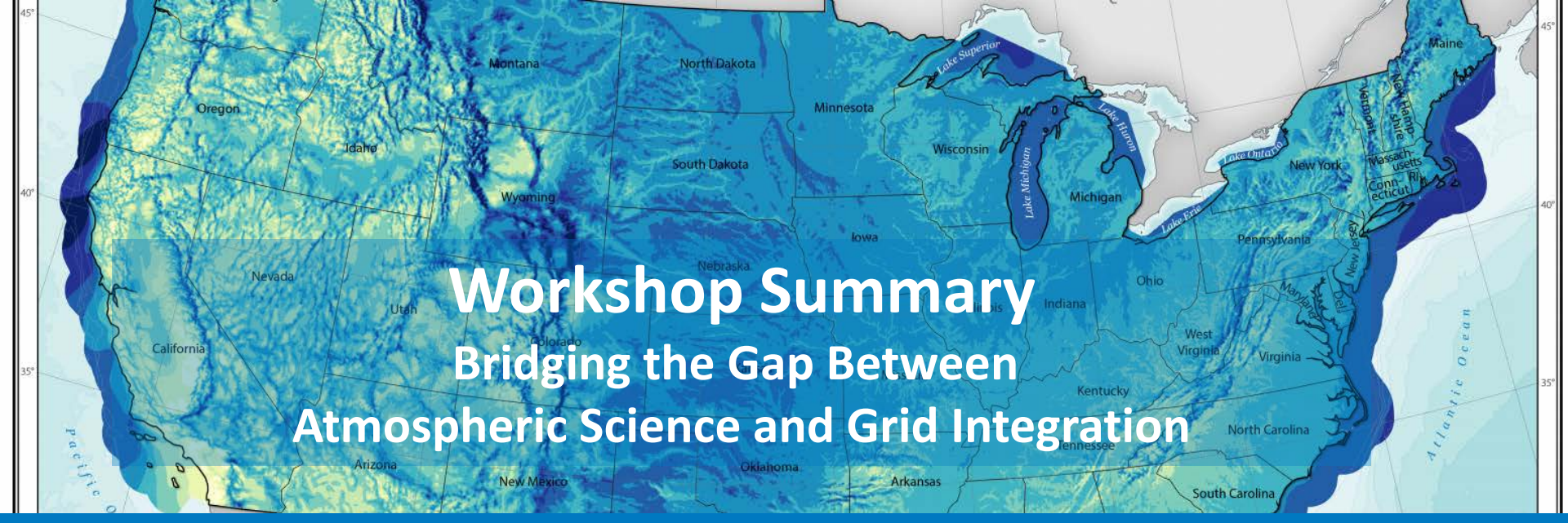

Workshop Summary

Bridging the Gap Between Atmospheric Science and Grid Integration

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Caroline Draxl
Dave Corbus
Greg Brinkman

National Renewable Energy Laboratory (NREL)

March 2024

NREL
Transforming ENERGY

Workshop addresses growing need for more high-quality resource data for power systems applications!

The need for dedicated, accurate, expertly curated weather data is increasingly important as the share of variable renewable energy increases on the power system. Projections for futures with very high (50+% annual energy) shares of variable generation require ongoing assessment of data requirements from industry stakeholders in their power system operation and planning contexts.
In March 2024, NREL organized a workshop entitled “Bridging the Gap Between Atmospheric Science and Grid Integration Workshop”, which brought atmospheric scientists and power system experts together to refine the requirements of atmospheric datasets for grid integration, and to describe a holistic approach to creating new and regularly updated national scale wind datasets for power system planning and operations. The results of this workshop are being used to inform the near-term development and a longer-term strategy for DOE to produce relevant wind resource datasets and inform wider use of wind/solar/load data sets in power system planning.

This presentation provides an overview of a preworkshop survey, an assessment of current state of the art of national-scale datasets for wind resource assessment and grid integration, insights on appropriate uses of the WTK-LED, power system perspectives on data needs, as well as recommended next steps as discussed in the workshop and how these steps support longer-term strategies.

What Are the Gaps Addressed in the Grid-Atmosphere Workshop?

Key grid integration needs:

- Capacity expansion models
- Resource adequacy calculations
- Production cost models
- Extreme events modeling
- General power system operation considerations
- Load following and regulation analysis
- Time series analysis for system ramping and flexibility

Goal:

Assess the current data requirements from industry stakeholders in their operation and planning contexts

NREL has produced wind resource data that is broadly used by NREL, DOE labs, and industry for leading edge grid integration studies. However, these successes have created a need for next-generation data sets and processes. This workshop aims to compare data pathways with industry needs and evaluate the improvements various data pathways can provide relative to current industry-grade data.

FOCUS IS ON THIS

This could be used to inform **near-term development and a longer-term strategy** for the U.S. Department of Energy (DOE) to produce relevant wind resource datasets, and to inform wider use of wind/solar/load datasets to evaluate future carbon reduction scenarios.

NREL's WIND Toolkit is used widely and successfully, but aging and no regular update

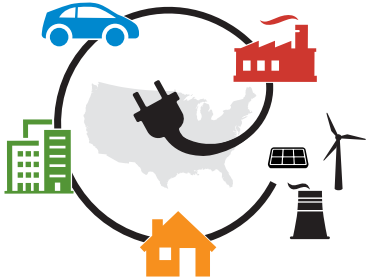
Attribute	WIND Toolkit/NSRDB Combination		ERA5
	For Wind/Load	For Solar	Wind/Solar/Load
Has required temporal resolution[a]	5-min produced	5-min since 2019	Hourly
Has required spatial resolution	2 km	4 km; 2 km since 2019	30 km
Includes multiple heights above the surface		N/A	
Available for several decades	8 years[b]	Since 1998	Yes
Has regular updates	Nothing formal	Annual	Daily (7-day lag)
Is future-proofed	Ad hoc	Yes	Yes
Is long enough to detect climate signals	Unlikely	Possibly	Yes
Models are adequately validated			
Accuracy assessed, including for risk periods	Against tall meteorology towers	Limited	Limited
Variability assessed, against reality	Limited	Limited	Several studies
Assessed power system modeling applicability?	Designed for this	No studies found	No studies found
Provides companion "forecasts"[c]	Produced	No, but possible	No
Is based on consistent input observations and/or models	Yes, except 2014	Yes	Yes (single modeling system)
Physical consistency between wind/solar	No; impact should be investigated		
Well documented and easy to use			
Limitations are clearly specified			

Fully Met · Close to Being Met · Partially Met · Met in a Very Limited Way · Not Met at All

Table from https://www.esig.energy/wp-content/uploads/2023/10/ESIG-Weather-Datasets-full-report-2023b.pdf

Used in major NREL studies for years!

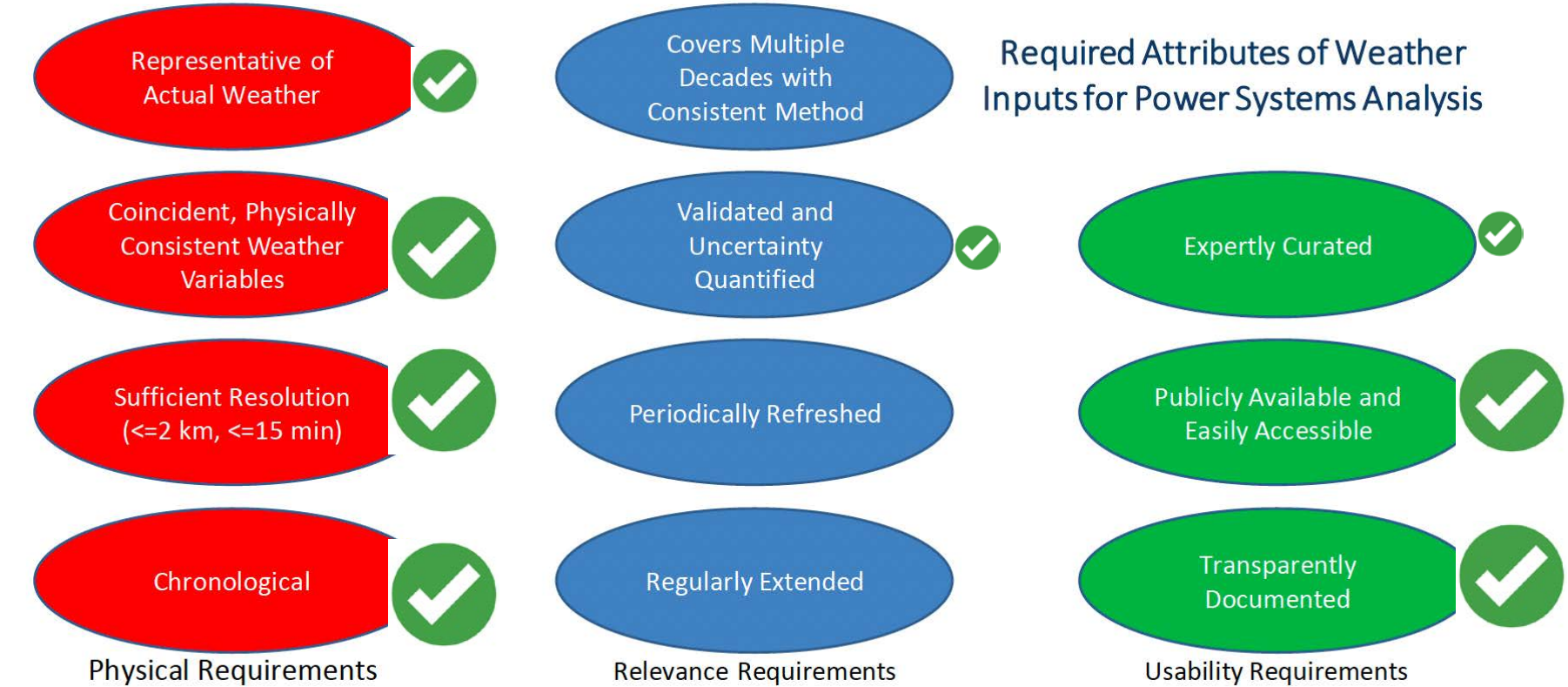
Electrification Futures Study (2018)



North American Renewable Integration Study (2021)

Atlantic Offshore Wind Transmission Project (2024)

NREL's new WIND Toolkit Long-Term Ensemble Dataset covers many physical and usability requirements for grid integration



Green checkmarks represent relative performance of the WIND Toolkit Long-Term Ensemble Dataset (WTK-LED)

Adapted from Justin Sharp's 2023 ESIG Webinar: https://www.esig.energy/event/webinar-weather-data-inputs-for-power-system-modeling-mind-the-gaps/

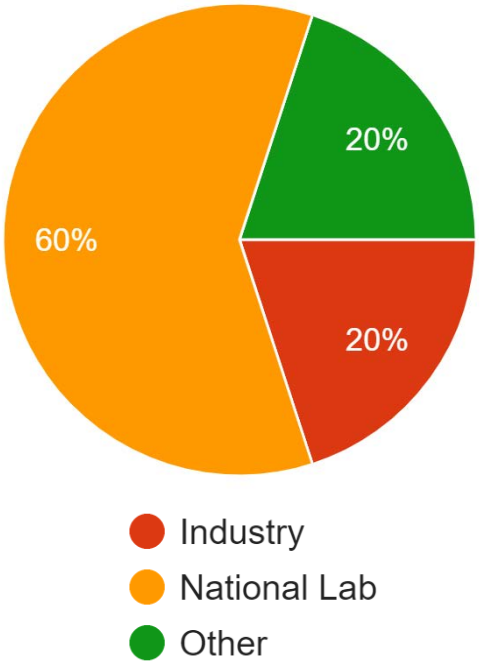
Workshop Identification of Gaps
Results from Preworkshop Survey

Workshop participants touring the Flatirons Campus
Photo from Justin Sharp

Needs Are Addressed in Preworkshop Survey and Workshop Whiteboard Responses

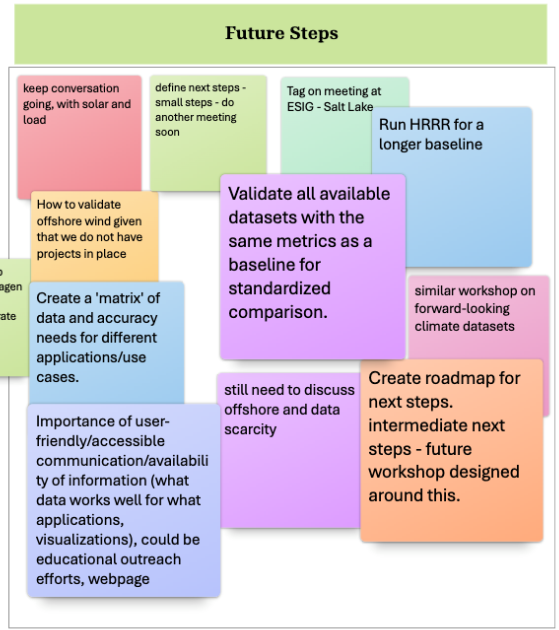
Which sector are you in?

15 responses

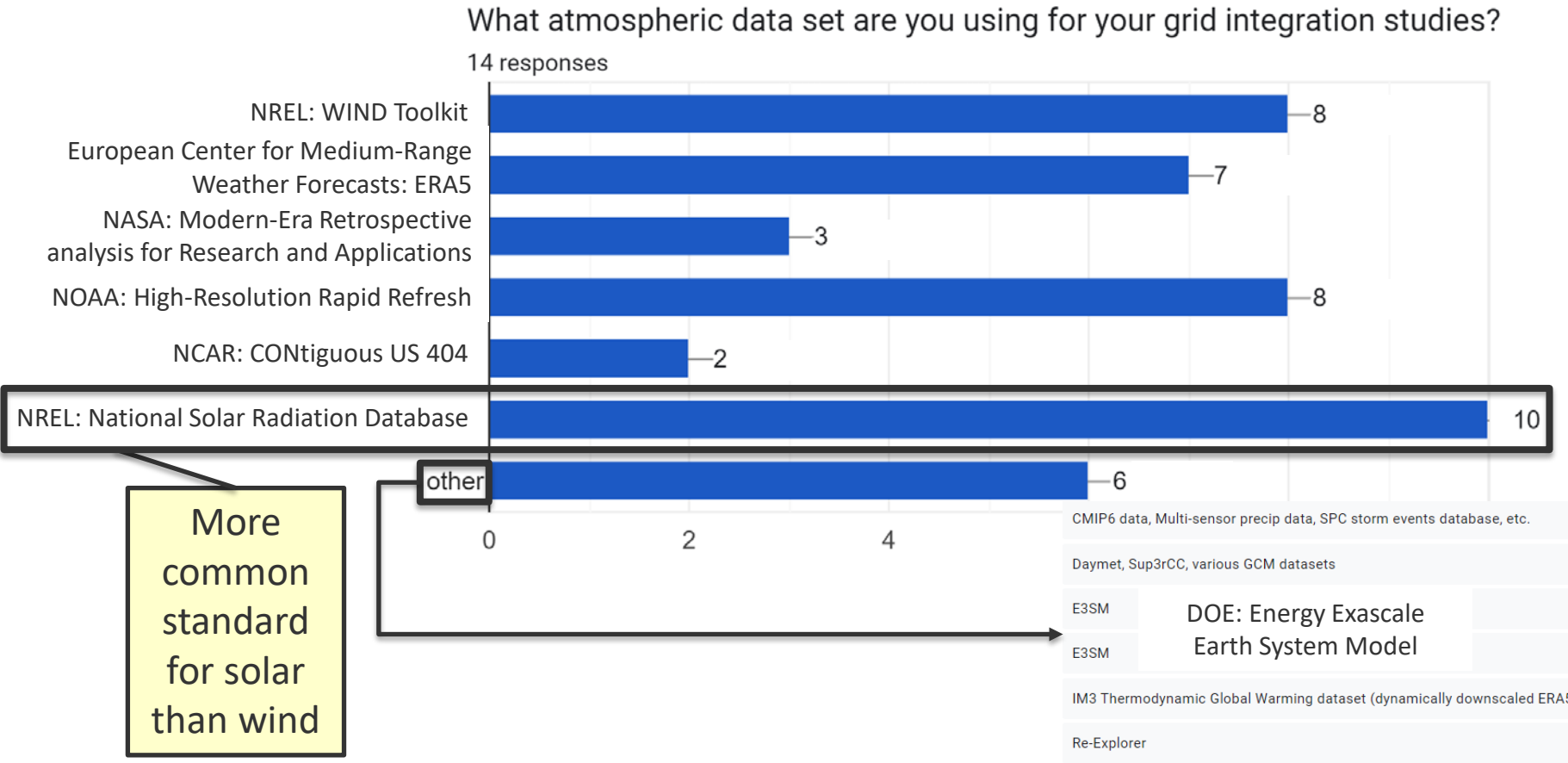


Need for transparency, accuracy, validation

Define priorities, keep conversation going!

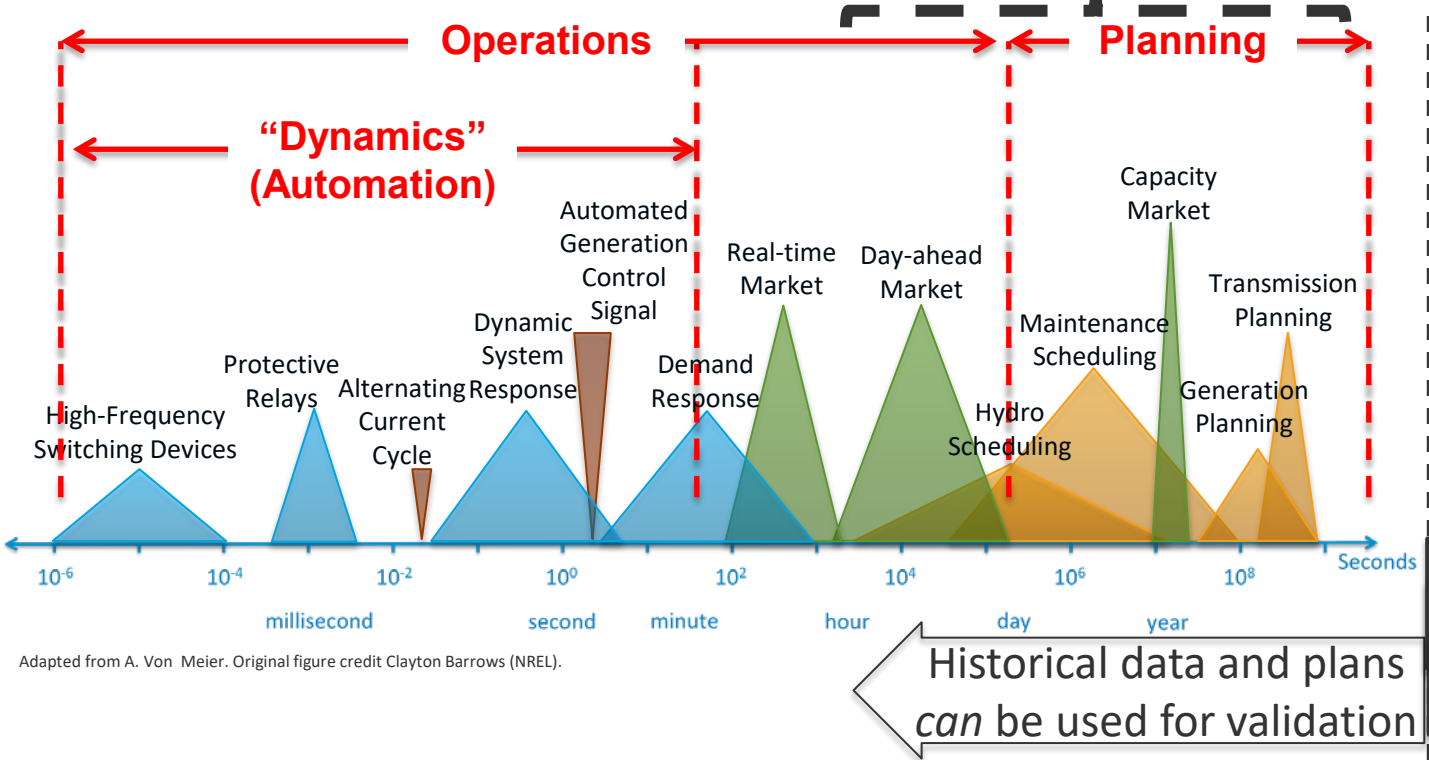


Grid Integration Practitioners Use Many Atmospheric Datasets



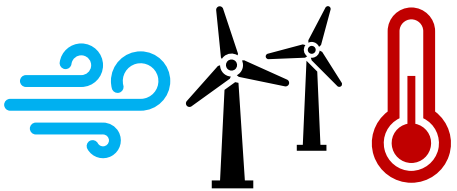
Common Priorities Are Many Years of Hourly Data Compatible With Forward-Looking Grid Scenarios

Common response wants wind data accurate to **hourly** resolution, spatially resolved **across nation**(s), for **10+ years** of weather data (e.g., for **resource adequacy**)



Adapted from A. Von Meier. Original figure credit Clayton Barrows (NREL).

And recognizes challenges of forward-looking planning



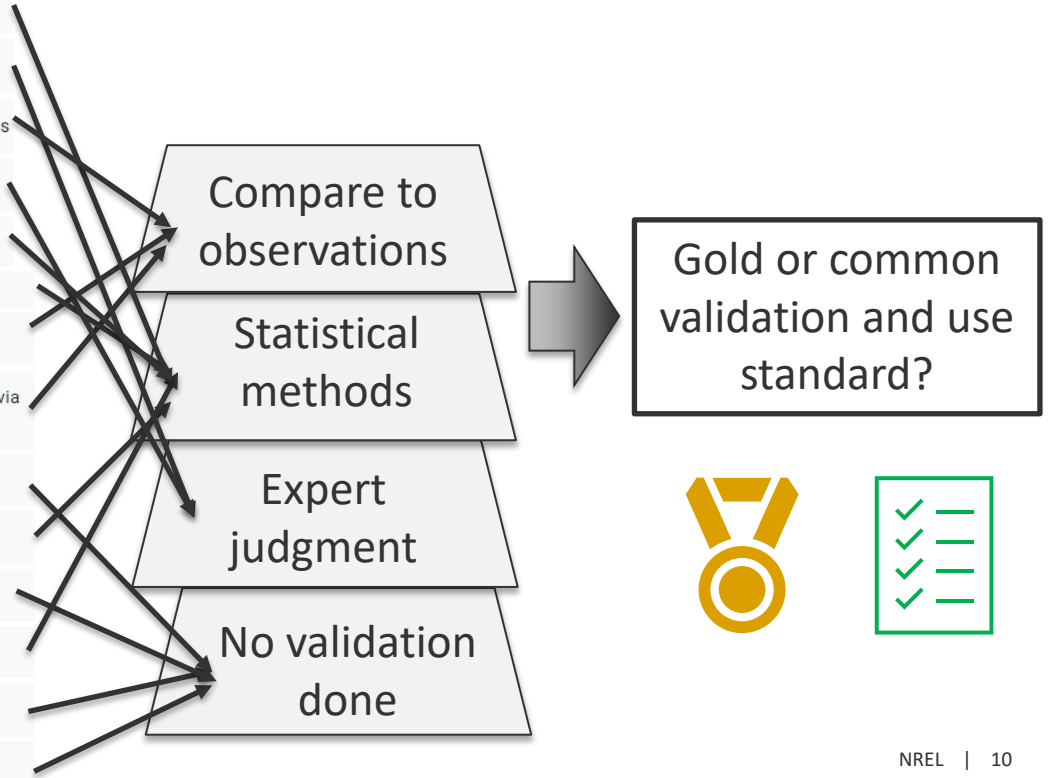
Historical data and plans *can* be used for validation

Futures?

Validation Practices Crucial to Best-Practice Data Use Vary in Absence of Standard Approach

Validation approaches of participants:

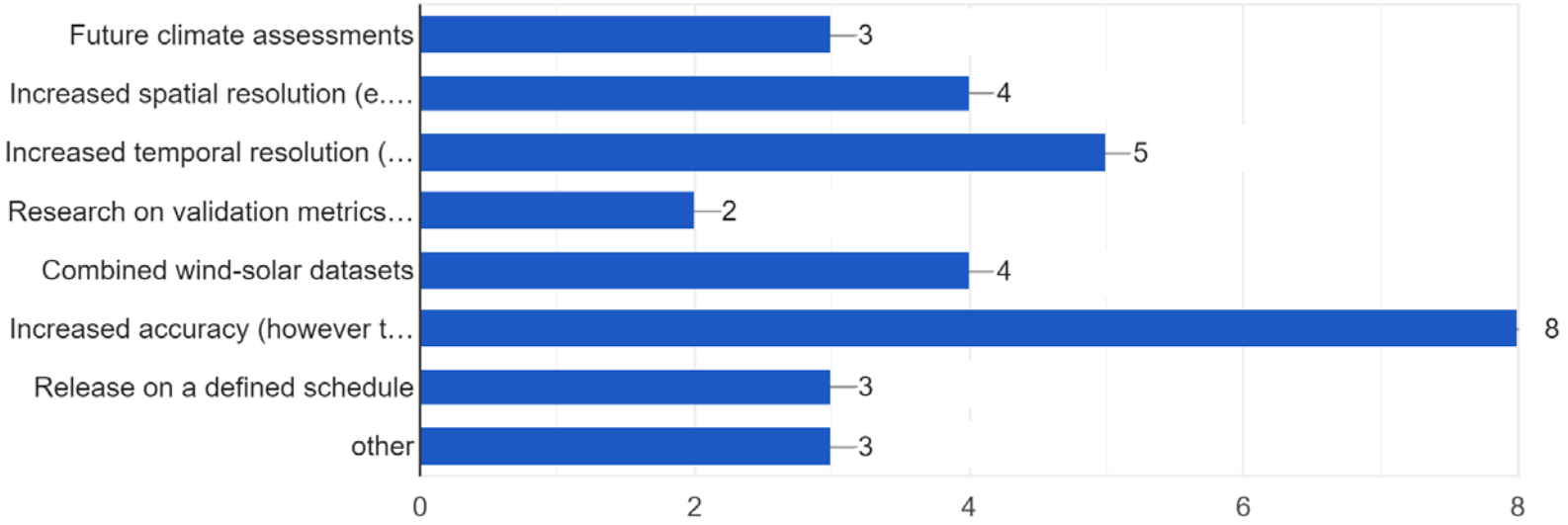
- We use a large ensemble. Usually a bigger ensemble for variables with more uncertainties.
- Scaling the 8760 up/down by a predetermined amount.
- Regular evaluation of model errors with observations, and consistency of time-lagged predictions
- using a spread of different representative days
- Deep uncertainty with climate ensembles
- Using multi-year averages, Calculating seasonal statistics and variability
- Mainly through comparison to observations
- Poorly. But we also try to include historical actual operating data where available and show results via modeled and actual weather data.
- Usually it's not taken into account
- Estimating errors by comparison with observed wind/irradiance, sensitivity tests.
- Not currently modeling
- Monte Carlo approach
- Not accounting for uncertainty
- not directly quantifying this



Accuracy Stands Out Among High-Priority Needs for Future Datasets

Which of these should have the highest priority for future atmospheric datasets for grid integration studies? (Choose one)

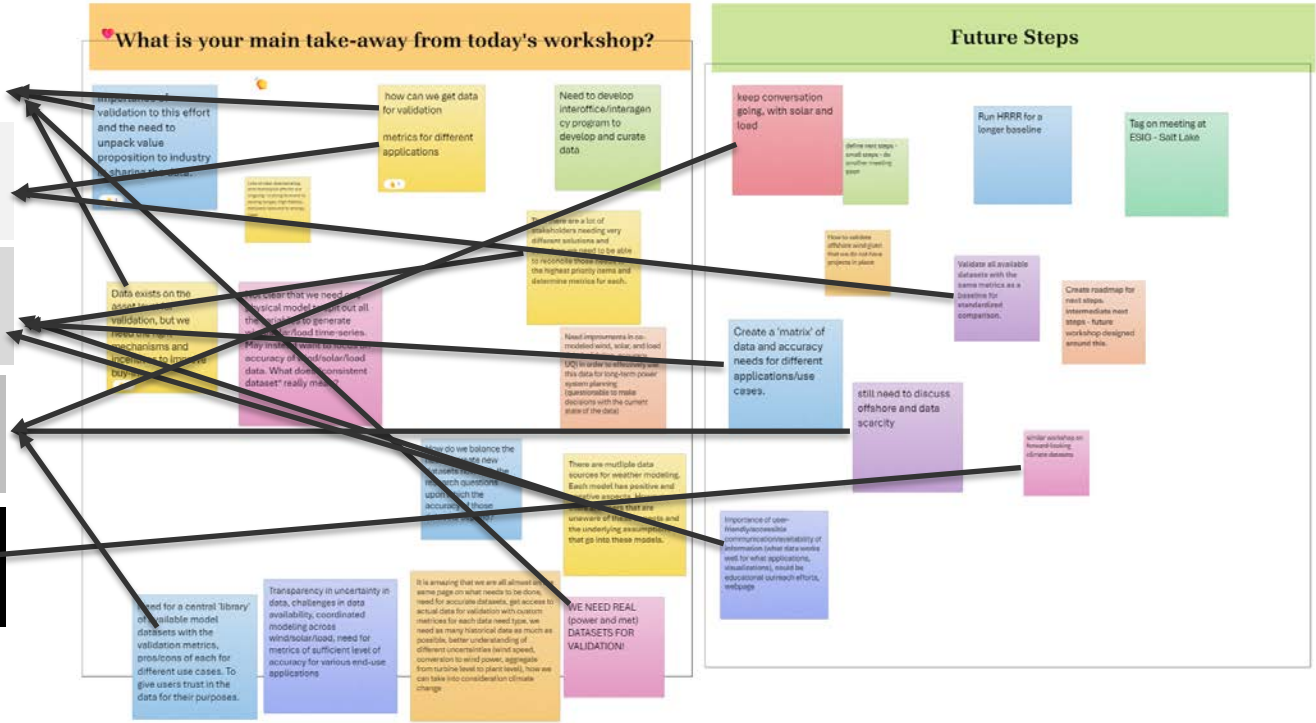
14 responses



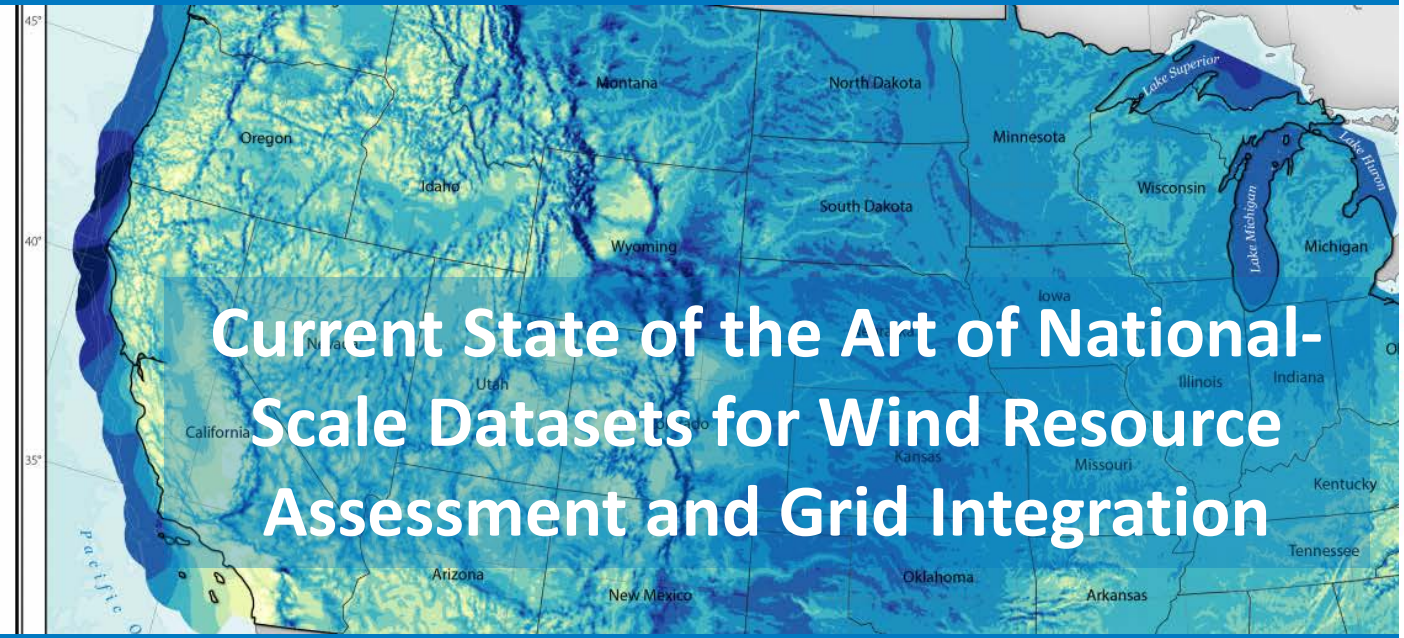
Increased accuracy could be achieved with better validation and combined wind/solar/load/hydropower data.

Workshop Whiteboard Identifies Five Key Focus Areas

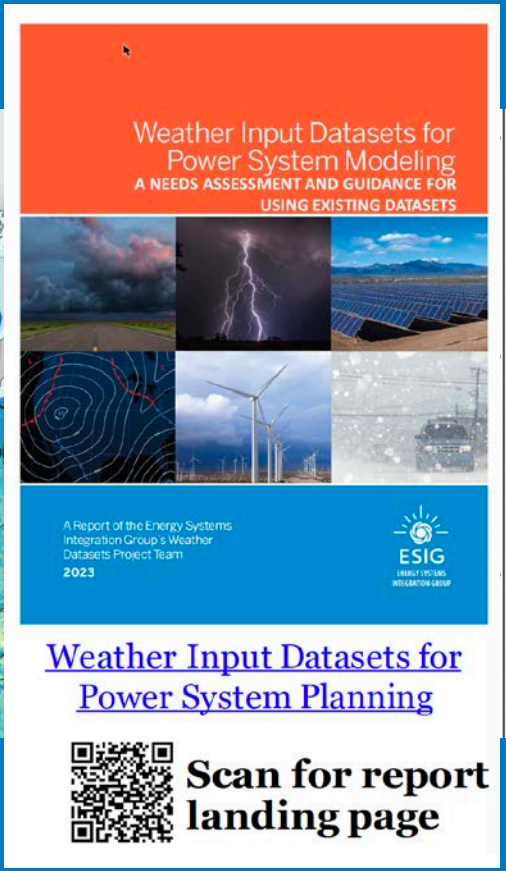
1. Validation is missing
2. No common set of metrics for usability
3. Clear definition of use cases needed
4. Relevant datasets not linked
5. What about the future?



These five key areas are used to inform next steps



Current State of the Art of National-Scale Datasets for Wind Resource Assessment and Grid Integration



Atmospheric science perspective

The next four slides are adapted from material by Justin Sharp (workshop participant)

Need for Dedicated, Accurate, Expertly Curated Weather Information

Inaction could lead to the following risks:

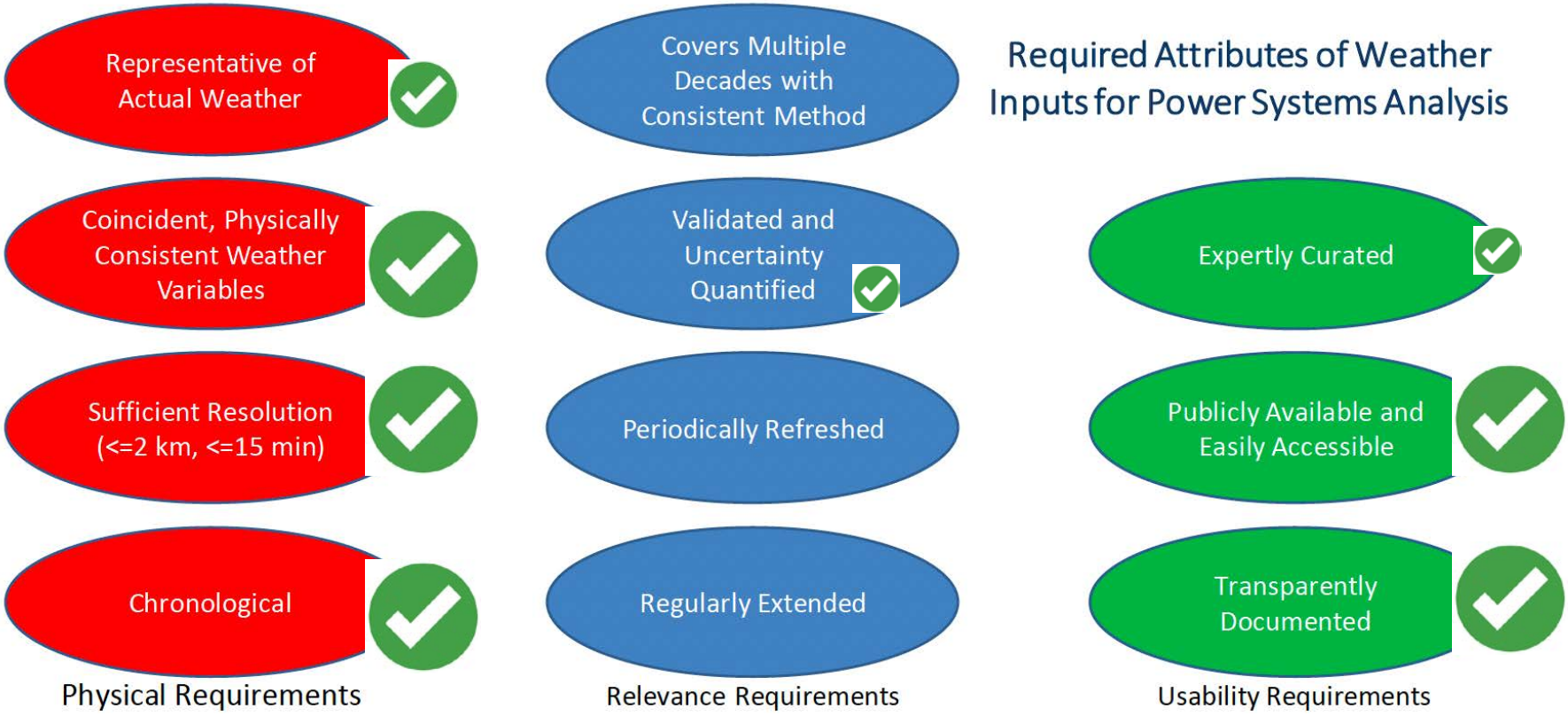
- Reliability issues tied to renewables
- Slowed/halted decarbonization
- Inefficient system design and planning.

- The risks are significantly more expensive that the investment to do things right.
- **Weather** dependence and complexity are increasing. This weather dependence must be managed/mitigated.
- **Forecasts** cannot reduce variability. Planning success depends on characterizing and addressing variability ahead of operations.
- **Weather** in all datasets is correlated. Capturing those correlations between outages and weather-driving load and wind/solar is important.

Current Limitations of Datasets

- Models will always be imperfect; they have limitations and weaknesses, which are understood by numerical weather prediction experts but not general data users
- Lack of validation (due to lack of observations)
- Lack of uncertainty quantification; Understanding uncertainty will lead to increased accuracy
- Observational data from renewable energy plants are proprietary–this must change to provide access to validation data
- Lack of transdisciplinary coordination and data curation
- Data distributions do not match reality, especially for extremes
- There is no existing dataset that is ideal for grid integration.

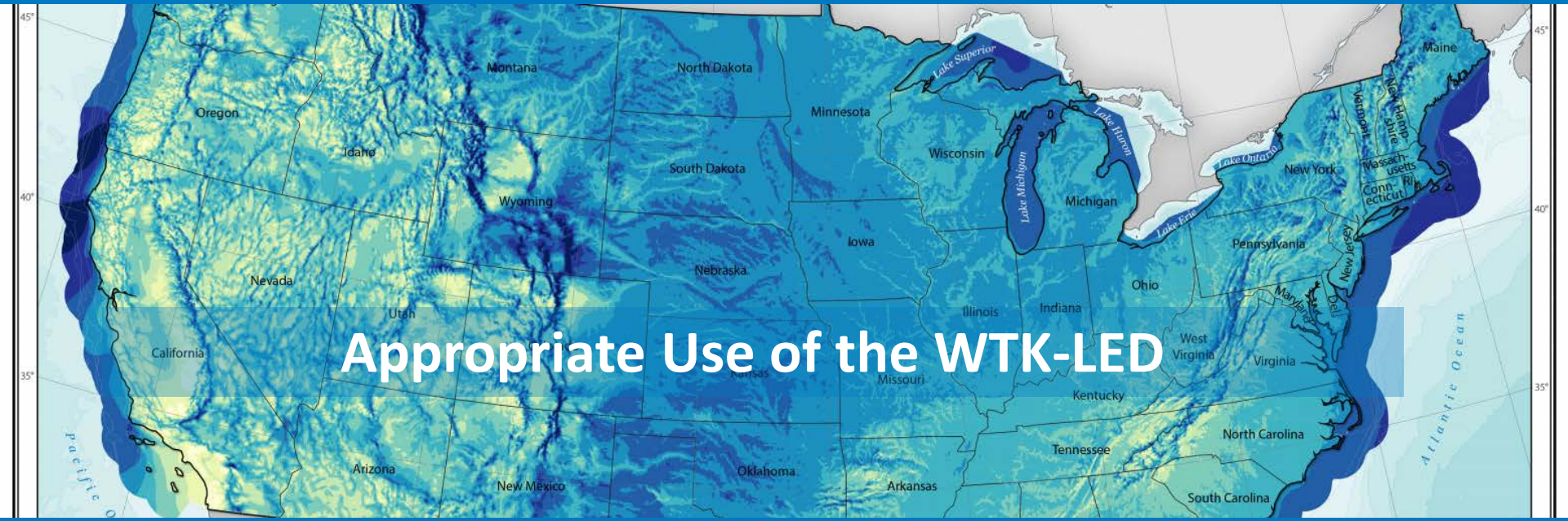
An Ideal Dataset for Grid Integration Looks Like This



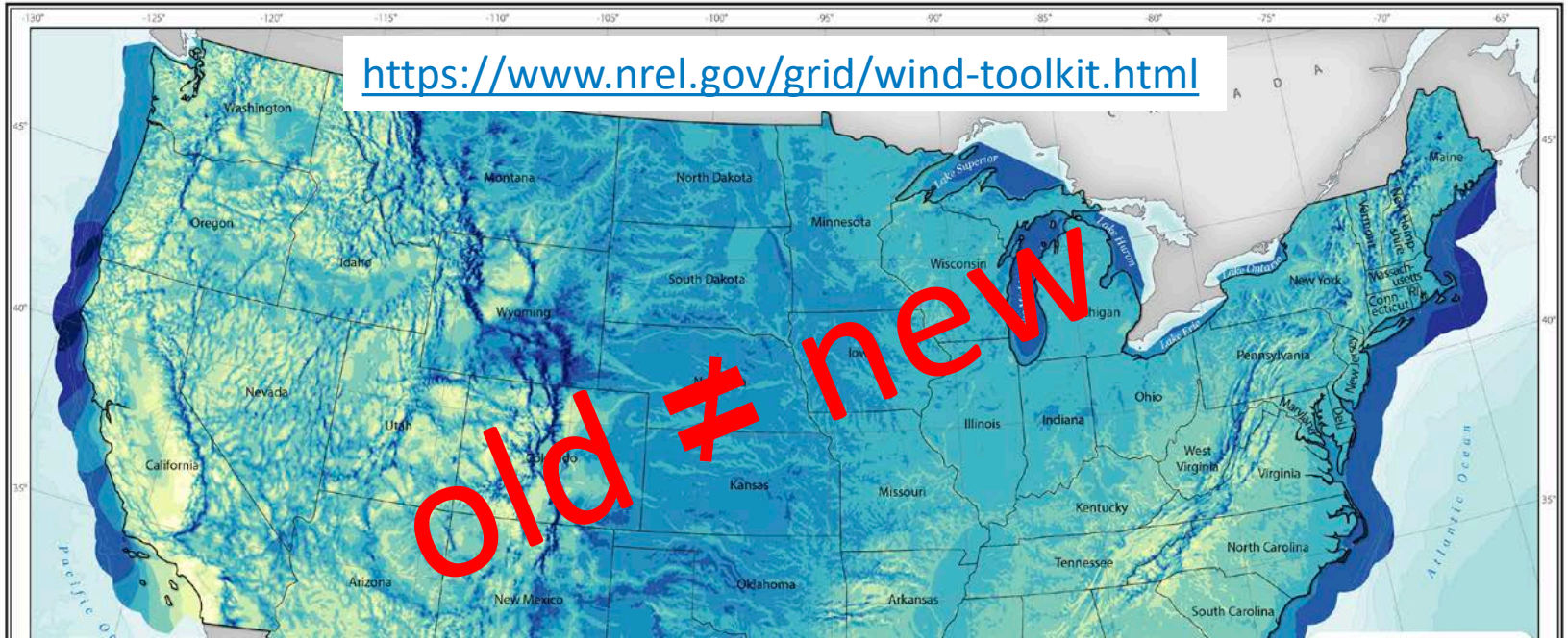
Checkmarks represent the performance of the WIND Toolkit Long-Term Ensemble Dataset (WTK-LED)

What Is Needed

- Address climate variability and quantify uncertainty of climate change models
- Validation according to the use case, distributions, and tails
- Comprehensive, industrywide data transparency and sharing of meteorological measurements, and generation and availability data; might require legislation/regulation
- Transdisciplinary coordination across meteorology and power systems modeling
- Combined wind/solar/load datasets
- $30–$55 million (Justin Sharp): includes overhead for all the tasks including detailed validation, curation, producer selection, overall management. Does not include budget for observational network for validation.



Appropriate Use of the WTK-LED



Original WIND Toolkit:

- 7 years (2007–2013) at 2 kilometers (km), 5 minutes (min)
- Deterministic dataset containing meteorological and power data
- Contiguous United States (CONUS)
- **Developed as a grid integration dataset to mimic forecast errors.**

WIND Toolkit LED:

- Updated Weather Research and Forecasting version (4.1.3)
- CONUS, Alaska, and Hawaii for 2018, 2019, and 2020 at 2 km, 5 min
- North America Climate dataset covering 20 years (2001–2020) at 4 km, hourly
- Model uncertainty quantified (ensembles)
- *NO power forecasts.*

Datasets Used at NREL

Validation focused on 2019-2020

2007-2013 // 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | **2021**

High Resolution Rapid Refresh (HRRR)
(National Oceanic and Atmospheric Administration [NOAA])

2 km over CONUS; hourly

Bias-corrected HRRR (by Quantile Mapping; BCHRRR) (NOAA/NREL)

2 km over CONUS; hourly

WTK-LED (NREL)

2 km over CONUS + Hawaii + Alaska; 5 min

WIND Toolkit (NREL)

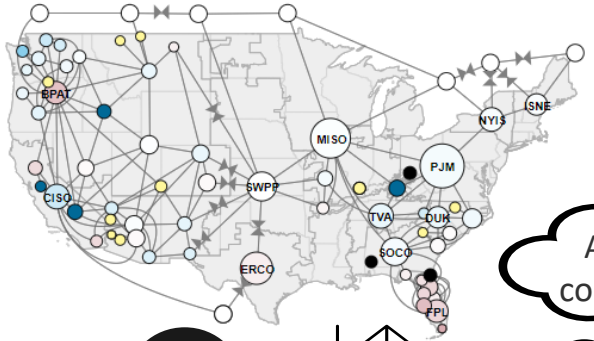
2 km over CONUS; 5 min

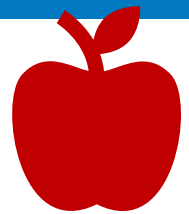
Energy Information Administration (EIA)-930 Generation Observations

EIA regions, hourly

However, Validating Against EIA-930 Requires Trying To Compare Apples to a…Similar Variety of Apple

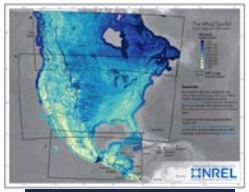
EIA observed wind generation *only* available hourly by EIA region





Are these comparable?

1

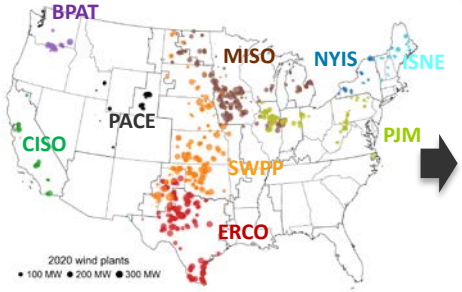


Synthetic wind speed data

2

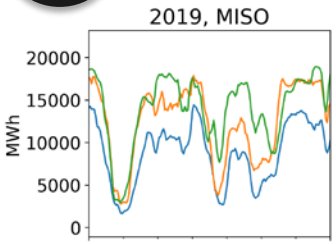
Estimate wind generation with 2018 turbine across CONUS

3

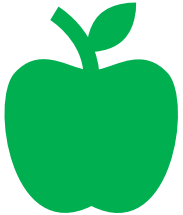


Map to existing wind sites in comparison year

4

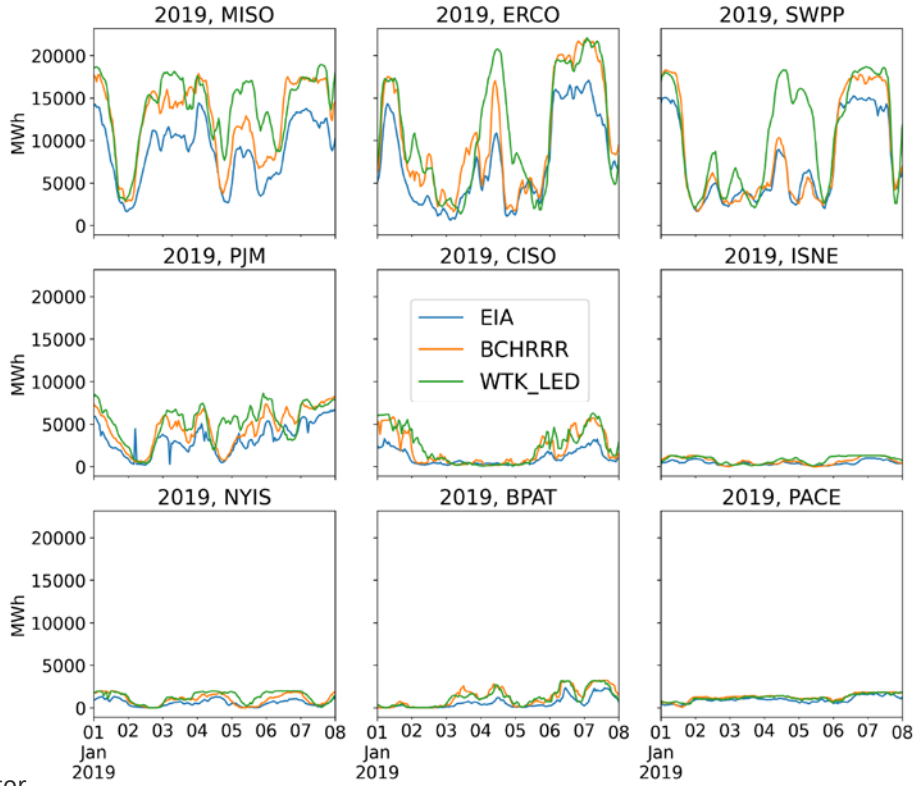


Aggregate to compare generation at EIA-930 region



Adjacent NREL Validation Effort Shows Both New WTK-LED and Bias-Corrected HRRR Correlate With Regional Generation Observations

- WTK-LED and BCHRRR generation estimates higher than EIA-930
- Nonharmonized assumptions could drive overestimation, including:
  - High wind resource
  - Curtailment not included in reV
  - Wake losses (internal)
  - Installed capacity differences
  - Technology vintage inconsistencies between model and EIA
  - Inconsistent boundaries.

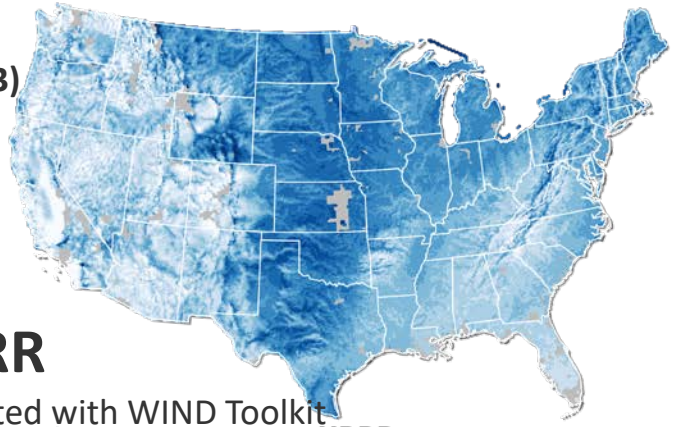


*All time stamps in Coordinated Universal Time (UTC)

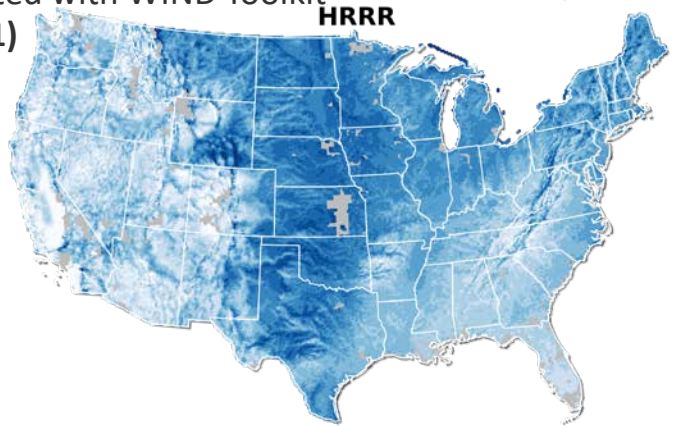
Figure uses four-letter abbreviations used in EIA-930 data. In the figure, MISO = Midcontinent Independent System Operator, ERCO = Electric Reliability Council of Texas, SWPP = Southwest Power Pool, CISO = California Independent System Operator, ISNE = Independent System Operator New England, NYIS = New York Independent System Operator, BPAT = Bonneville Power Authority, PACE = PacifiCorp East.

Wind Capacity Factors Higher in WTK-LED

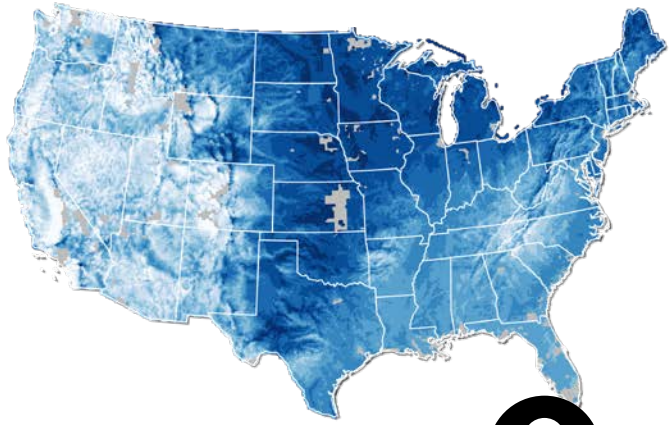
WTK
(2007–2013)



BCHRRR
Bias corrected with WIND Toolkit
(2015–2021)



WTK-LED
(2018–2019)



Capacity Factor
- 0 - 0.15
- 0.15 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.55
- > 0.55

?

?

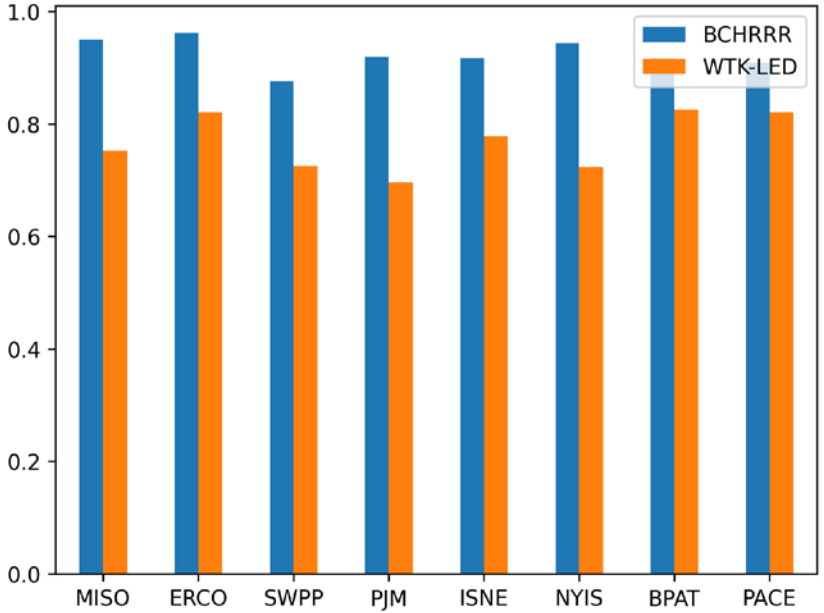
This has not been validated, therefore these capacity factors contain uncertainty.

?

?

Correlation Shown in Time Series Is Present Across Full Year of Hourly Wind Data

Pearson's Correlation Coefficient for 2019



Abbreviations are as defined on Slide 19

Shows correlation over a longer time period than previous plots (year vs. week)

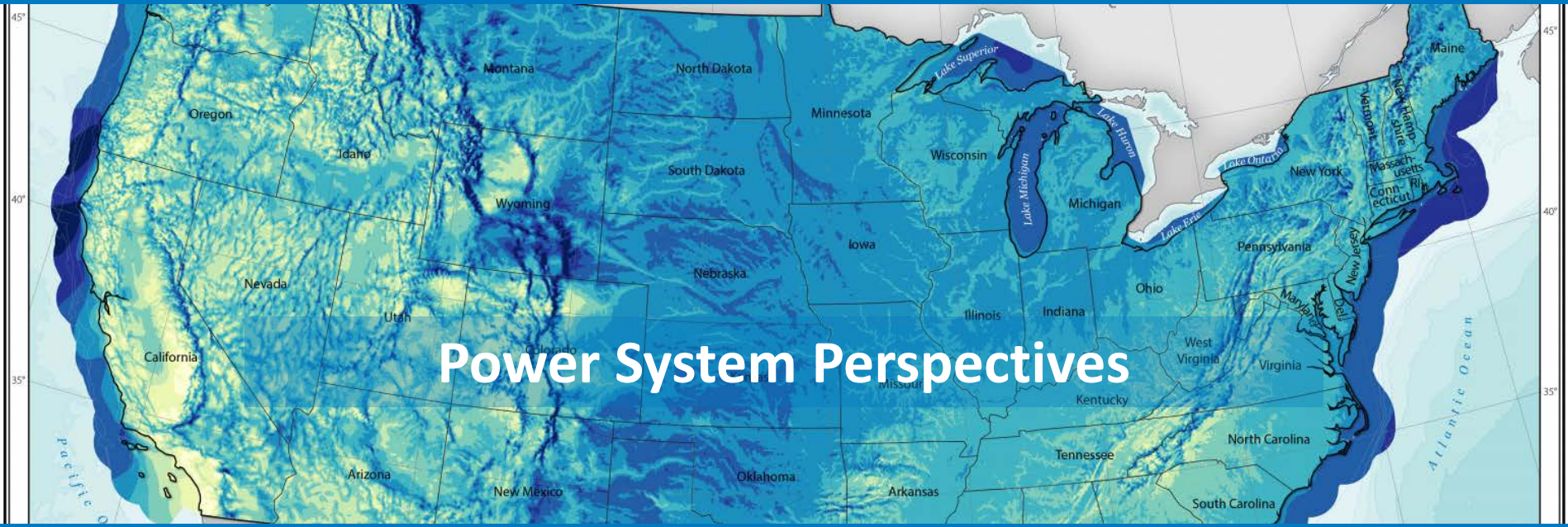
Higher correlation of BCHRRR with EIA-930

HRRR data are taken from the analyses, not the forecasts

Conclusion of Validation Efforts and Appropriate Use of WTK-LED

Without a clearly defined end-use standard for grid integration studies, it is challenging to say what “appropriate use” is, or what improvements would bridge a gap to making a specific atmospheric dataset the gold standard.

Next steps address some of these issues and the earlier five key gaps.



Power System Perspectives

General Workshop Observations From Power System Perspective

- The future of power system planning and operations is now closely tied to the weather.
- Forecasts reduce uncertainty but not variability (nondispatchable system).
- Power system question to be answered drives the specification for the dataset:

  Distributions (e.g., “tails”) and duration are important for resource assessments, icing events, transmission outages, etc; averages matter more for developers/asset owners; integration studies require total production, tails and variability
- Certain time frames are more important (e.g., periods of high net load).
- *Need combined wind/solar/load datasets and validation thereof.*
- Model bias compared to uncertainty important for power datasets.
- Future climate change trends are important, but the first focus must be on recreating historical datasets.

Power System Observations on Wind Dataset Specification

- Development of a specification for atmospheric datasets and methodology for conversion to wind power generation
  - existing parameters and desired requirements include…
    - 2-km grid spatial resolution (mention of need for 1 km)
    - 5 min to hourly average temporal resolution
    - 1-,4-,6-, 24-hour forecasts of wind speed and/or power generation
    - 10+ years of historical data with the above-specified resolution
    - wind data time-synchronous with historical solar and load data, preserving temporal correlations needed to study weather-dependency in high wind and solar power systems
- Need to define acceptable accuracy for power system datasets with above specifications
  - can vary depending on specific power system question and temporal/spatial considerations (e.g., large regional analysis versus impact of specific wind power plant)
  - Error in specific wind plant power output can partially smooth out when averaged over larger areas, but not model biases (analogy to geographic diversity)
- Final validation of datasets should be performed by an organization that is independent of the one that produced them.

Why Do Grid Modelers Want Historical Data?

- To be able to produce time-synchronous, meteorologically consistent wind, solar, and load data (historical load data can be used directly if the modeled wind and solar distributions result in the same overall conditions. Data should represent realistic net load across the use case)
  - Need could be somewhat mitigated if all three could be confidently produced from one source (load needs to be simulated in this situation)
- To be able to perform validation using real wind speed and/or generation data
- To be able to answer questions such as "*how could a low-carbon grid operate during last year's fill-in-the-blank event that caused operators headaches?*"

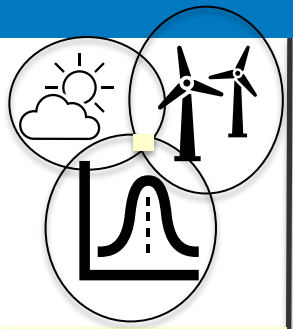
Data Needs for Power Systems Modeling

- Capacity expansion, resource adequacy, extreme events
  - Hourly actual wind **power** data at plant level for as many years as possible
- Production cost modeling:
  - Day-ahead **forecasts**
  - Hour-ahead **forecasts**
  - Real-time **forecasts**
  - 5-min average actual
- Calculation of balancing reserves:
  - Generating multiple sets of hour-ahead forecasts (needed in Monte-Carlo simulations)
  - Generating multiple sets of real-time forecasts (Monte-Carlo simulations).

How To Meet Data Needs

- Datasets based on different weather models
- Quantify the uncertainly associated with **conversion from wind speed to wind power**
- High actual wind power time resolution (5 min at least) to capture wind variability
- Day-ahead and hour-ahead **wind power forecasts**
- Statistical **forecast error models** to capture wind uncertainty
- Validation with actual data
- Databases linked with other public data sources, such as:
  - EIA: EIA 680 (plant data), EIA 923 (plant monthly energy), EIA 930 (hourly for balancing authorities)
  - The United States Wind Turbine Database (USWTDB)
  - Actual wind turbine layout and power curves.

Years of Grid Uses Inform Development of Updated Datasets



Future

Historical

Time-synchronous?

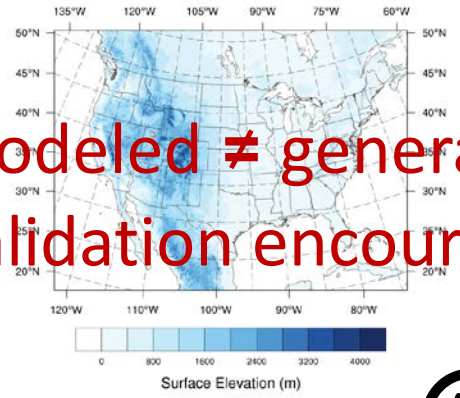
YOU ARE HERE

Set of requirements for use case

Wind and Solar data developed

Grid uses proliferate

Identify core needs for grid use cases



modeled ≠ generation

Validation encouraged

- Technology assessment
- Market research
- Asset utilization
- Energy justice analysis
- Academic thesis
- and many more!

Maintaining Workshop Momentum

Small-to-Medium-Size Next Steps for labs/NREL

- Validate and compare NREL products
- Enhance coordination of existing efforts for solar, wind, and load data between DOE and labs
- Determine value of HRRR bias corrections to supplement WTK-LED
- Define grid-related end uses and prioritization ranking for wind and solar datasets
- Define validation quality standard applicable for defined grid end uses for wind, solar, and load
- Define validation metrics for offshore wind energy, even though we lack operating data
- Extend WTK-LED (particularly 2014 and 2015 to complete time series with WTK-LED and HRRR)
- Release validation data (including BCHRRR) in a user-friendly format
- Conduct stakeholder workshops to define end uses of data for industry, regulators, consultants, and system operators/utilities.

Larger Efforts for labs/NREL

- Develop climate-informed wind and solar datasets
- Create a user-friendly interface for all existing historical and forward-looking wind and solar data; specifically, a one-stop data shop/library of what the labs provide to consultants/industry
- Work with NOAA, the National Weather Service, National Center for Atmospheric Research, and others to leverage/extend their efforts to get the relevant simulations that are needed for grid applications
- Develop DOE's/lab's capability for creating fully public time-synchronous wind-solar-load data with validation against historical data
- Funding Opportunity Announcement for industry to produce data with DOE/labs serving as validators and/or curators.

Participants show interest in investment to get high-quality observational data as lab-adjacent effort

1. Release of industry-grade data usable for validating atmospheric models for grid integration applications
   - There should be existing data provided to power system operators (e.g., PJM, Midcontinent Independent System Operator)
   - Best way to validate against actual generation at plant level?
   - Not clear what missing incentive is for industry to release, but workshop provided some ideas for how to better incentivize (tie data release standards to signing interconnection agreement at Federal-Energy-Regulatory-Commission-regulated independent system operators?)
2. Investment in network of meteorological towers
   - Current observational data is limited and often not at wind power hub heights
3. Investment in Light Detection and Ranging (LiDAR) wind speed sensors

Requires coordination with entities like Independent System Operators and wind generation operators that have this data

Unknown cost; suggested by multiple participants at workshop

Thank You

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