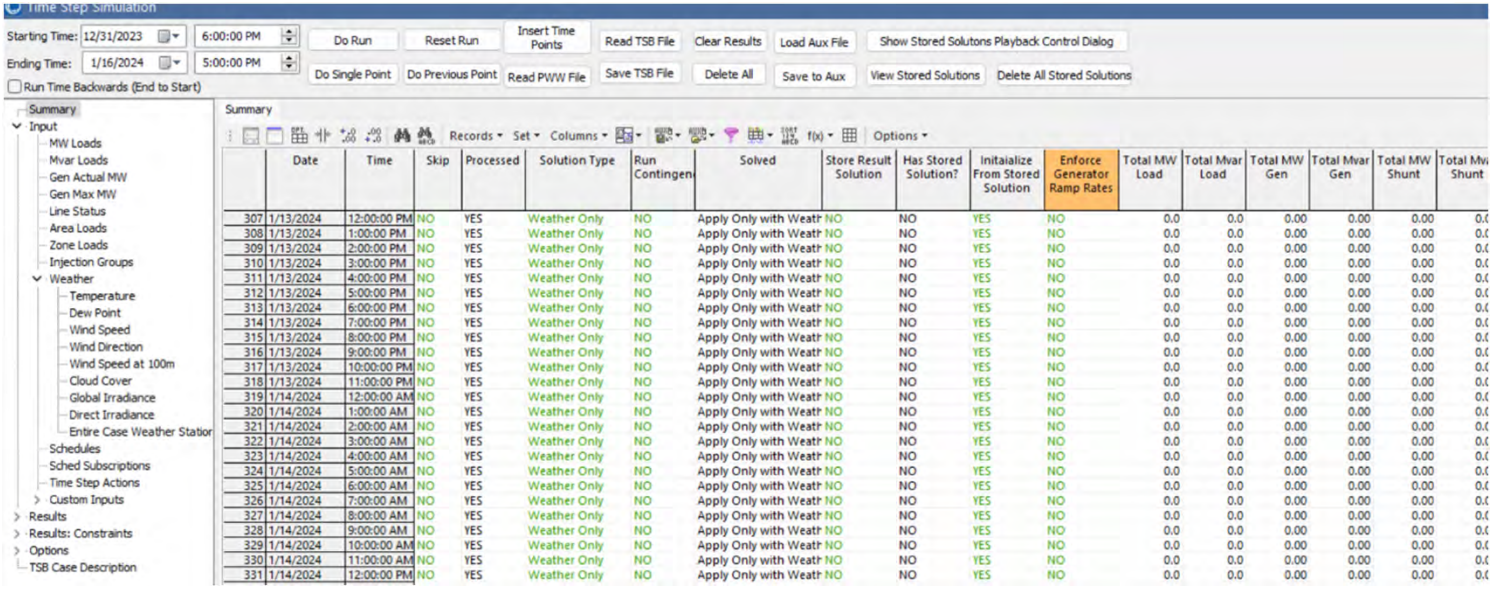


The impacts of changing model parameters can also be easily determined; for example changing the hub height to 100 m increases the capacity factor to from 39.5% to 44.5%



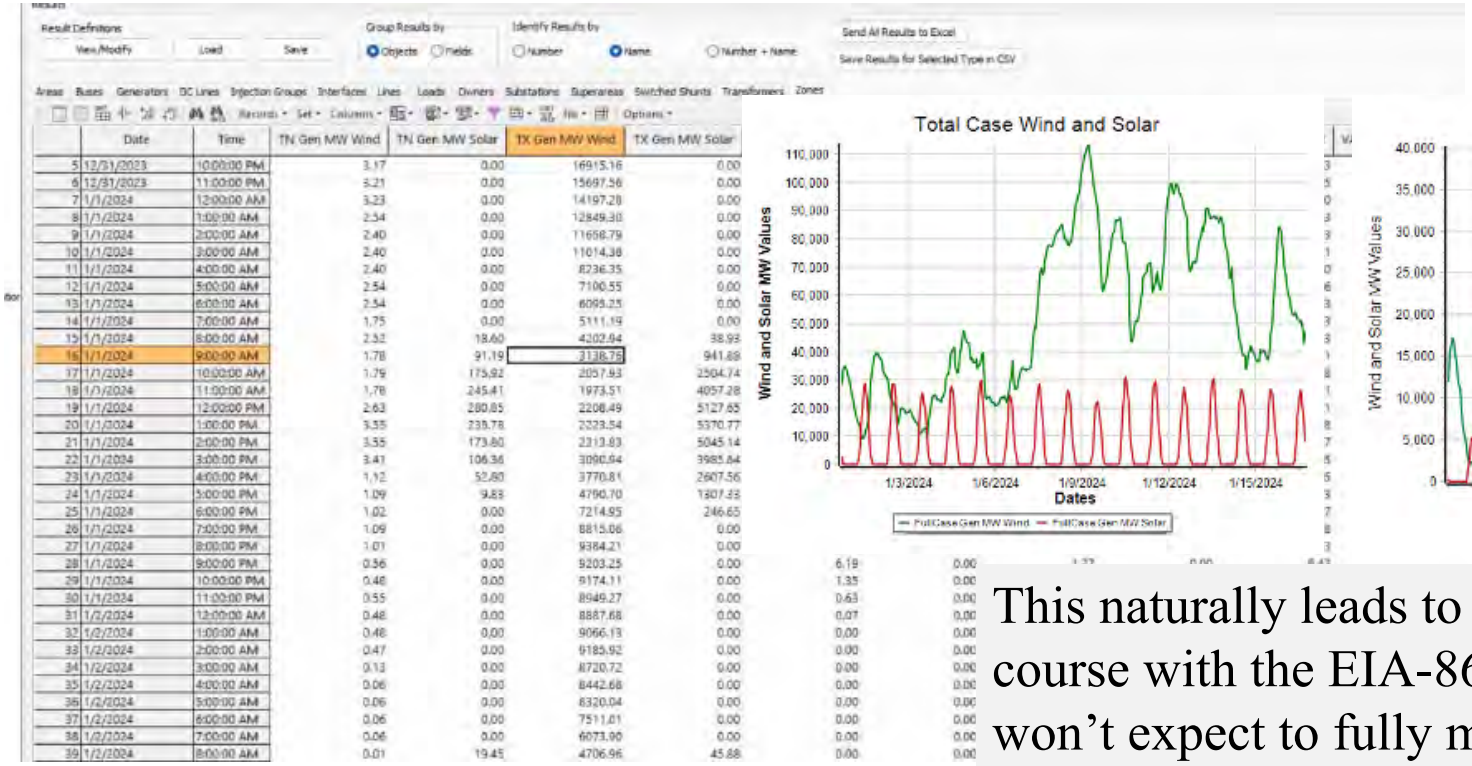
Running All Timepoints

- When running all timepoints there are many options for applying inputs, storing results, and the associated solution type
- Here just the weather is applying, and the solar/wind results for the entire case and the individual states saved



Results

- The results can be viewed in either tabular displays or with graphs



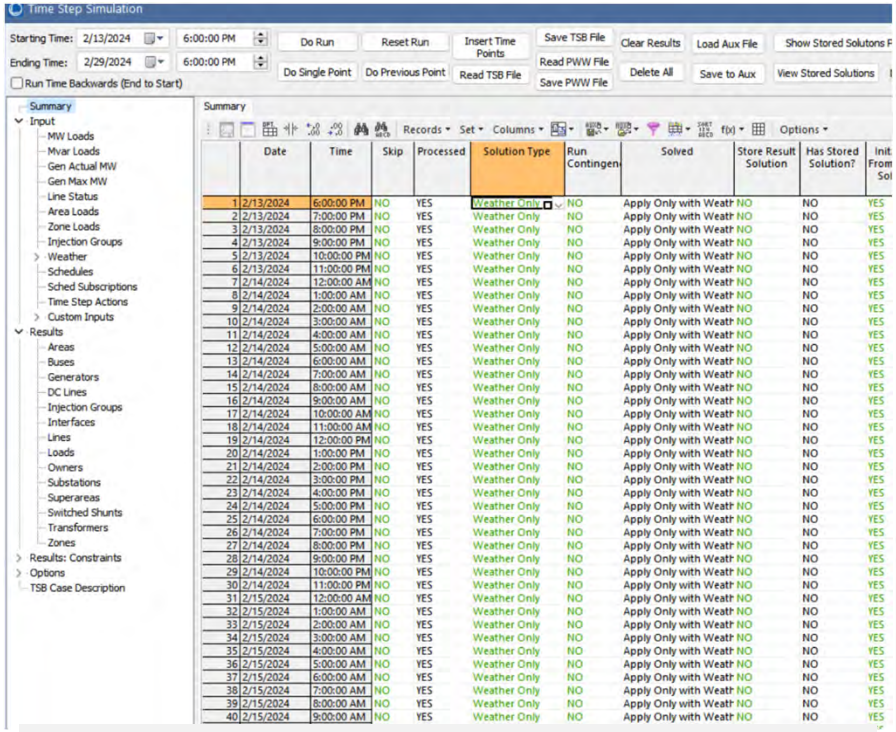
	Date	Time	TN Gen MW Wind	TN Gen MW Solar	TX Gen MW Wind	TX Gen MW Solar
5	12/31/2023	10:00:00 PM	3.17	0.00	16915.16	0.00
6	12/31/2023	11:00:00 PM	3.21	0.00	15697.56	0.00
7	1/1/2024	12:00:00 AM	3.23	0.00	14197.28	0.00
8	1/1/2024	1:00:00 AM	2.54	0.00	12849.30	0.00
9	1/1/2024	2:00:00 AM	2.40	0.00	11658.79	0.00
10	1/1/2024	3:00:00 AM	2.40	0.00	11014.38	0.00
11	1/1/2024	4:00:00 AM	2.40	0.00	8236.35	0.00
12	1/1/2024	5:00:00 AM	2.54	0.00	7100.55	0.00
13	1/1/2024	6:00:00 AM	2.54	0.00	6095.25	0.00
14	1/1/2024	7:00:00 AM	1.75	0.00	5111.19	0.00
15	1/1/2024	8:00:00 AM	2.52	18.60	4202.84	38.93
16	1/1/2024	9:00:00 AM	1.78	91.19	3138.75	941.69
17	1/1/2024	10:00:00 AM	1.79	175.92	2057.93	2504.74
18	1/1/2024	11:00:00 AM	1.78	245.41	1973.51	4057.28
19	1/1/2024	12:00:00 PM	2.63	280.85	2208.49	5127.65
20	1/1/2024	1:00:00 PM	3.55	239.78	2223.54	5370.77
21	1/1/2024	2:00:00 PM	3.55	173.80	2313.83	5045.14
22	1/1/2024	3:00:00 PM	3.41	106.36	3090.94	3985.84
23	1/1/2024	4:00:00 PM	1.12	52.80	3770.81	2607.56
24	1/1/2024	5:00:00 PM	1.09	9.83	4790.70	1307.33
25	1/1/2024	6:00:00 PM	1.02	0.00	7214.95	246.65
26	1/1/2024	7:00:00 PM	1.09	0.00	8815.06	0.00
27	1/1/2024	8:00:00 PM	1.01	0.00	9384.21	0.00
28	1/1/2024	9:00:00 PM	0.56	0.00	9203.25	0.00
29	1/1/2024	10:00:00 PM	0.46	0.00	9174.11	0.00
30	1/1/2024	11:00:00 PM	0.55	0.00	8949.27	0.00
31	1/2/2024	12:00:00 AM	0.48	0.00	8887.68	0.00
32	1/2/2024	1:00:00 AM	0.48	0.00	9066.13	0.00
33	1/2/2024	2:00:00 AM	0.47	0.00	9185.92	0.00
34	1/2/2024	3:00:00 AM	0.13	0.00	8720.72	0.00
35	1/2/2024	4:00:00 AM	0.06	0.00	8442.68	0.00
36	1/2/2024	5:00:00 AM	0.06	0.00	8320.04	0.00
37	1/2/2024	6:00:00 AM	0.06	0.00	7511.01	0.00
38	1/2/2024	7:00:00 AM	0.06	0.00	6073.90	0.00
39	1/2/2024	8:00:00 AM	0.01	19.45	4706.96	45.88

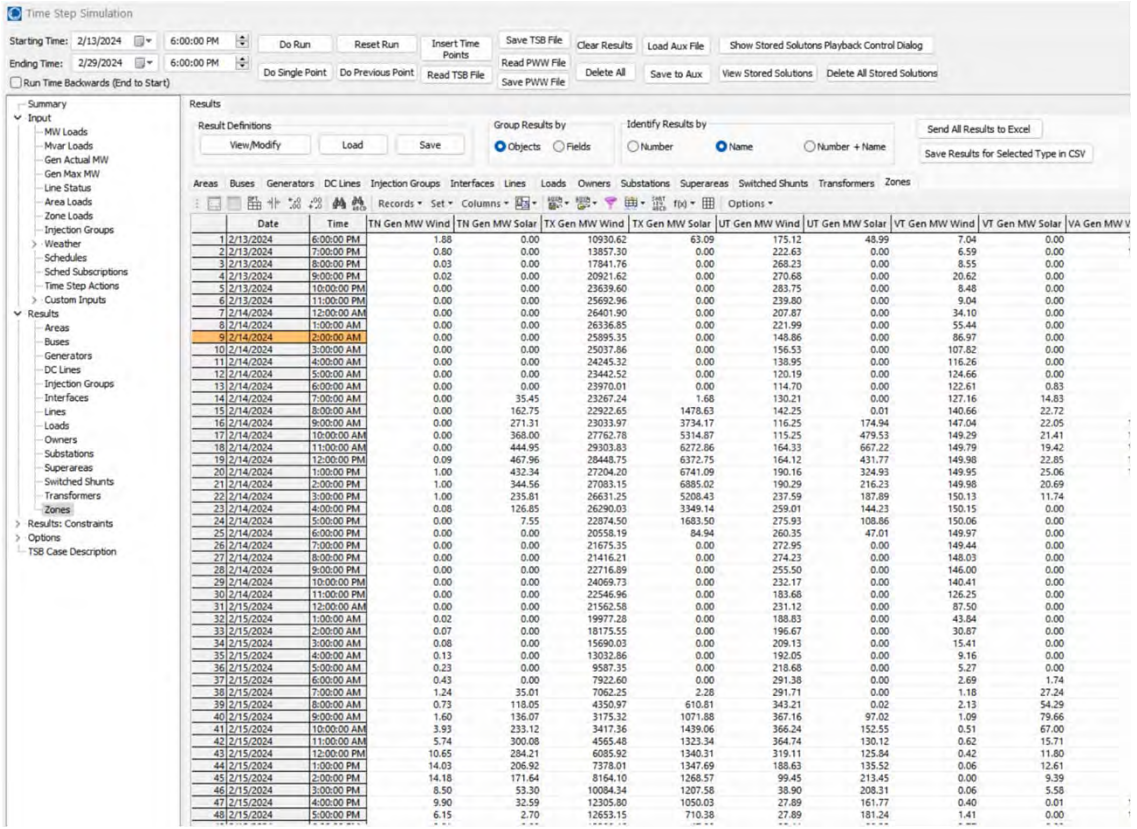
This naturally leads to validation! Of course with the EIA-860 case we won't expect to fully match actuals.

Cookbook: Estimating US Wind and Solar for Next 15 Days

- If you don't already have PFW wind and solar models in a case, a copper plate case for the US is available at electricgrids.engr.tamu.edu/eia-860-generator-data-cases/
- Get the latest forecast pww from electricgrids.engr.tamu.edu/weather-data/
- Select **Tools, Time Step Simulation** to show the Time Step Simulation form, click **Read PWW File** and load the forecast
- Set the Time Step Simulation to store the desired fields (super area and zones with the EIA860; you can load the EIA860OptionsSaveValues.aux included with the EIA860 download)
- In Time Step Simulation set the Solution Type to "Weather Only" and click **Do Run**

Cookbook: Estimating US Wind and Solar for Next 15 Days

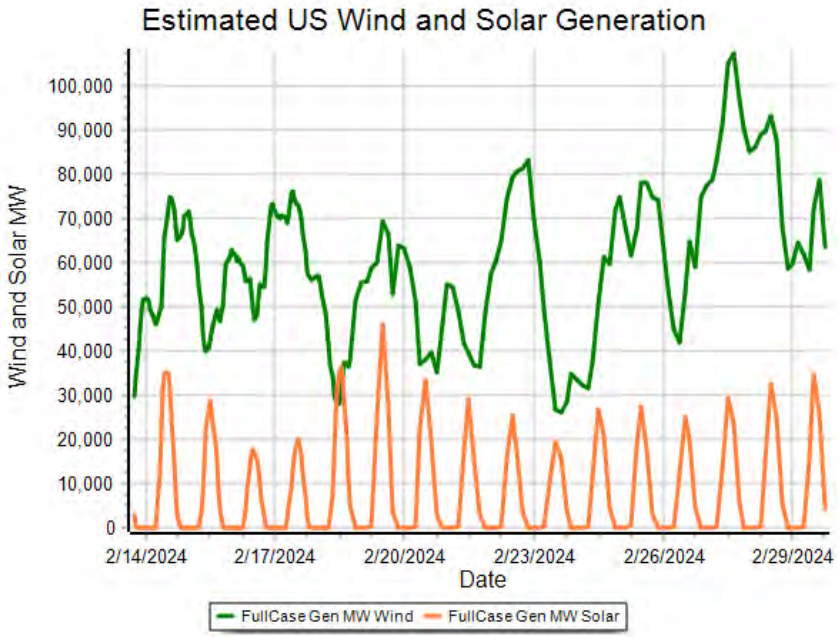


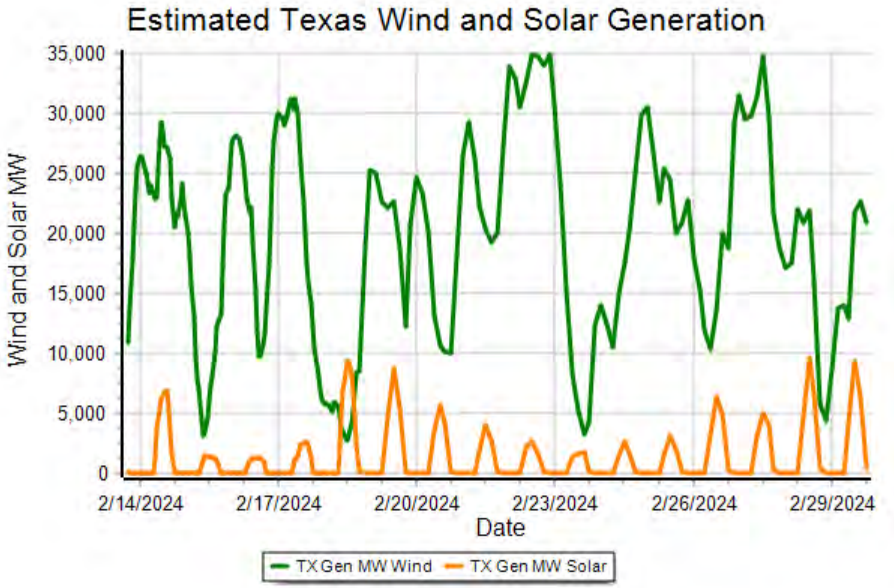


Done using a forecast that was run on Feb 14, 2024 at 0 hour UTC

Cookbook: Estimating US Wind and Solar for Next 15 Days

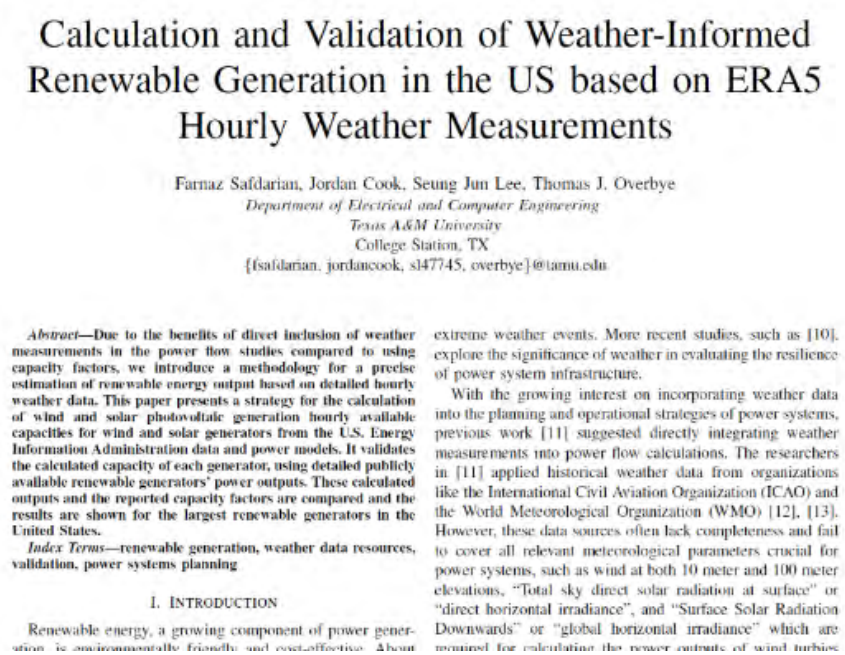
- These estimates are far from perfect, but they were done quickly using free public information, and they can certainly be improved; key takeaway is this functionality is available now





Validation

- An important aspect of this work is validating the results by comparing the simulated values with actual results
  - This can be at an aggregate level (e.g., state level using EIA data) or at an individual plant level using
  - Errors can arise because of actual weather differences and because of inaccurate models
- We recently submitted a four page digest to the Power and Energy Conference at Illinois (PECI) on generator output validation



Calculation and Validation of Weather-Informed Renewable Generation in the US based on ERA5 Hourly Weather Measurements

Farnaz Safdarian, Jordan Cook, Seung Jun Lee, Thomas J. Overbye
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX
{fsafdarian, jordancook, sl47745, overbye}@tamu.edu

***Abstract*—Due to the benefits of direct inclusion of weather measurements in the power flow studies compared to using capacity factors, we introduce a methodology for a precise estimation of renewable energy output based on detailed hourly weather data. This paper presents a strategy for the calculation of wind and solar photovoltaic generation hourly available capacities for wind and solar generators from the U.S. Energy Information Administration data and power models. It validates the calculated capacity of each generator, using detailed publicly available renewable generators' power outputs. These calculated outputs and the reported capacity factors are compared and the results are shown for the largest renewable generators in the United States.**

***Index Terms*—renewable generation, weather data resources, validation, power systems planning**

I. Introduction

Renewable energy, a growing component of power generation, is environmentally friendly and cost-effective. About

extreme weather events. More recent studies, such as [10], explore the significance of weather in evaluating the resilience of power system infrastructure.

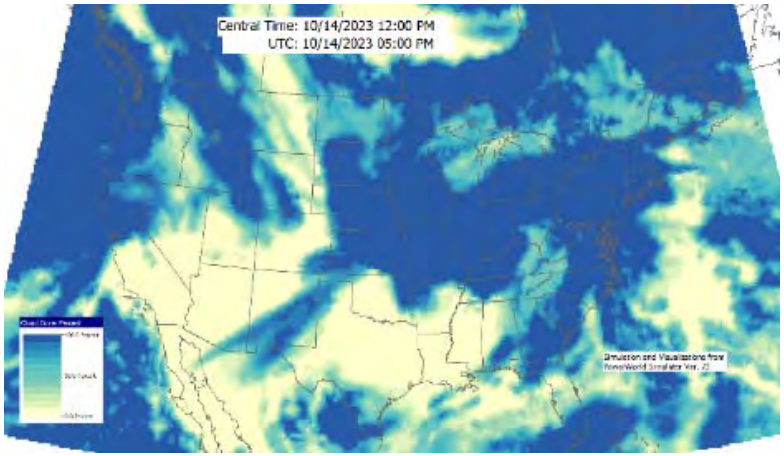
With the growing interest on incorporating weather data into the planning and operational strategies of power systems, previous work [11] suggested directly integrating weather measurements into power flow calculations. The researchers in [11] applied historical weather data from organizations like the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO) [12], [13]. However, these data sources often lack completeness and fail to cover all relevant meteorological parameters crucial for power systems, such as wind at both 10 meter and 100 meter elevations, "Total sky direct solar radiation at surface" or "direct horizontal irradiance", and "Surface Solar Radiation Downwards" or "global horizontal irradiance" which are required for calculating the power outputs of wind turbines

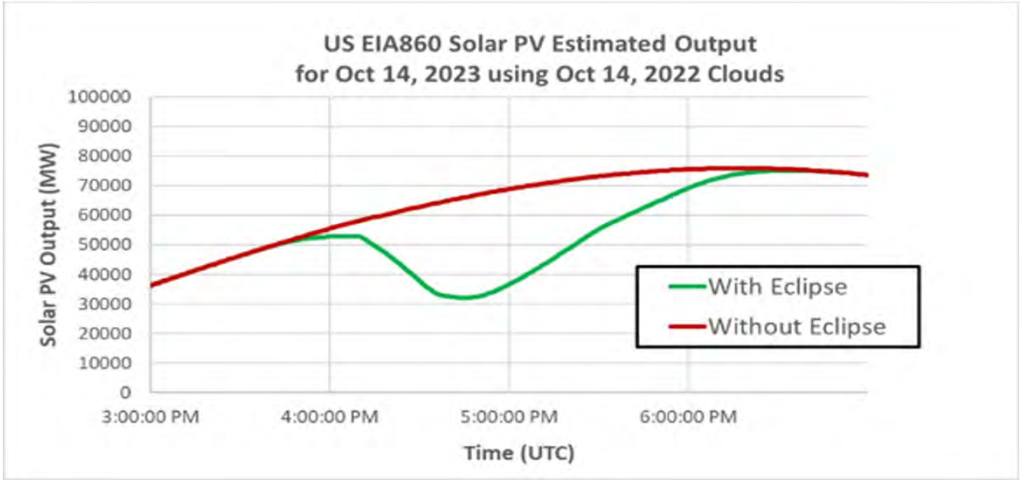
Some Potential Additional Models

- 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.

Other Resiliency Events

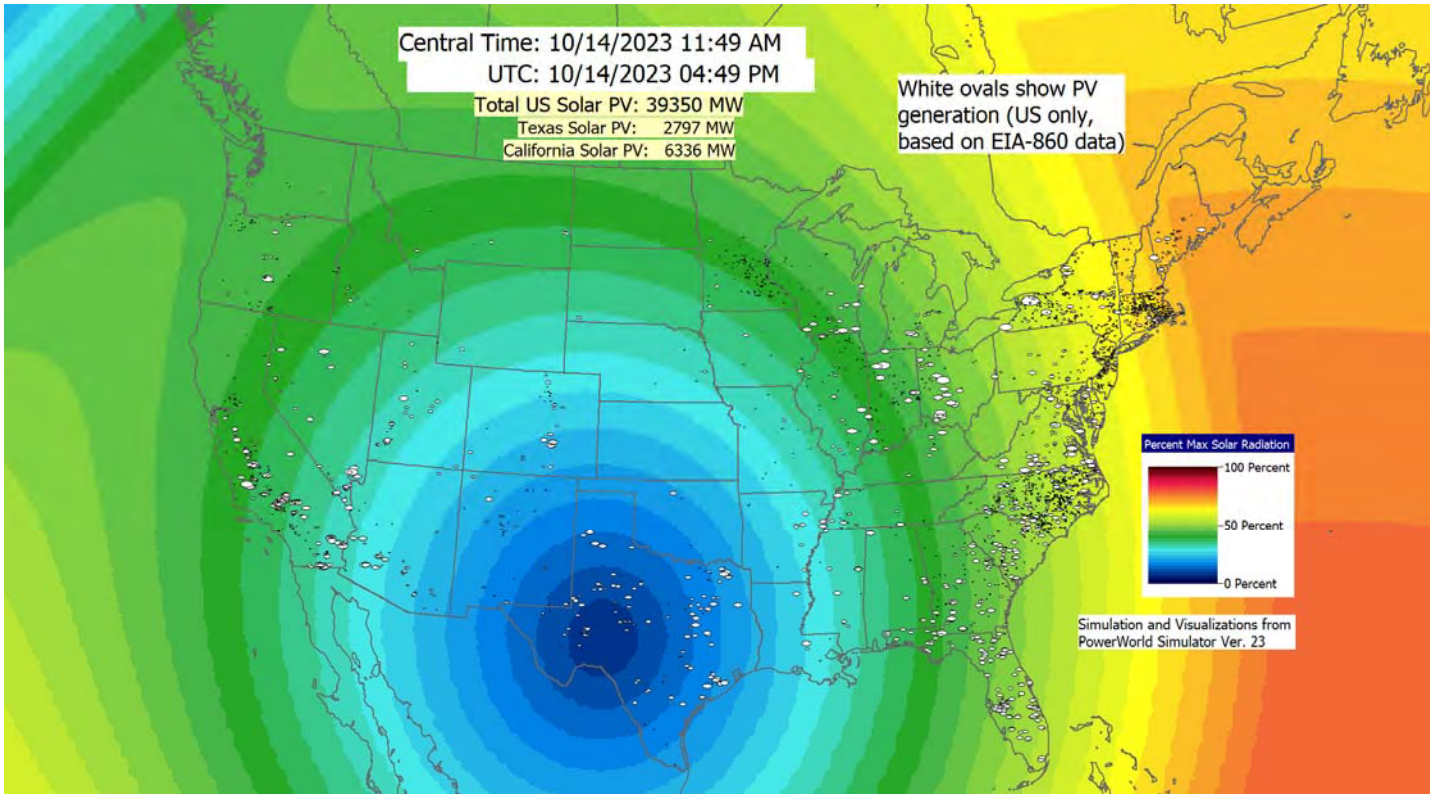
- A similar process can be used for modeling the impacts of other resiliency events
- An example of a relatively benign event is a solar eclipse, something that occurred in North America on 10/14/23, and will occur on 04/08/24
- Thanks to Zach Zornes (Chelanpud) for getting us started on this!!





Other Resiliency Events, Eclipse, cont.

- Image shows the estimated solar radiation as a percentage of maximum (one sun) during the Oct 14, 2023 event assuming no clouds



Future Directions – Joining Project IAB

- There are many future directions to pursue
  - A number of models that relate weather to electric grid values already exist, but more certainly should be developed
  - More validation!!
  - Increased automation of the updating process; maybe more footprints
  - Machine learning applications given lots of potential operating points
  - Determining the required level of weather details; higher resolution datasets are available; also other potentially severe resiliency events
- We are in the process of developing a large proposal in this area, and would love to have some more industry partners join the team, including being on an IAB and perhaps being demonstration sites
- For more details email me (Overbye@tamu.edu)

Thank You! Questions?

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