

GRIDLAB PRESENTS:

WEATHER DATASETS FOR POWER SYSTEM MODELING IN INDIA

Join GridLab in collaboration with RMI, Tata Power, National Renewable Energy Laboratory (NREL), Electric Power Research Institute (EPRI), and Vaisala, for a release of weather datasets that can enable analysis of power systems with variable renewable energy resources in India.

WEBINAR

THURSDAY SEPTEMBER 4TH | 8:30 PM PDT

FRIDAY SEPTEMBER 5TH | 9:00 AM IST

GridLAB

Moderator



Dr. Priya Sreedharan
Senior Program Director, GridLab

Panelists



Dr. Praveer Sinha
CEO, Tata Power



Sonika Choudhary
Principal, RMI



Dr. Pascal Storck
Head of Technology,
Vaisala Xweather
Renewable Energy



Prateek Joshi
Researcher, National
Renewable Energy
Laboratory (NREL)



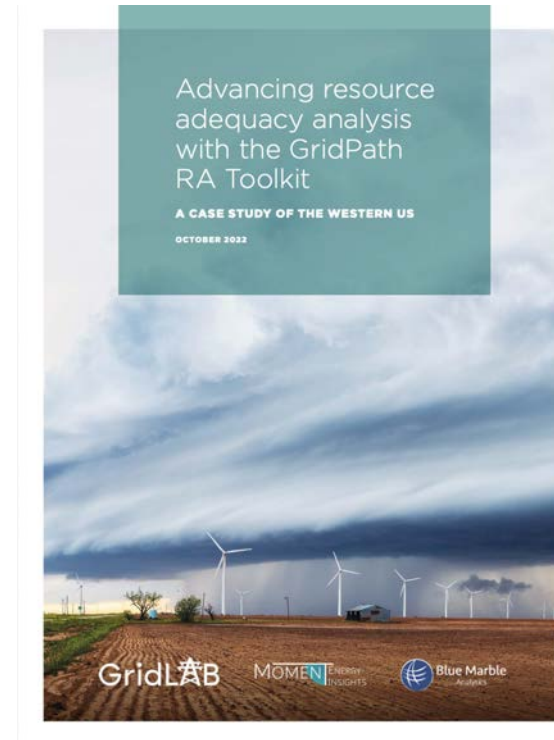
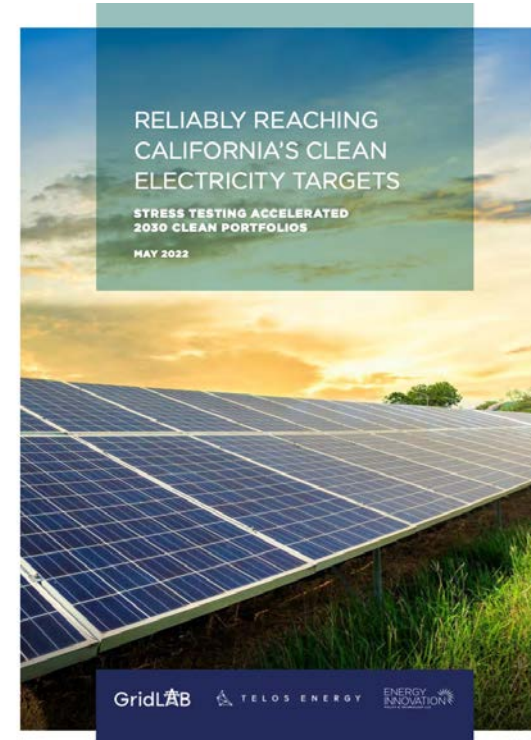
Dr. Justin Sharp
Senior Principal Technical
Leader, Electric Power
Research Institute

GridLAB

GridLab is a non-profit technical assistance organization that supports a transition to a reliable, low-carbon, and affordable grid.

GridLab's program areas include the bulk and distribution system with a heavy focus on resource adequacy.

GridLab is dedicated to advancing accessibility to robust modeling methods, tools and datasets that can support reliable clean power systems.



Clean Energy Future



Smart Transmission



Rethinking Reliability



Modernizing the Grid

[Gridlab.org](https://gridlab.org)

Agenda for the webinar

Formal presentations: 1 hour	
Opening remarks	Dr. Praveer Sinha, Tata Power
<u>Overview of India grid study</u>	Sonika Choudhary, RMI
<u>Importance of weather datasets for power system</u>	Dr. Justin Sharp, EPRI
<u>Raw weather datasets for India (5 km by 5km)</u>	Dr. Pascal Storck, Vaisala
<u>Processed datasets for representing RE profiles for India</u>	Prateek Joshi, NREL
<u>Overview of the GridLab website</u>	Dr. Priya Sreedharan, GridLab
Q&A Session: 30 minutes	Questions can be typed in Q&A portal

Overview of India Grid Study

Sonika Choudhary, Principal, RMI India Program

Dr. Priya Sreedharan, Senior Program Director, GridLab



Context: Power system planning is rapidly changing

Past approach with thermally dominated systems

Main drivers were peak demand and annual energy

Heuristic approaches (LDCs and 15% PRMs) common

Reliability impacted mainly by summer peak demand

Systems with high renewables and storage

Net load rather than gross load drives the system need and determines dispatch

Storage is playing an increasing role — currently moving energy within a day and over the long term may move energy across seasons

Variability of renewables is a risk planners have to deal with (across a day; across seasons; year to year)

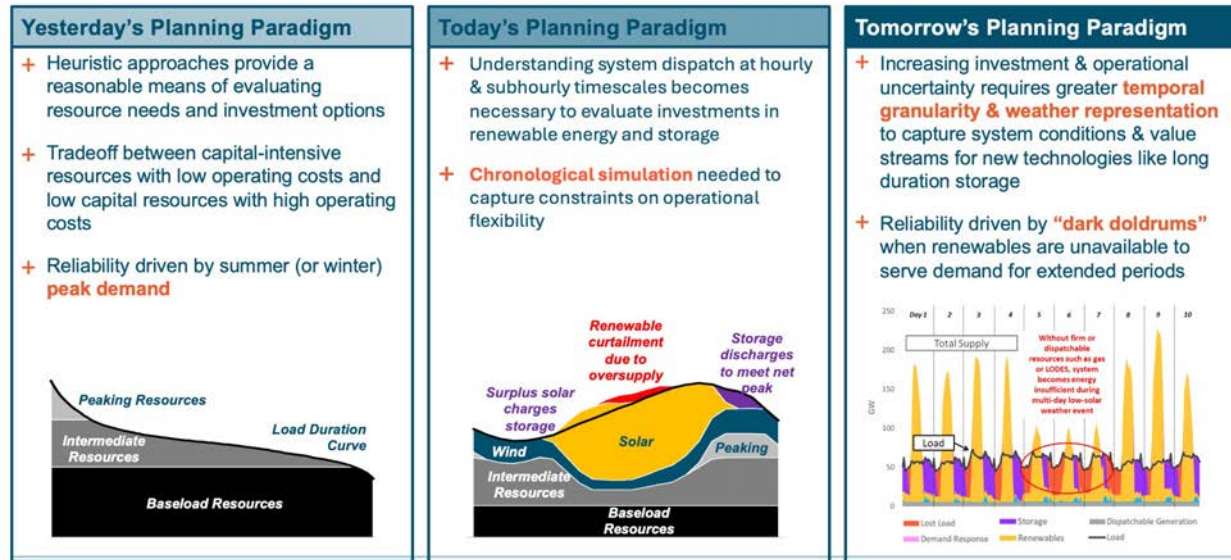


Image courtesy of E3, Utility Dive, 2020, "To build a zero-carbon grid, we first need to model it accurately"

India Grid Study: context and objectives

Context

India has a power goal of 50% non-fossil capacity by 2030 (already reached in 2025!) and a net zero target by 2070

Confidence in the reliability of a high renewables system is essential to sustain and advance these targets

Weather fluctuations and impact on renewables availability, especially wind, is a concern

Objectives

The study aims to identify the feasibility of different paths toward meeting 60% to 80% clean power milestones in 2040 with an emphasis on understanding the reliability impacts

- Identify a set of low-risk solutions on resource choices including the tradeoffs between them
- Contribute to the evolving planning sector with datasets, tools, methods that can be used by stakeholders
- Focus on core building blocks, especially on the **weather datasets** and **load forecasting** fronts
- Help understand the role of coal as the system moves towards more renewables and storage
- Understand how uncertainty in load growth, technology/fuel costs, weather, outages affect performance

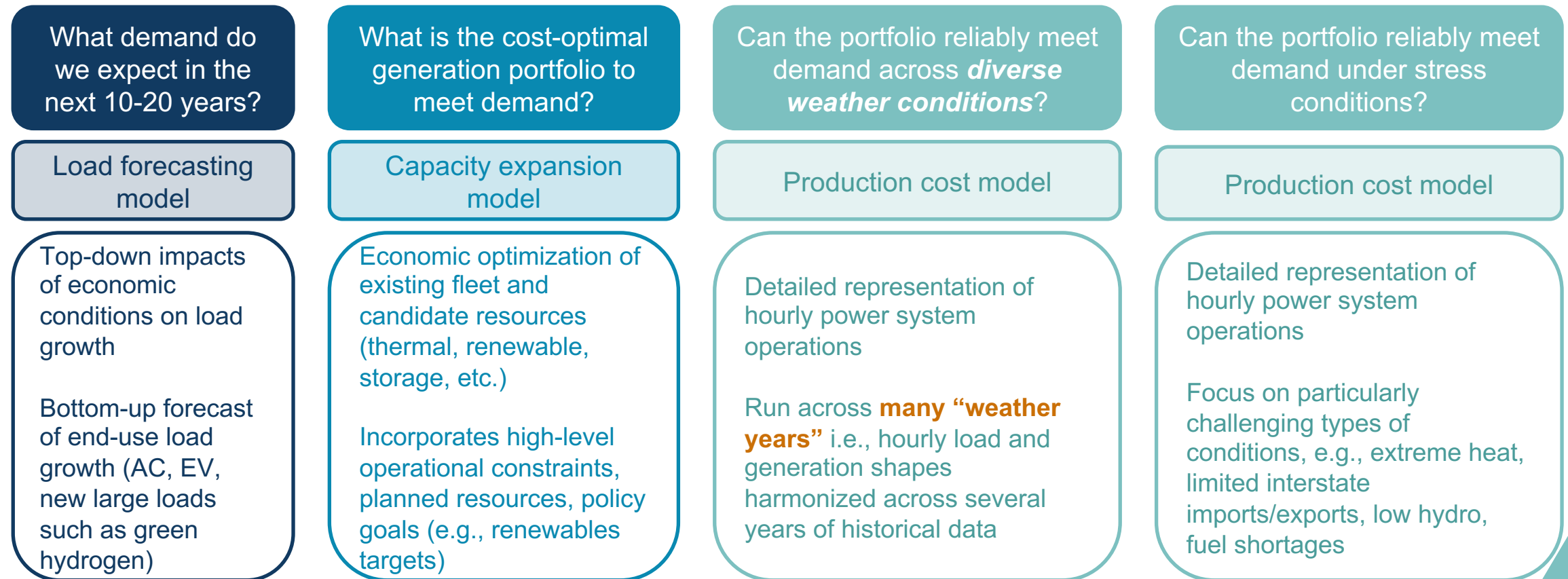
Lead
Organizations



Key
Partners



Power system modeling steps and reliability testing across multiple weather years



Summary elements of the project

Multi-step comprehensive analysis that addresses different power system generation planning steps

Core components of the study:

Multiple weather year raw data and model ready inputs to inform renewables (solar and wind) hourly shapes - releasing today!

Multiple demand scenarios and varying load shapes

Assessing reliability through a “stress testing” approach that evaluates multiple portfolios across many weather years and grid stress factors



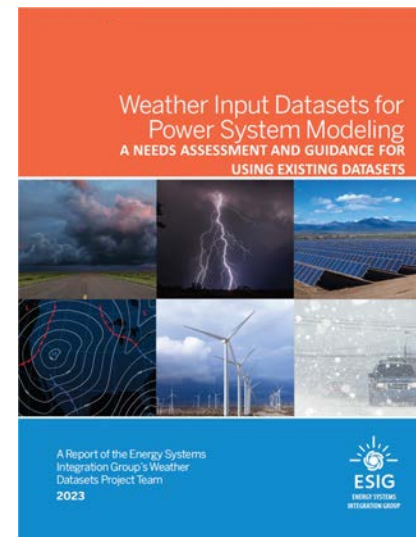
Weather Datasets for Power System Modeling in India

Why are robust weather datasets needed?
What is the definition of robust?
What are the common pitfalls and challenges?



Justin Sharp
Senior Principal Technical Leader

GridLab Webinar
September 4 (US)/September 5 (India)

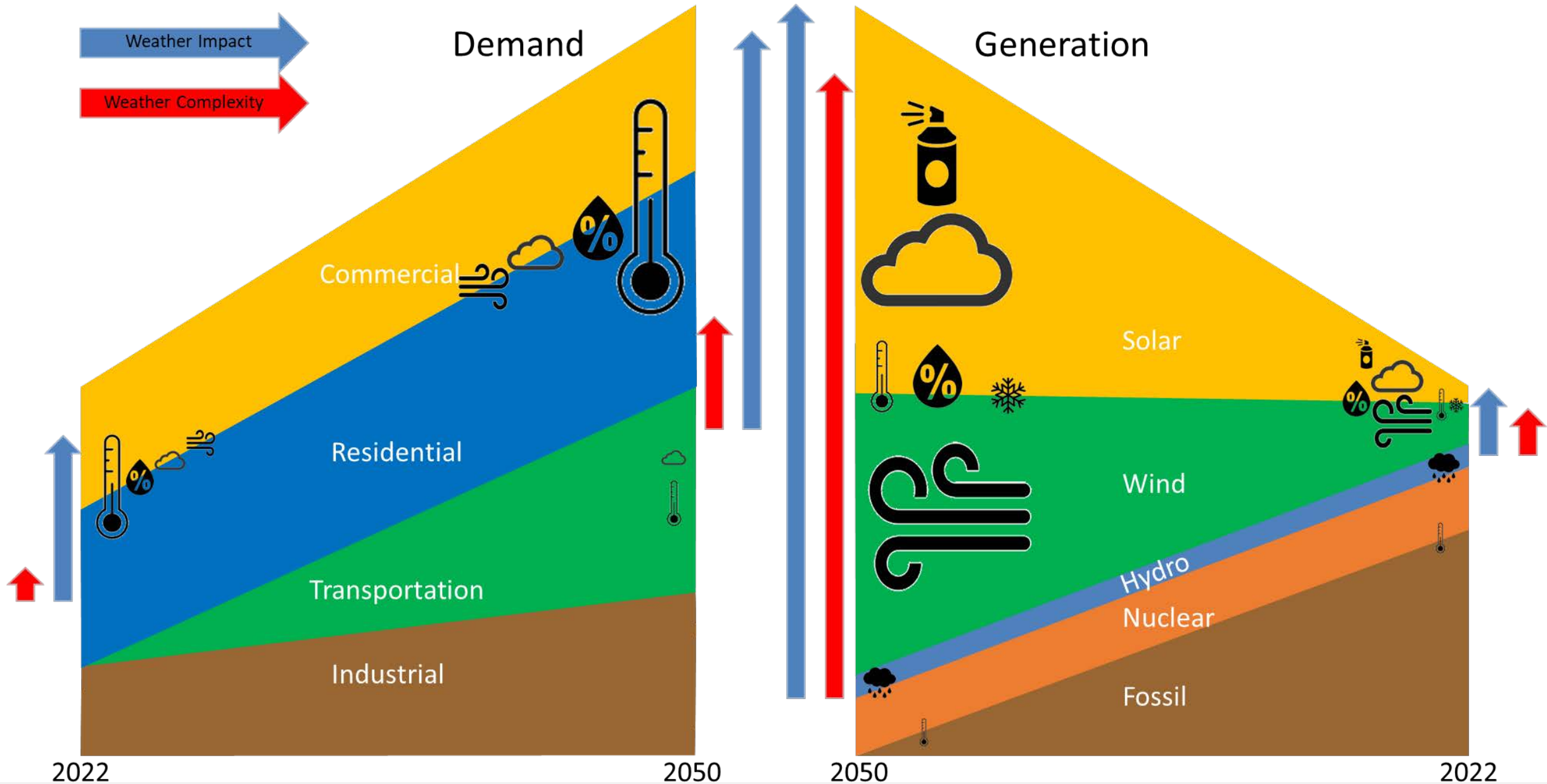


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[landing page](#)

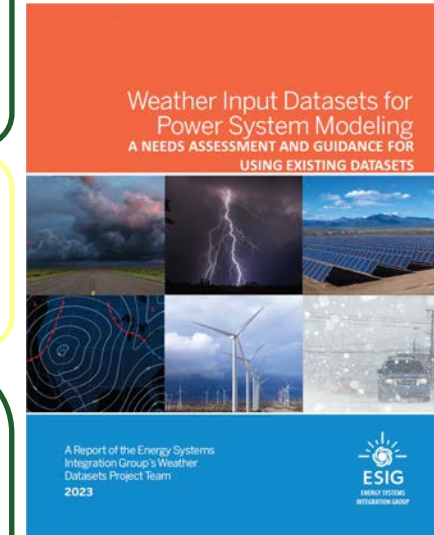
The Evolving Energy – Weather Nexus



The Main Attributes of Time Series Data Necessary to Meet General Power System Modeling Needs

Source: ESIG Weather Data for Power System Planning
<https://www.esig.energy/weather-data-for-power-system-planning/>

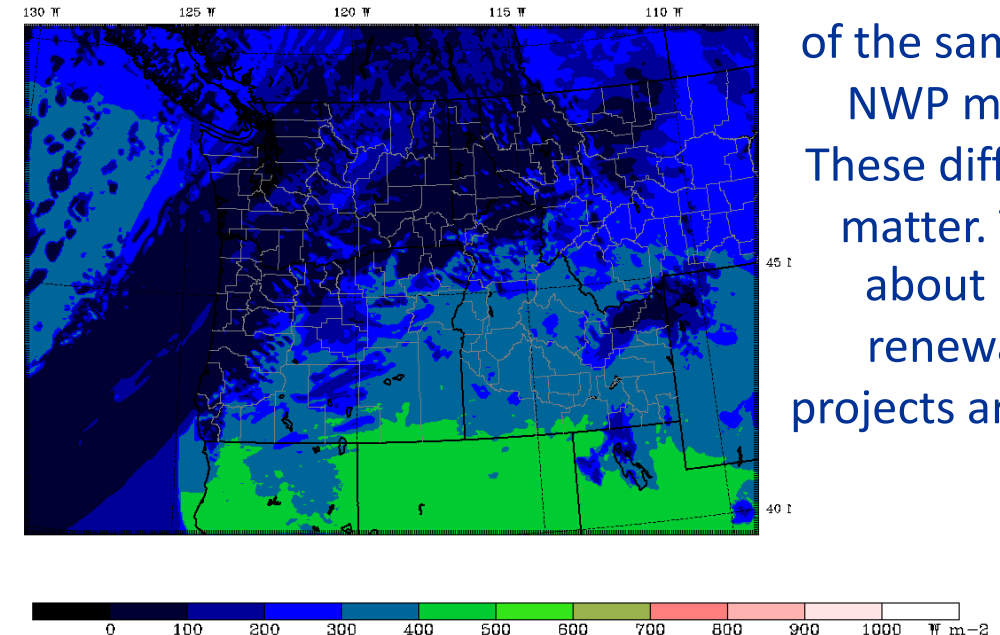
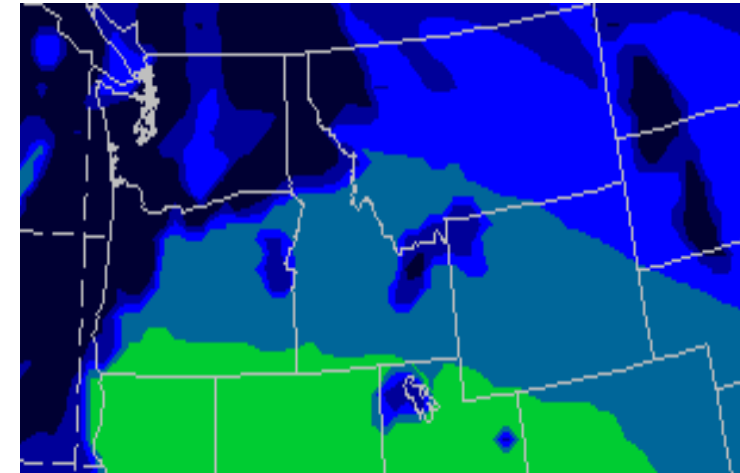
Including the necessary variables	Include the necessary variables at sufficient spatio-temporal resolution and accuracy to reflect actual conditions that define the generation potential at current and future wind/solar sites and temperature at load centers
Covering multiple decades with ongoing extension	Cover multiple decades with consistent methodology and be extended on an ongoing basis to capture the most recent conditions and allow climate trends to be identified
Coincident and physically consistent	Are coincident and physically consistent, in space and time, across weather variables
Validated	Are validated against real conditions with uncertainty quantified
Documented	Are documented transparently and in detail, including limitations and a guide for usage
Periodically refreshed	Are periodically refreshed to account for scientific and technological advancements
Available and accessible	Publicly available, expertly curated, and easily accessible



Typical Weather Data Sources Used in Power System Modeling

When and Why Are Synthetic Data Needed?

- Load and Hydro
 - Typically, from observations
 - Sometimes from models for consistency
 - Centralized load centers and hydro basins
- Wind and solar
 - Rapid variability in time and space
 - Observations are always best but...
 - Usually not available esp. for future project locations & QA/QC problems
 - What about for future project locations?
 - Synthetic data from models or data derived from satellite remote sensing usually used
- Different sources are often used
 - e.g. WIND Toolkit for wind, NSRDB for solar, observations for load and hydro



All models are not created equal!
Dec 5, 2023 solar from outer (36 km; similar to ERA5) and inner (4 km; similar, to Vaisala data) nests of the same WRF NWP model. These differences matter. Think about how renewable projects are sited!

	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

Are Today’s Datasets Robust?

The data currently available to the sector (on left) is not adequate for the tasks at hand. No single dataset meets all the needs. Mixing and matching causes physical consistency issues.

TABLE 2
 Summary of Current Power System Modeling Weather Input Data Sources

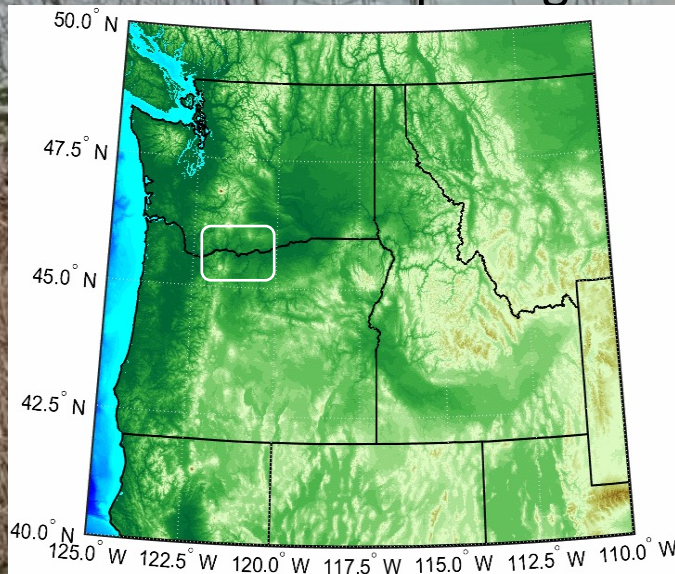
Summary of the most applicable datasets globally that are (or can be) used to provide weather inputs for power system analysis tasks, especially for providing estimate of site-level generation, and concurrent weather-driven load and generation outage risks. The degree to which the needs of each column heading are met is estimated with color coding. See documentation for each dataset for all details. Footnotes on next page. P76, main report.

Source: Energy Systems Integration Group

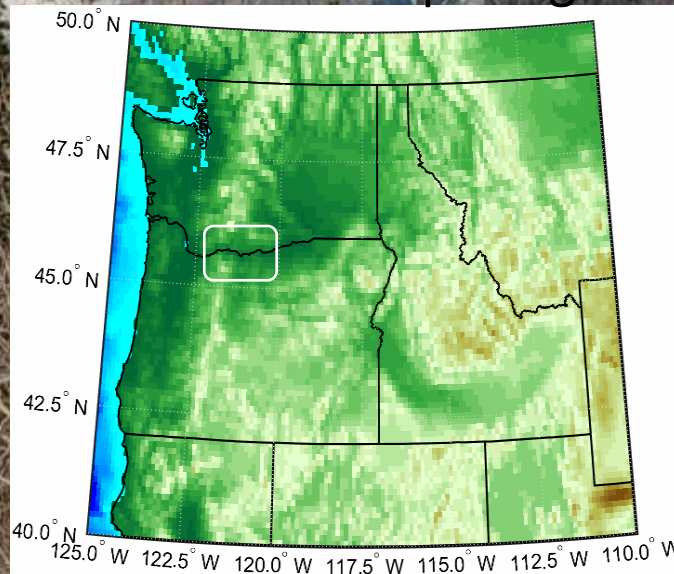
Model Space is NOT Physical Space



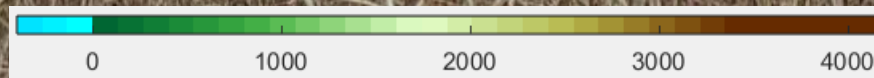
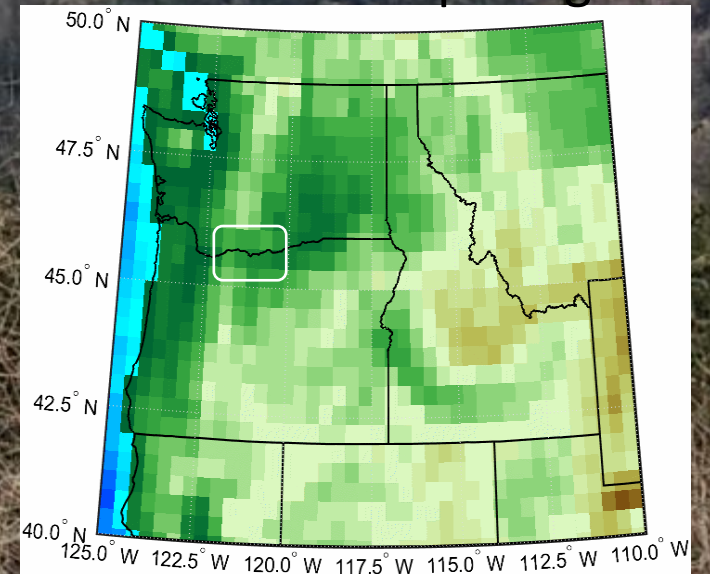
1 km Grid Spacing



9 km Grid Spacing

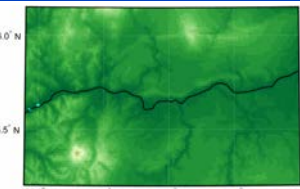


30 km Grid Spacing



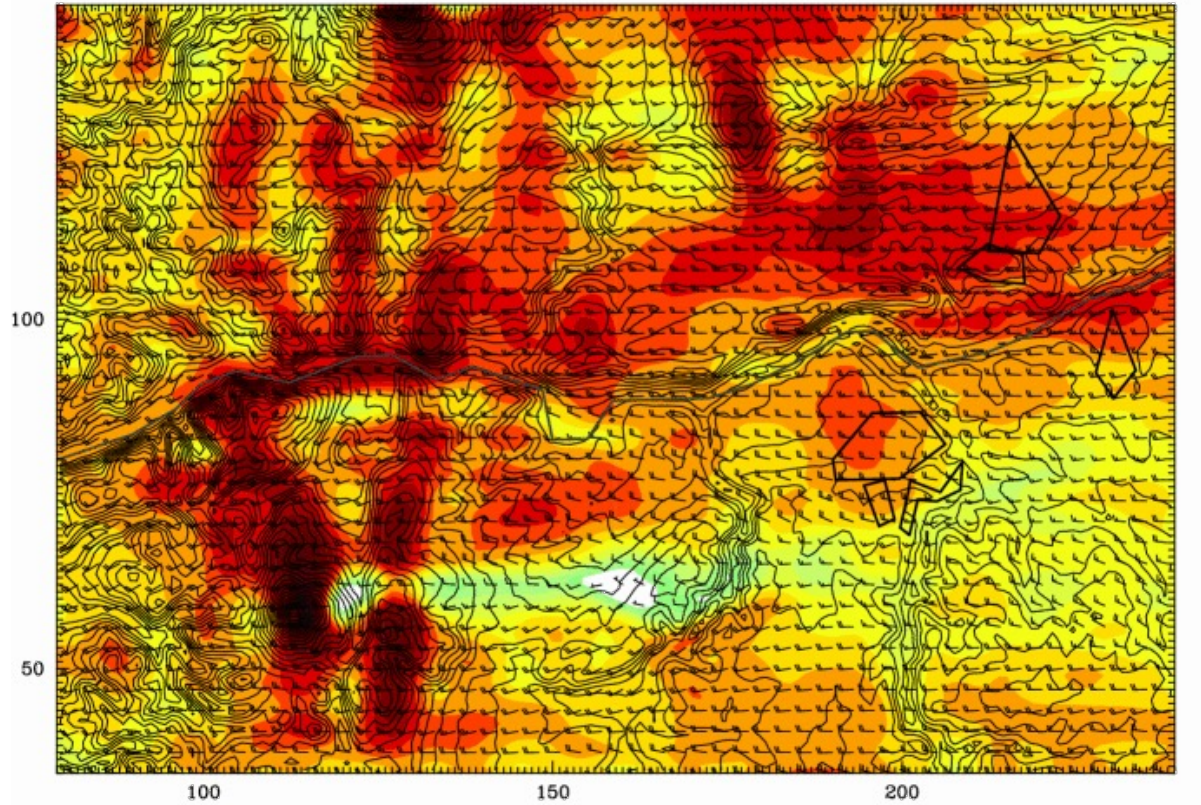
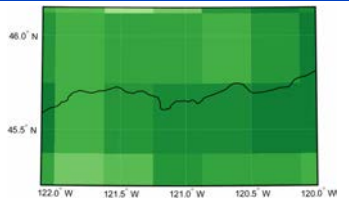
Model Space is NOT Physical Space

All Models are Always Wrong, Some Are Useful

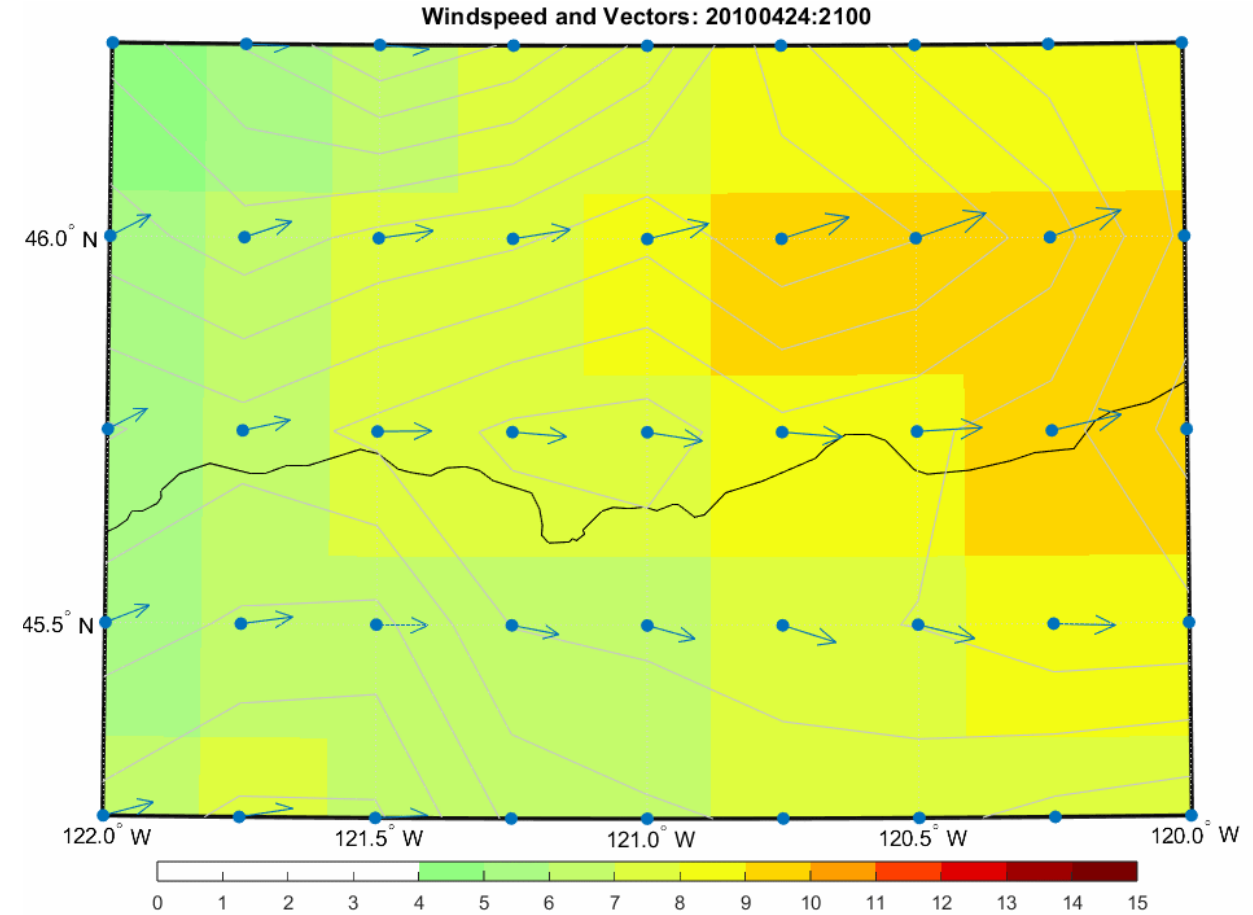


1KIN WRF GEORGE RESEARCH SIMULATION
Fcst: 9.00 h

Init: 1200 UTC Sat 24 Apr 10
Valid: 2100 UTC Sat 24 Apr 10 (1400 PDT Sat 24 Apr 10)



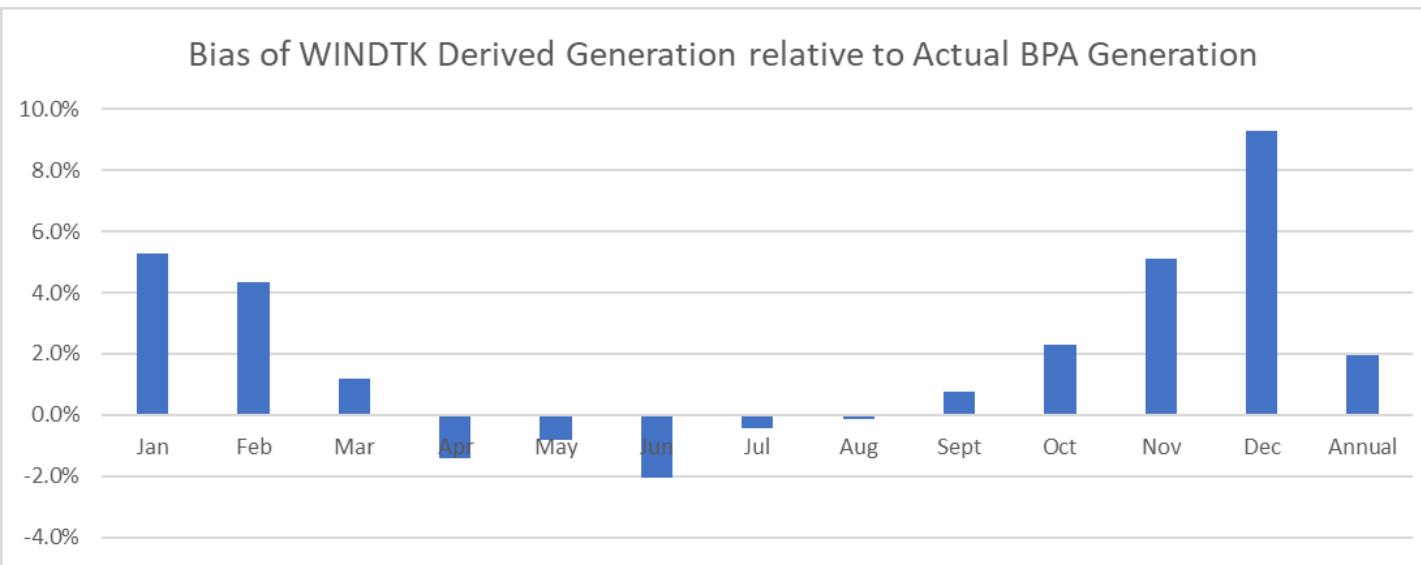
Model Info: V3.0 No Cu YSU PBL Ferrier Ther-Diff 1.0 km, 30 levels, 6 sec
LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor



Which is Best? Validation and Uncertainty Quantification are Essential

Use Case Specific Validation and Uncertainty Quantification

- We must validate according to the use case.
 - E.g. For RA, the distributions, and especially the tails, matter more than the averages; the distribution of coincident tail events must be close to reality
 - E.g. For integration studies, wind ramp artifacts must be removed



Bias correlated with high risk events ↗:

High bias in WIND Toolkit simulated winds is correlated with high load events due to regional mesoscale meteorology
Tail event deviations can lead to >7x bias in model vs actual.
e.g. BA wide wind gen. estimates of 23% vs 3% in reality.

2000-2023 ERA5 Average 1-h Absolute Wind Speed Change (m/s) by Month & Hour of Day

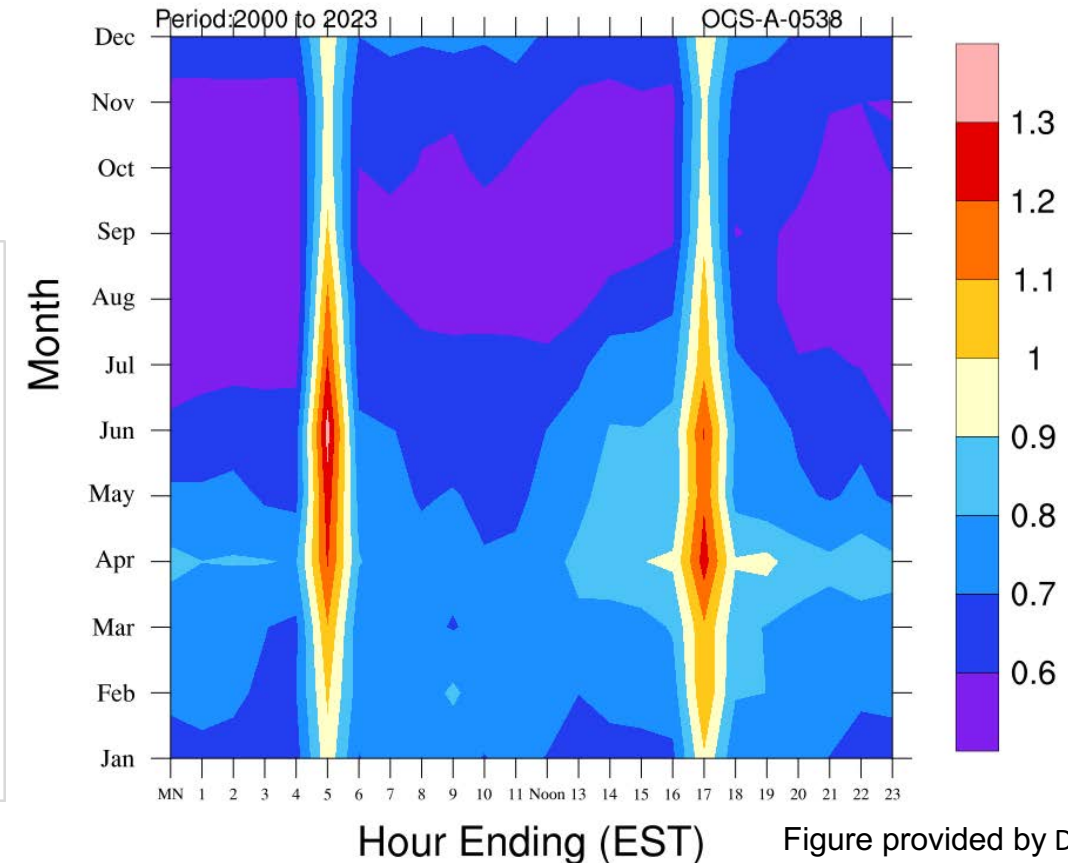


Figure provided by Dr. John Zack, MESO Inc. and used with permission

Assimilation Artifacts ↗:

This is among the list of known problems listed on the ERA5 web page...but who has time to read the manual or footnotes?

Low Hanging Fruit for Validation and Uncertainty Quantification

- Comprehensive industry wide data transparency and sharing is required: Met., generation, and availability data
 - Little proprietary value per site but a tremendous untapped asset if made public across all generators
- This will enable validation and UQ of synthetic datasets which is imperative for valid application. Ground truth data is also key to the model improvement process
- ERCOT is leading the way. Others should follow ASAP
 - Voluntary adoption preferred to legislation/regulation.



User Knowledge/Education

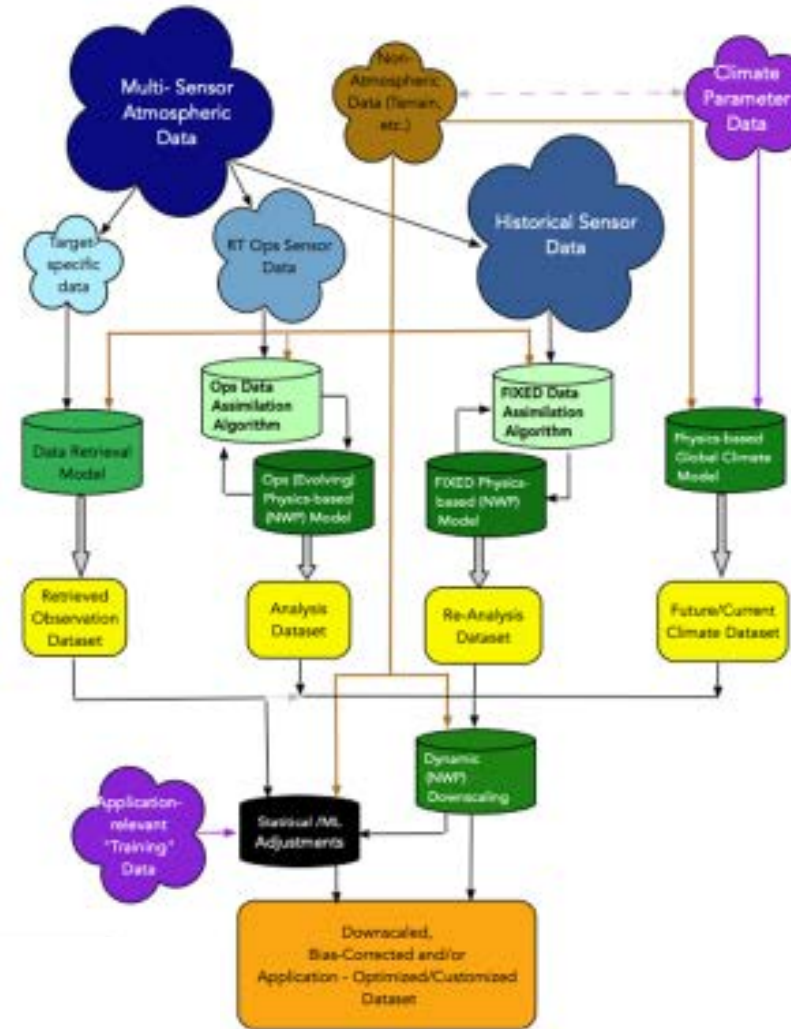
Overview of the Current World of Datasets for Power System Planning

❑ Wide Range of Methods to Construct Datasets

- **A few fundamental types of approaches**
- Enormous number of significant variations within types

❑ Therefore: Wide Range of Datasets Exist

- **Typically have very different attributes depending on how they were constructed**
- Consistency of data attributes (e.g. spatial/temporal correlations) between datasets should not be assumed
- **Critical need to evaluate comparative performance on parameters/scales important to specific applications**



Slide courtesy of:



Used with permission.

**It's complicated! Do our best with the available resources!
Above All, Understand the Inadequacies and Limitations**

Creating the weather data sets for power system modeling in India

Pascal Storck, Ph.D.
Webinar | September 5, 2025

Weather is constantly changing. Weather intelligence and forecasting turn a challenge into an advantage.

We have provided wind and solar weather data and energy services to the India market for over 15 years



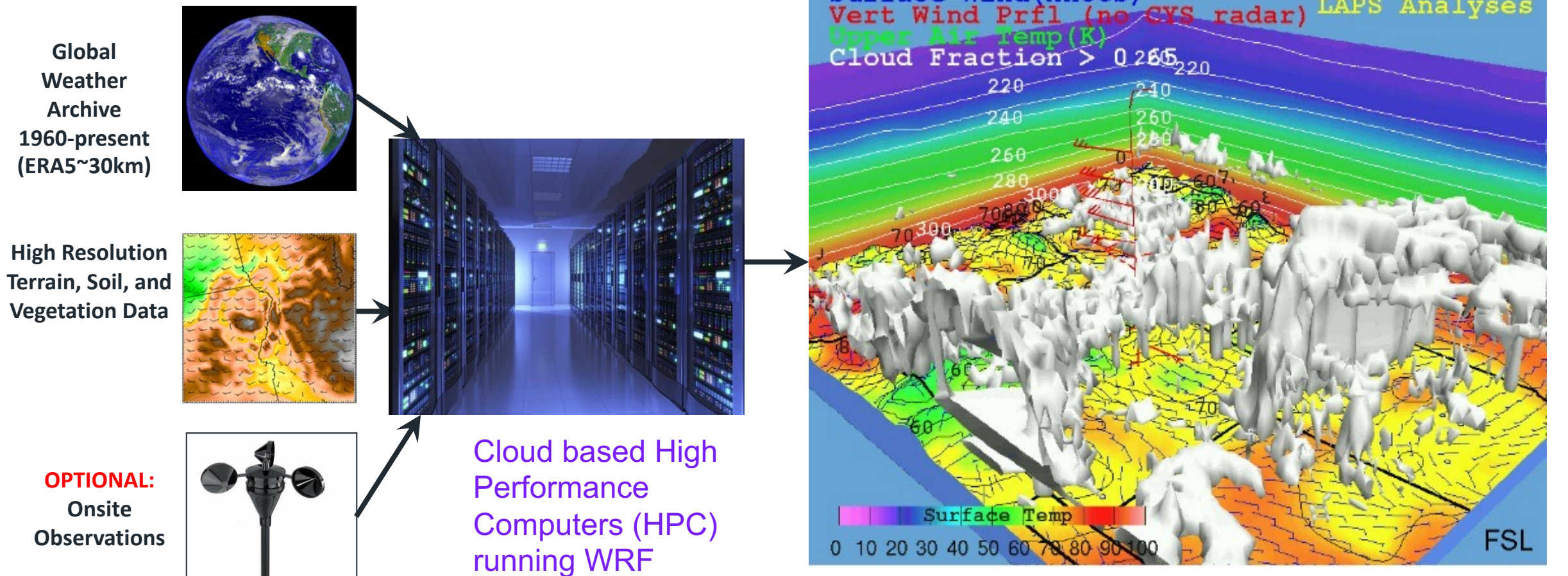
A tale of two technologies

**Wind and Solar – each have
unique weather challenges**

**Part 1: Creating the wind data
using an NWP approach**



Wind: How we made it: Numerical Weather Prediction (NWP)



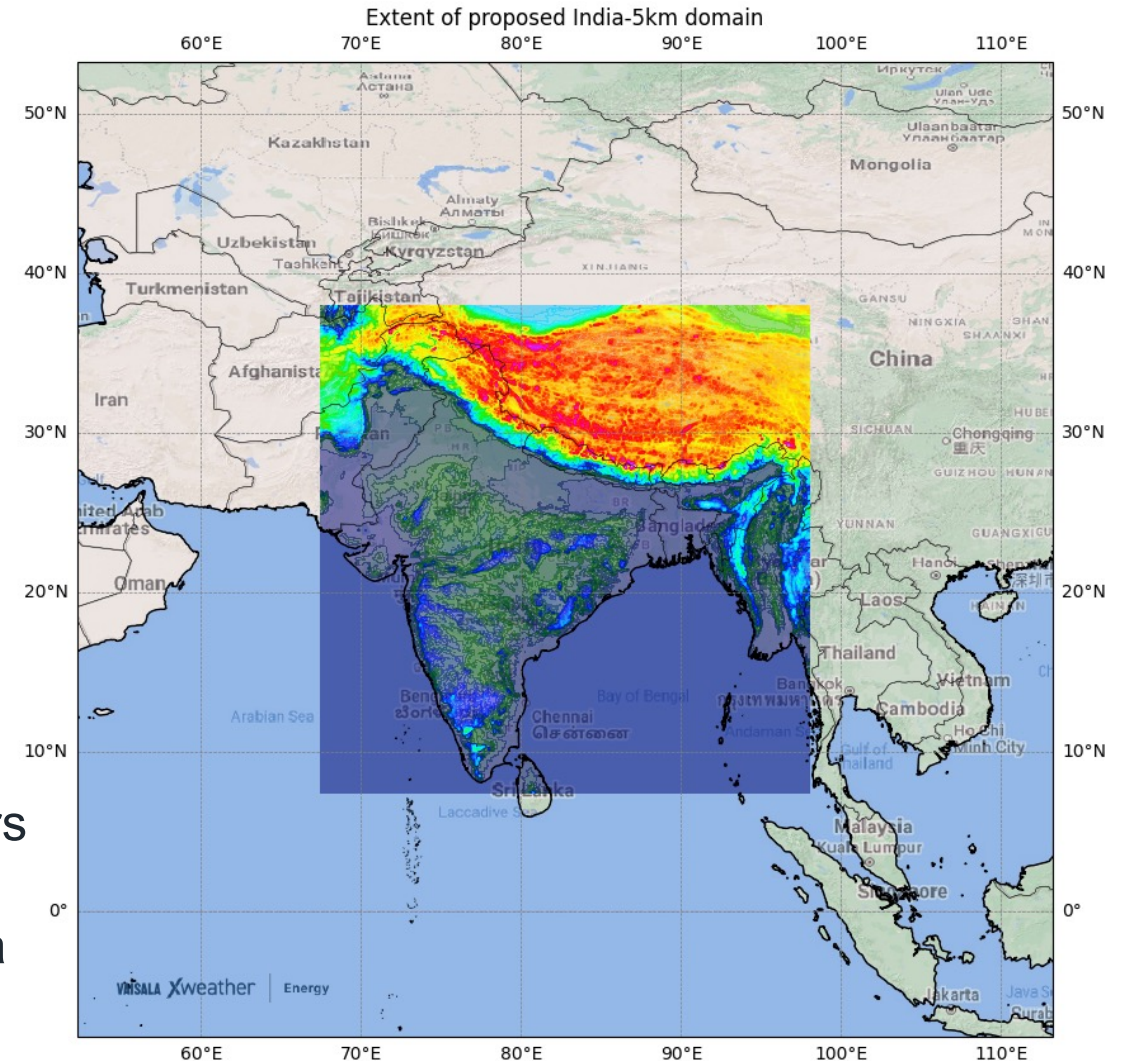
Models the full 4-dimensional motion, thermodynamics, cloud evolution, etc. at 30 second timestep resolution

Wind: How we made it: the details

WRF MODEL SPECIFICATIONS

NWP model and version:	WRF version 3.9.1
Boundary conditions inputs	ERA5
Length of simulation:	10 years, Jan 2014 – Dec 2024
Horizontal Resolution:	5km
Modeled Saved Vertical Levels:	10, 28, 88, 161, 247, 351, 500: mAGL
Interpolated Vertical Levels:	80, 100, 120, 140: mAGL
Temporal Resolution:	15-min
Area Covered:	920471 km ²
Dimensions:	3242.2 km x 3370.8 km
East boundary:	97.3°
South boundary:	8.0°
West boundary:	68.2°
North boundary:	37.5°

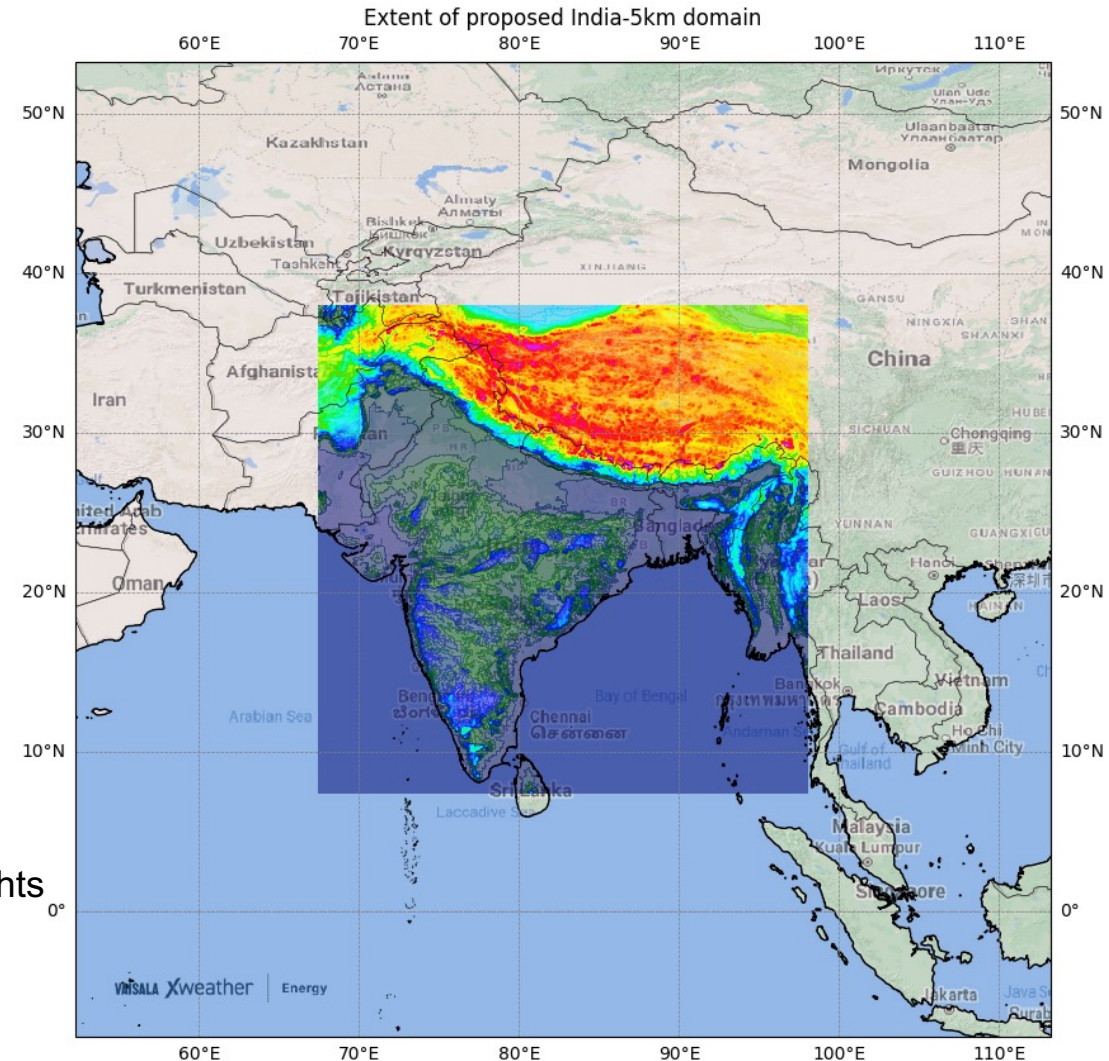
- 10 years of simulation required 260 simulations
- Each simulation was 15 days long with ~24 hours of spin-up and 14 days of saved output.
- "Temporal Seams" aligned at 4:30 am local India time – a "quiet time" on the grid.

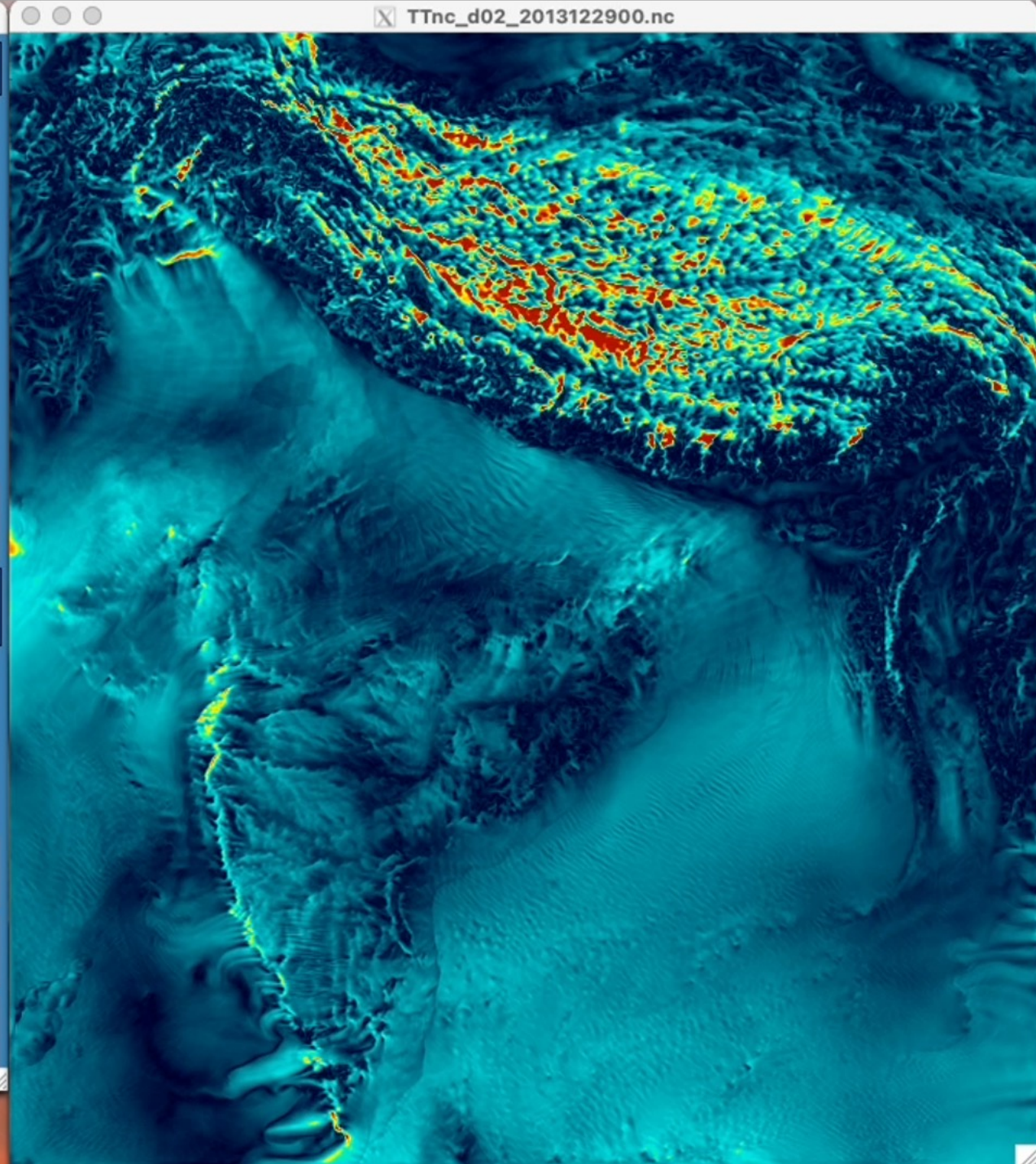
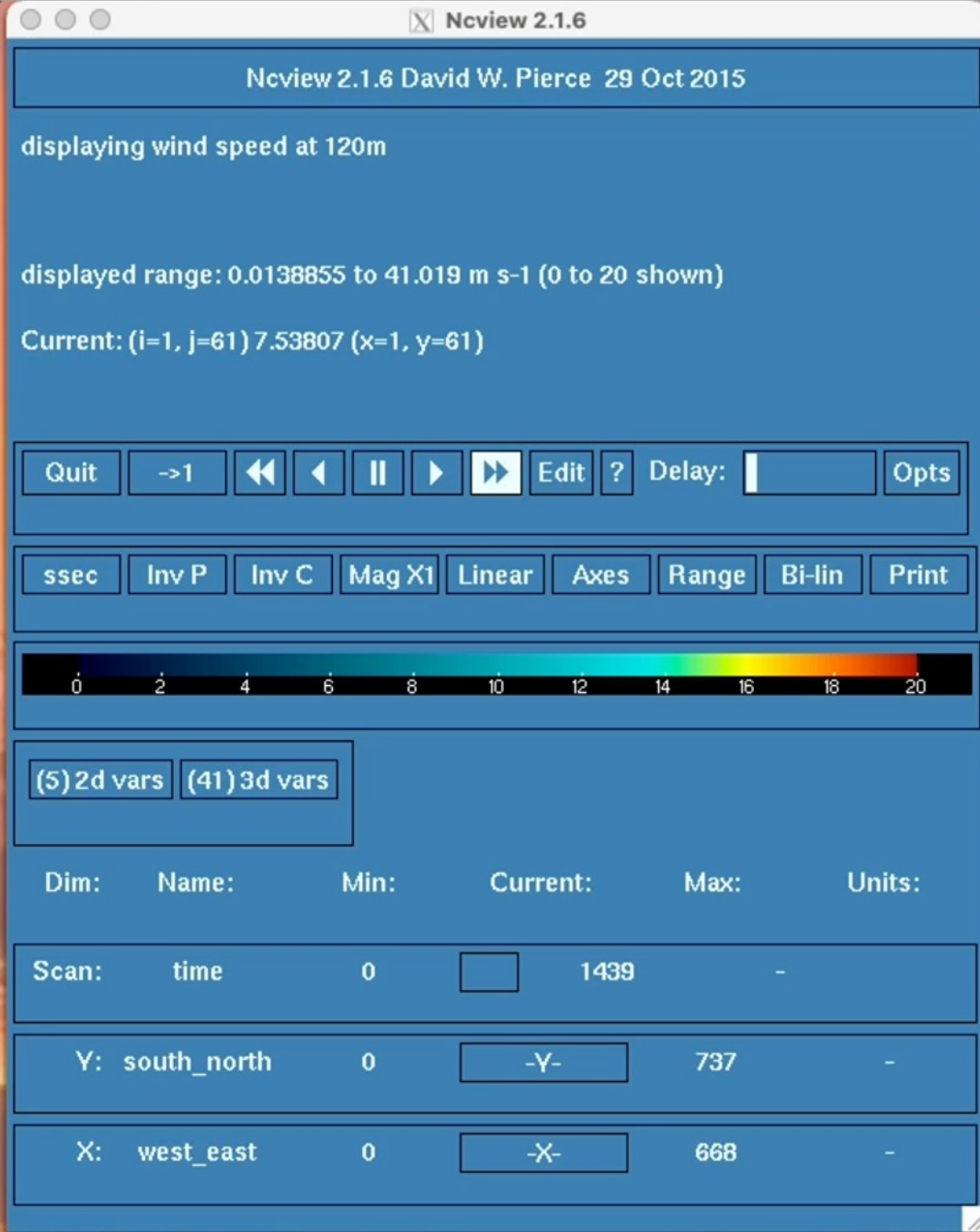


Wind: What is available to download

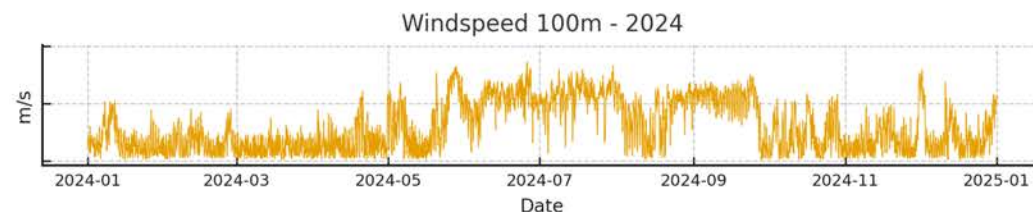
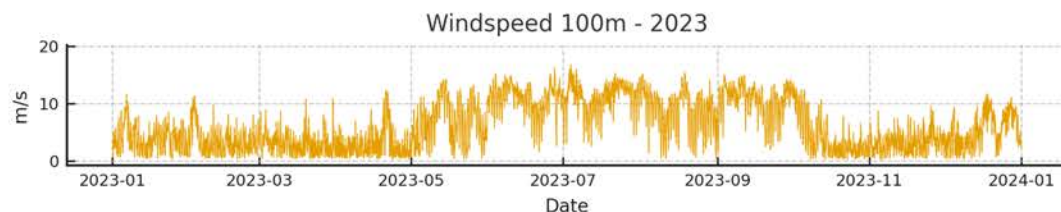
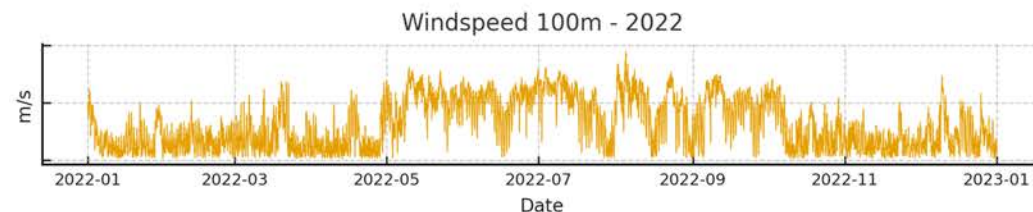
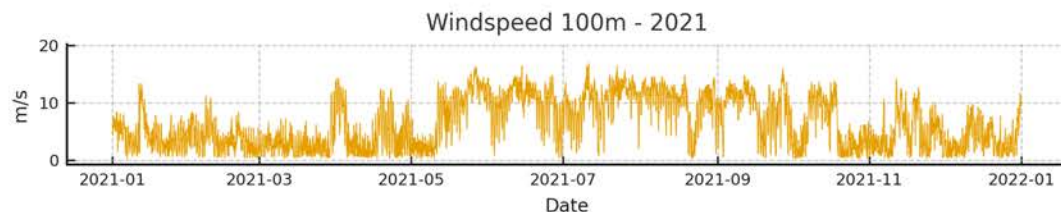
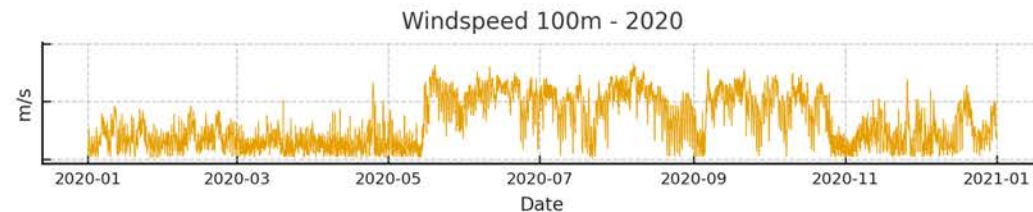
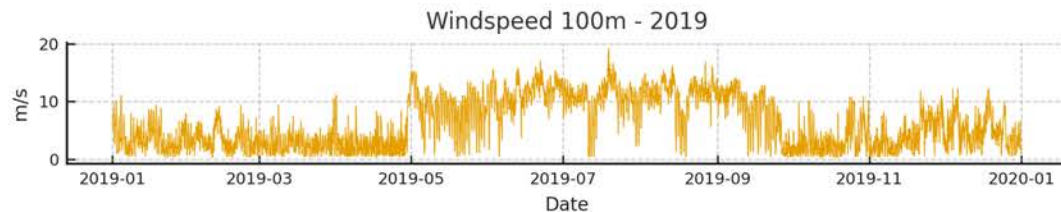
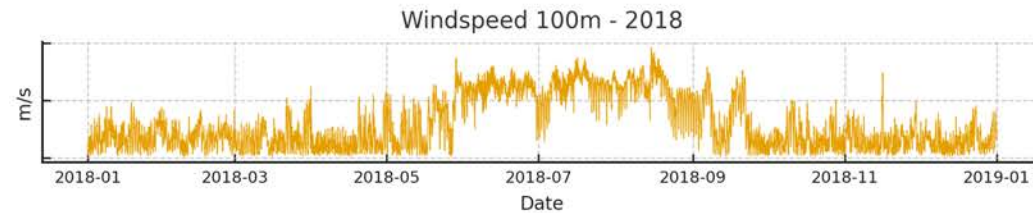
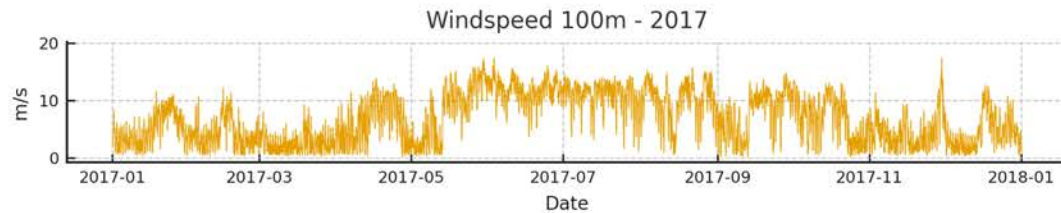
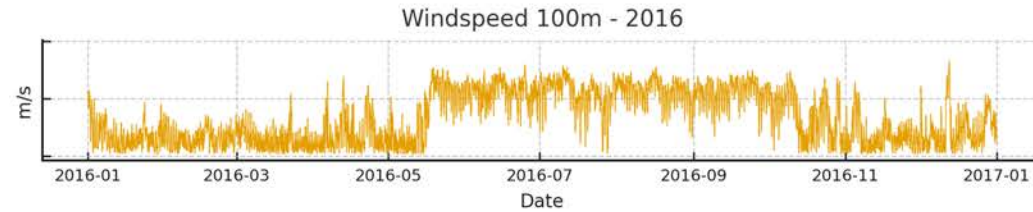
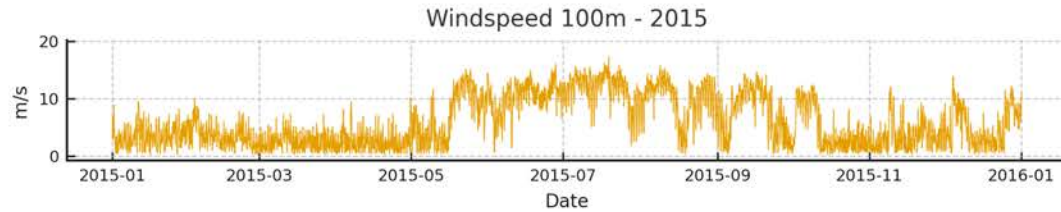
Every 15 minutes for 10 years on a 5km by 5km grid:

- Single level - surface or near surface.
 - Longwave down_0m
 - precipitation_0m
 - pressure_0m
 - Sensible heat flux_0m
 - Shortwave down_0m (aka GHI)
 - Specific humidity_2m
 - Air temperature_2m
 - Wind speed_10m
 - Wind direction_10m
- Multi-level
 - Wind speed_@XXm
 - Wind direction_@XXm
 - Air temperature_@XXm
 - Air density_@XXm
- Multi-level variables are at model levels and interpolated to common hub heights
 - Model levels – 28m, 88m, 161m, 247m, 351m, 500m,
 - Interpolated – 80m, 100m, 120m, 140m





10 years of 100m wind speed at one location (every 15 minutes)

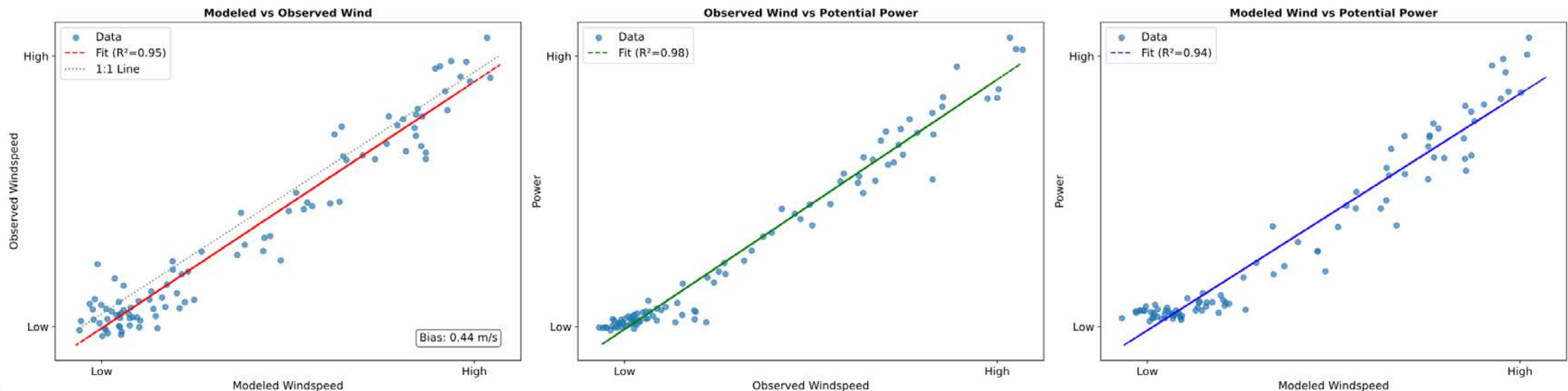


Wind: Light validation: 10 locations

Observed wind speed was 5.5 m/s on average.
Modeled wind speed was 5.6 m/s on average.
Standard deviation of differences was 9%.

Ability of modeled wind speed to explain monthly power was almost as good as on-site met towers.

On-site met towers R-squared of 0.89
Modeled data R-squared of 0.86



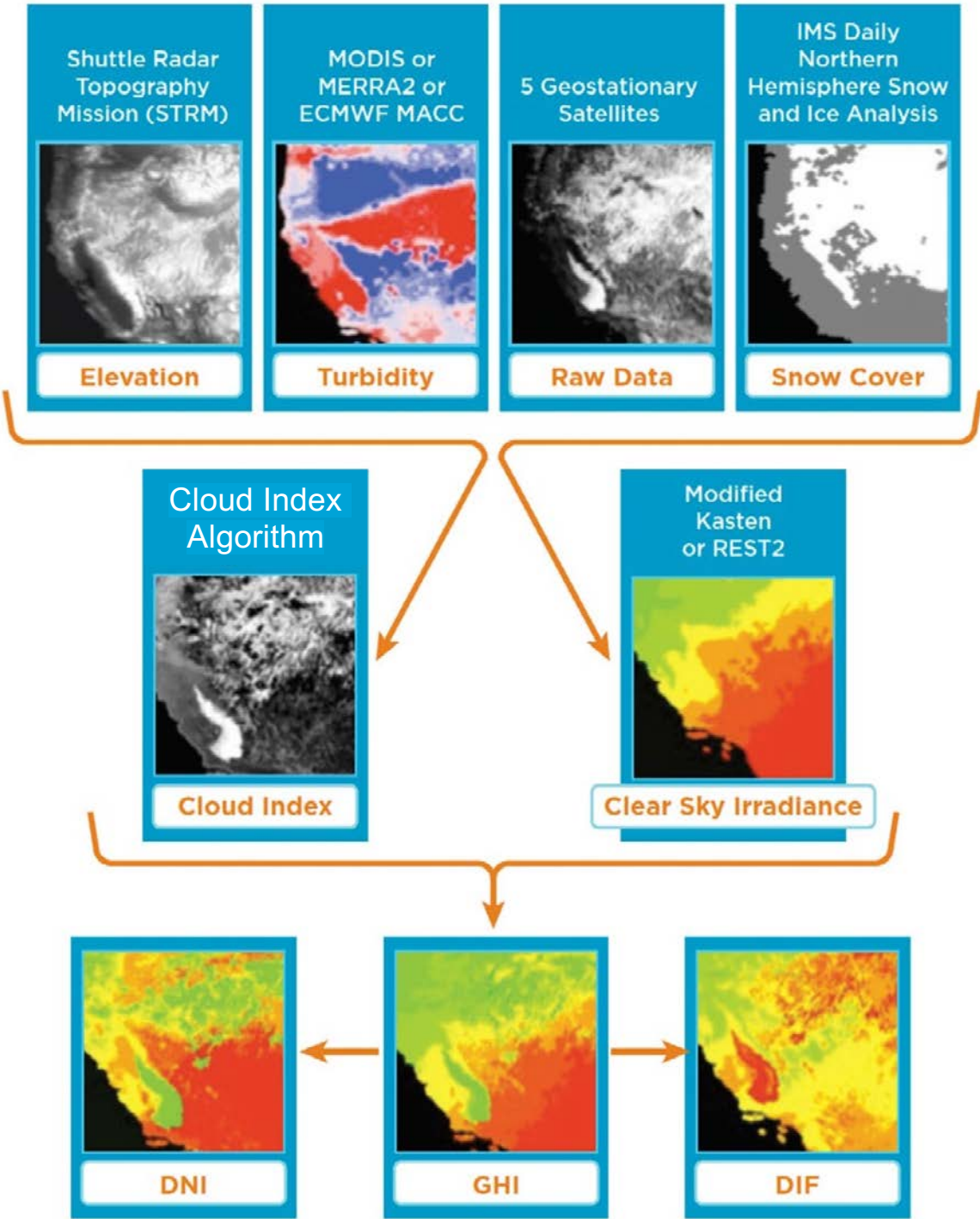
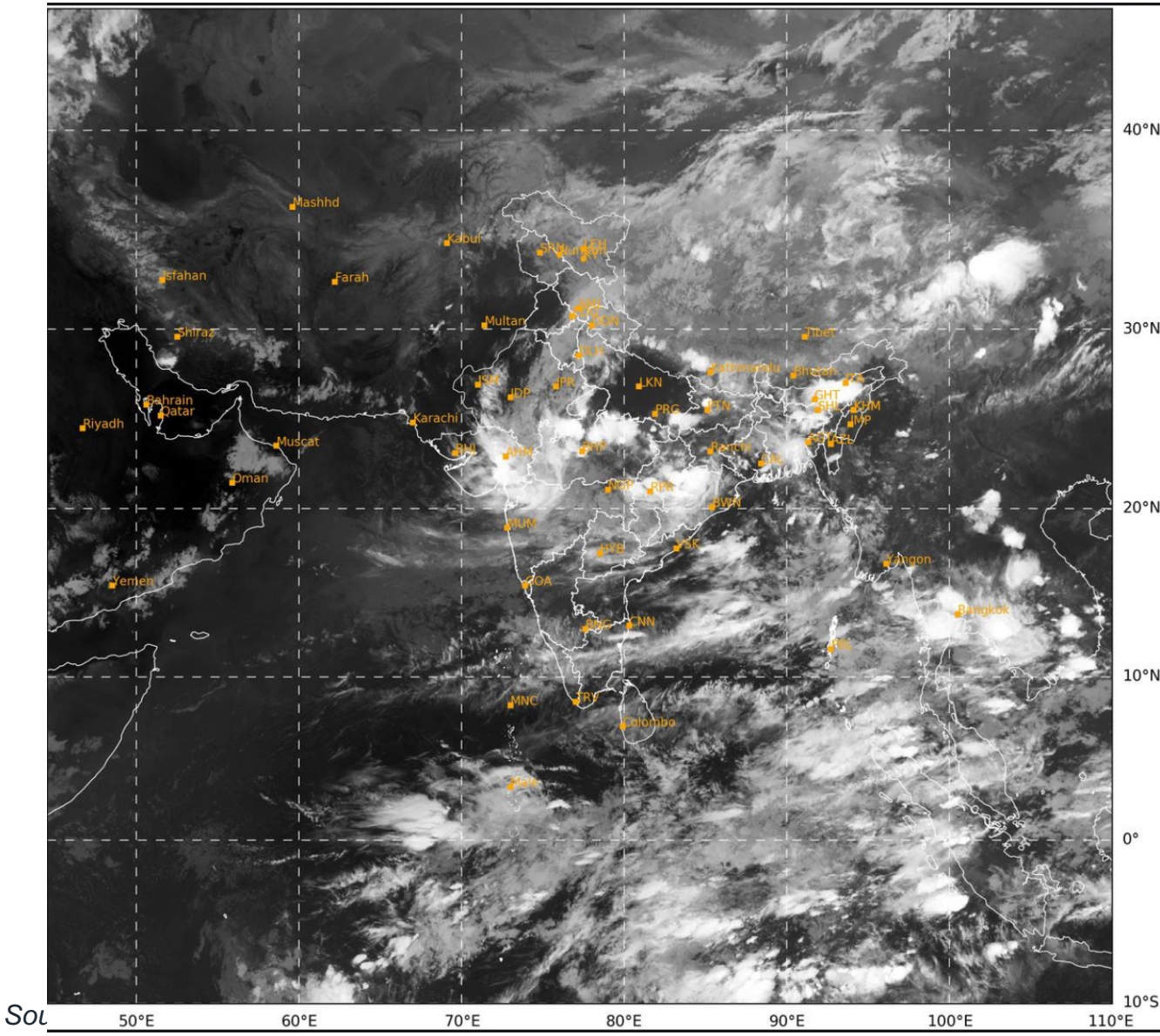
A tale of two technologies

**Wind and Solar – each have
unique weather challenges**

**Part 2: Creating the solar data
using satellite-based approach**



Solar: How we made it



Solar: What is available to download

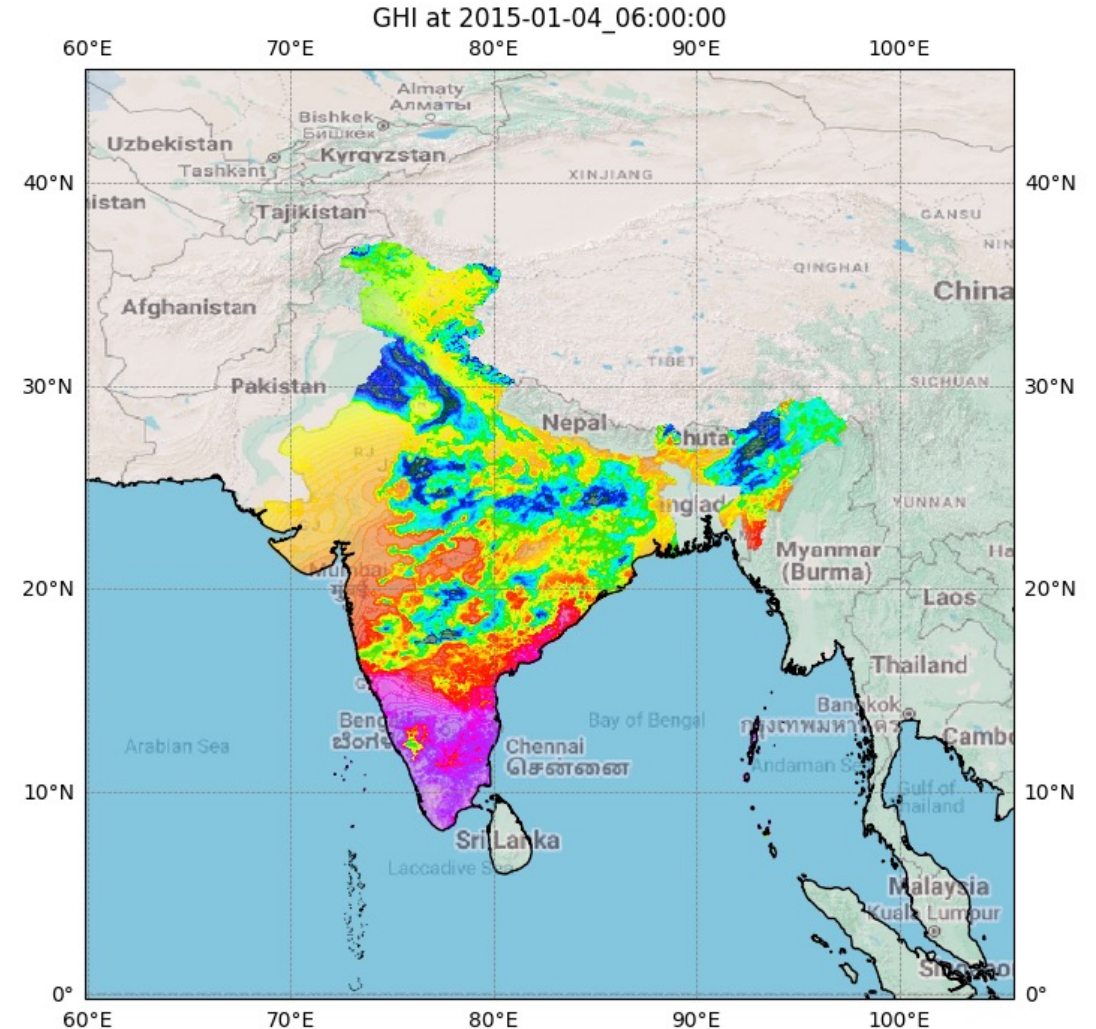
Every 15 minutes for 10 years on a 5km by 5km grid:

Solar Variables from Vaisala Algorithms:

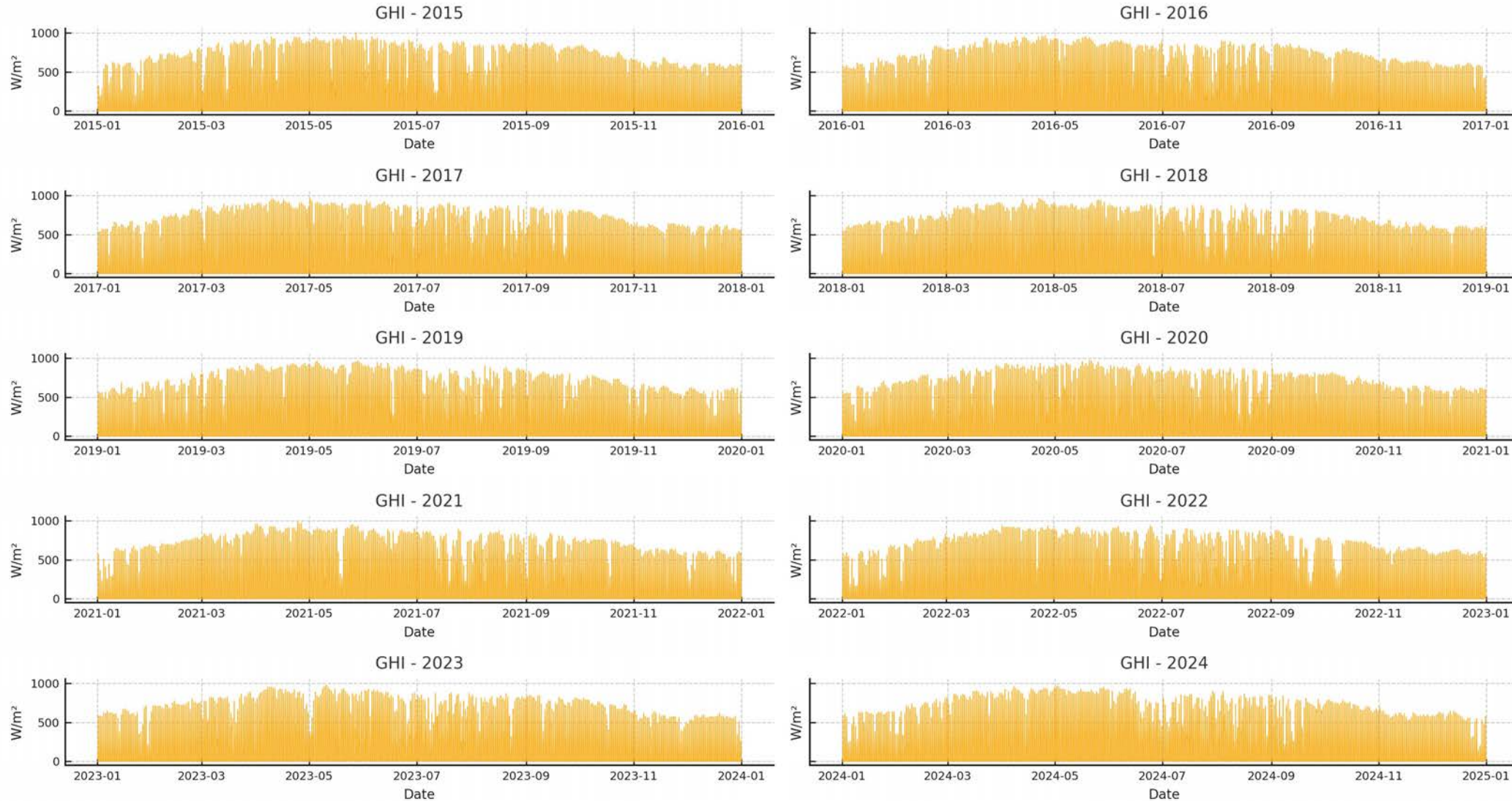
- GHI (Global Horizontal Irradiance)
- DNI (Direct Normal Irradiance)
- DIF (Diffuse)
- clearsky_GHI
- cloud_index
- linke (turbidity index)
- azimuth
- zenith

Other “weather” variables from ERA5

- windspeed_10m
- winddirection_10m
- temperature_2m
- pressure_0m
- tpwv (total precipitable water vapor)
- albedo
- precipitation
- snowfall
- snowdepth



10 years of solar (GHI) at one location (every 15 minutes)



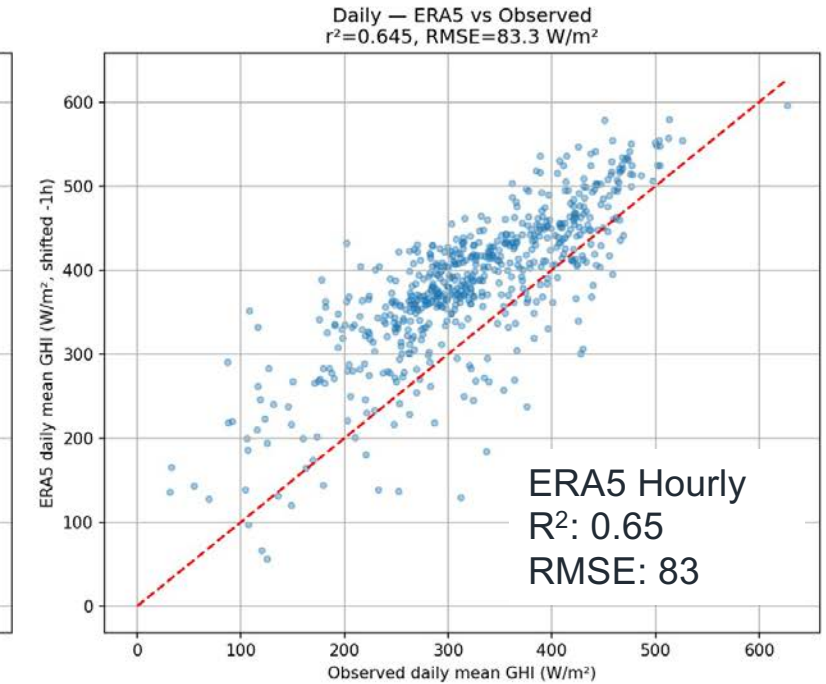
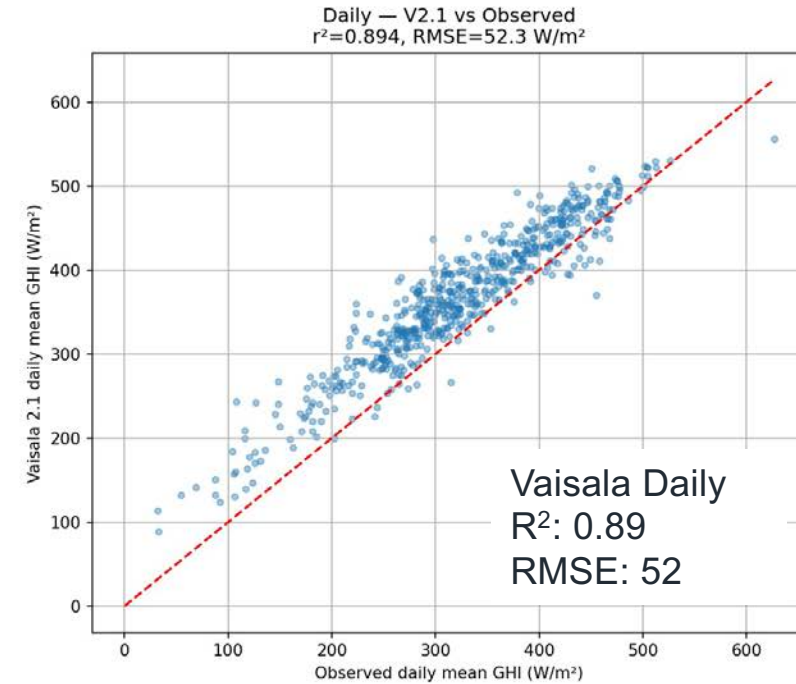
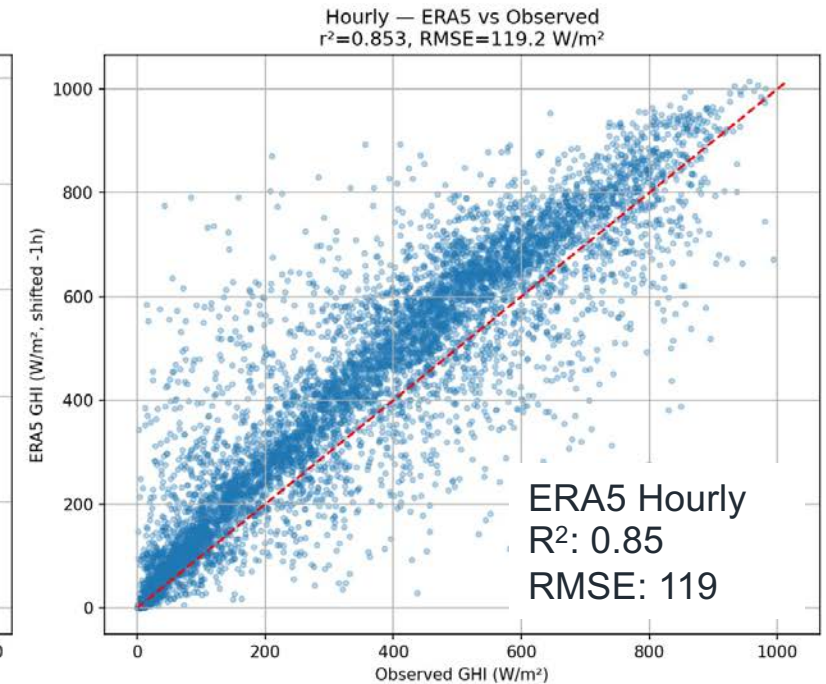
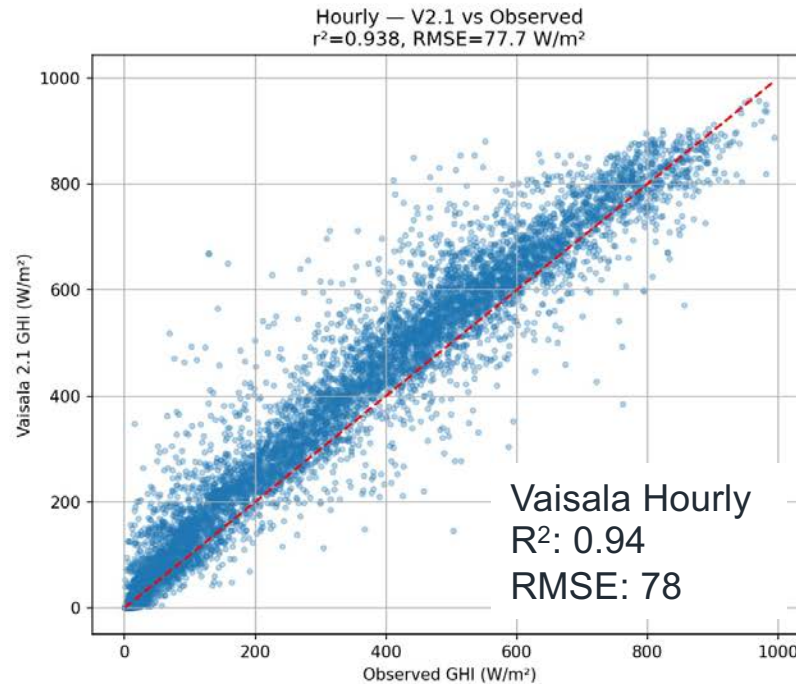
Satellite solar data versus ERA5

Global experience:

Satellite solar data has time series errors (MAE, RMSE) approximately 40% smaller than ERA5.

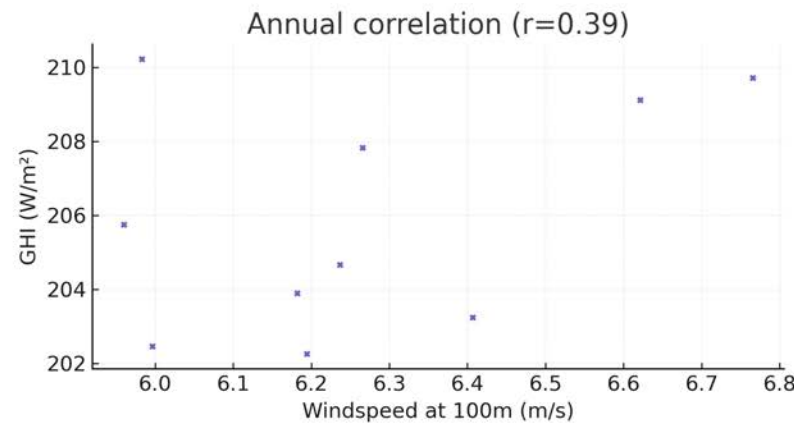
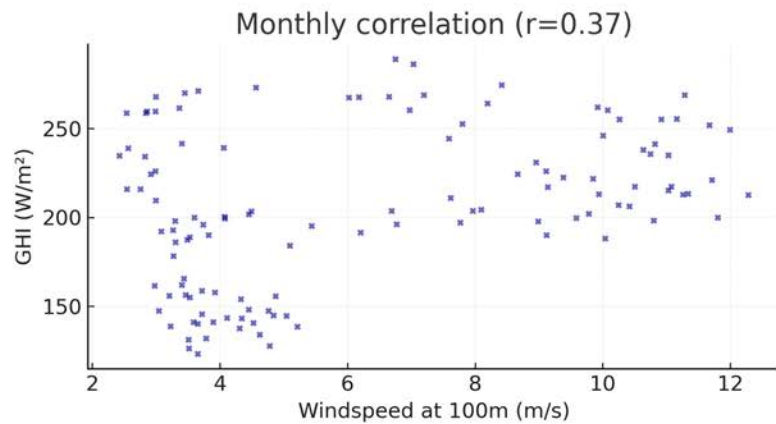
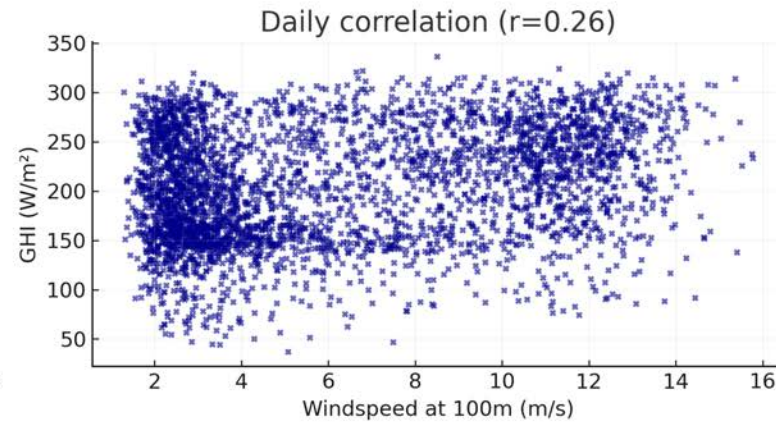
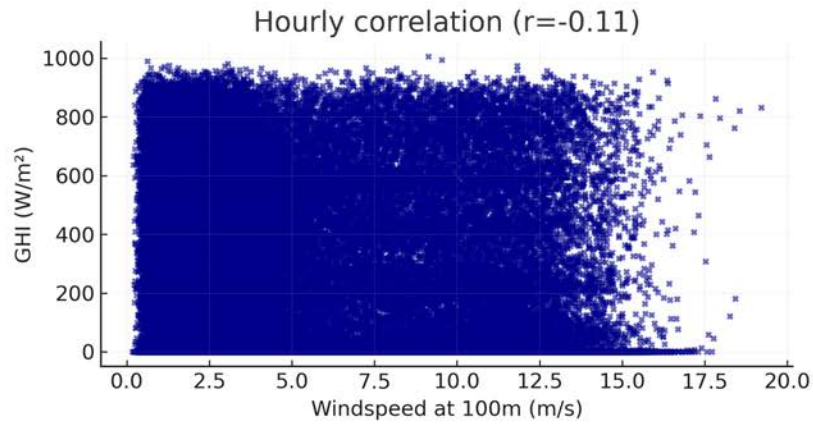
Improved correlations as well.

We see the same in India
(Gurgaon Site: BSRN)



The full weather data are available – have at it!

For example: Hourly, Daily, Monthly and Annual wind/solar correlations at those two sites.



Slight negative at hourly, increasingly positive at coarser averaging periods.

Best solar was one of the worst wind years.

But what we really want is all of this in terms of ENERGY, at times and at a scale that matters to the power system (the next part of the story)



Assessing Wind and Solar Resources in India Using 10-Years of Historical Weather Data

Prateek Joshi, Marie Rivers, and Jesse Cohen (RMI)

September 2025

Incorporation of Resource Data into Modeling Chain



Weather Data

- Vaisala generated 10 years of historical wind (e.g., wind speeds, etc.) and solar (e.g., irradiance, etc.) resource data for India (2015-2024)

Incorporation of Resource Data into Modeling Chain



Weather Data

Renewable Energy Potential (reV) Model

- Vaisala generated 10 years of historical wind (e.g., wind speeds, etc.) and solar (e.g., irradiance, etc.) resource data for India (2015-2024)
- The reV model is a detailed spatio-temporal tool that calculates renewable energy capacity, generation, and cost accounting for grid infrastructure and land use

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ReEDS to Production Cost Modeling (R2X) Tools

- R2X translates the ReEDS capacity expansion results into inputs for production cost models (e.g., PLEXOS, Sienna, etc.), allowing for detailed hourly dispatch analysis

Technology Assumptions

These technology assumptions are based on input from a broad set of stakeholders in India, as well as input from Tata Power.

Solar PV Technologies



Utility-Scale Solar PV



Distributed Solar PV

- ❖ System Type: Fixed Tilt (angle equal to latitude)
- ❖ DC to AC Ratio: 1.4
- ❖ Inverter Efficiency: 97.5%
- ❖ Total Losses: 17.8%

Wind Technologies



Onshore Wind

- ❖ Hub Height: 135 m
- ❖ Rotor Diameter: 145 m
- ❖ Turbine Capacity: 3.5 MW

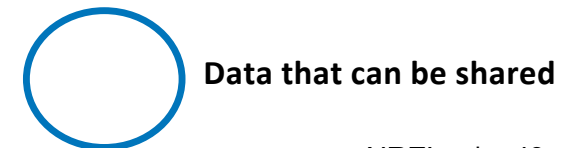
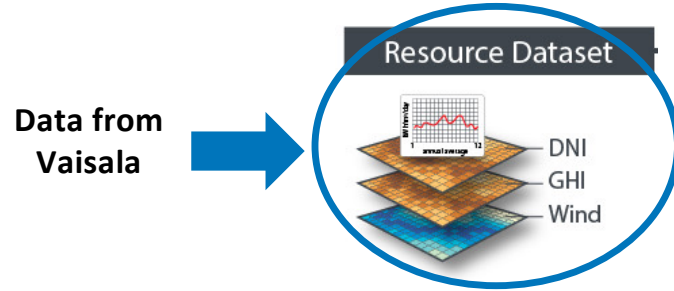


Offshore Wind

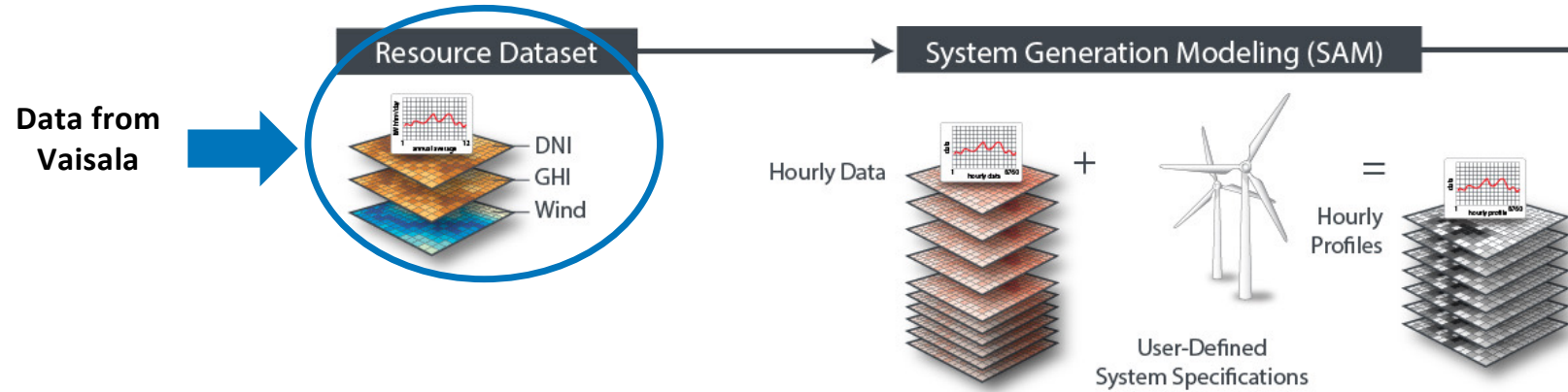
- ❖ Hub Height: 150 m
- ❖ Rotor Diameter: 242 m
- ❖ Turbine Capacity: 15 MW

Methodology

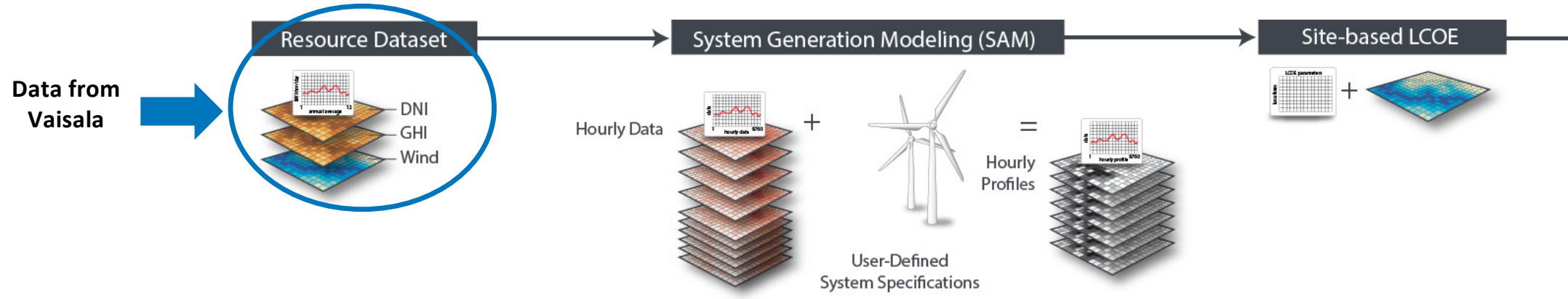
Renewable Energy Potential (reV) Model Workflow

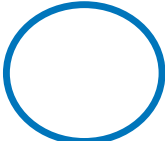


Renewable Energy Potential (reV) Model Workflow

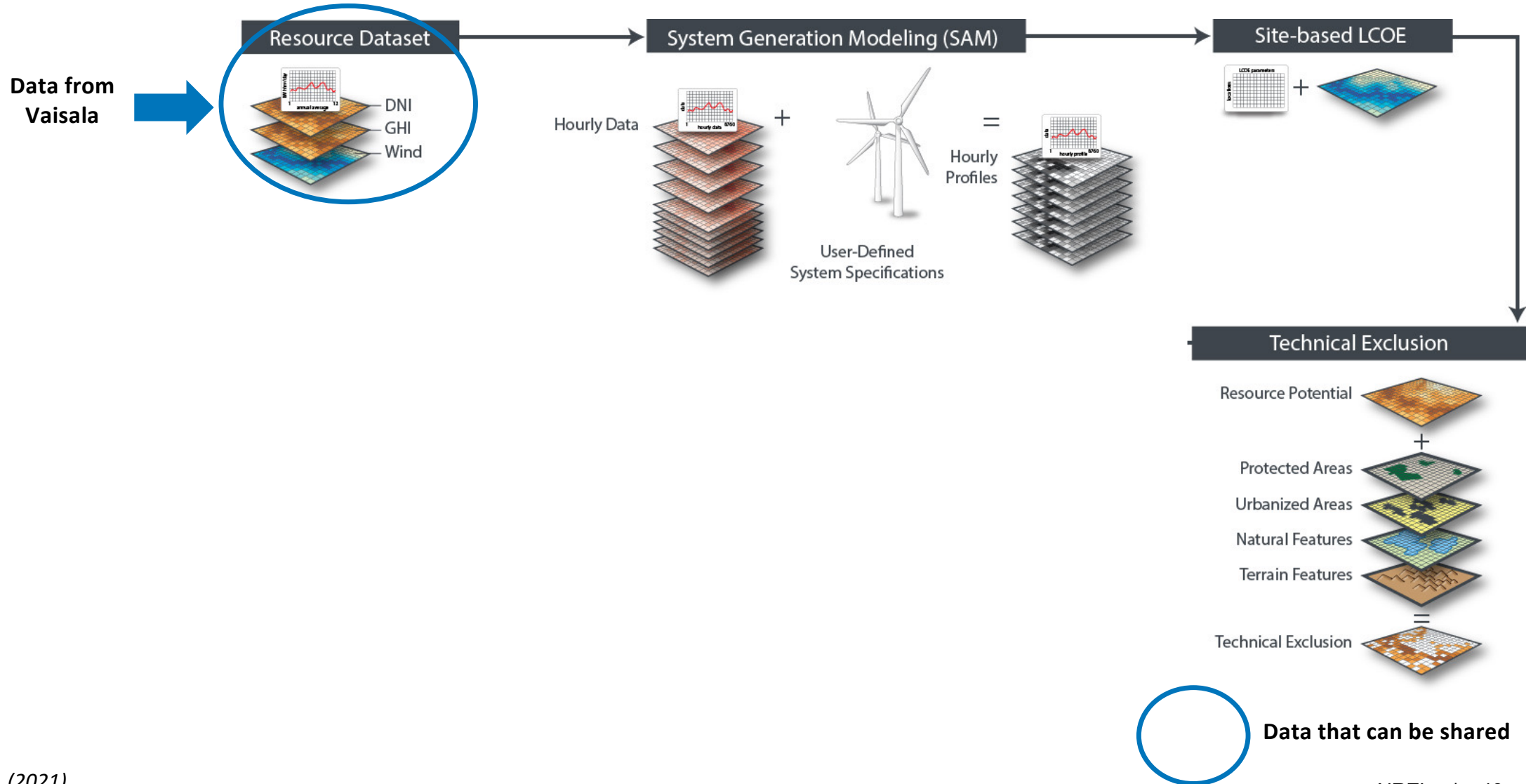


Renewable Energy Potential (reV) Model Workflow

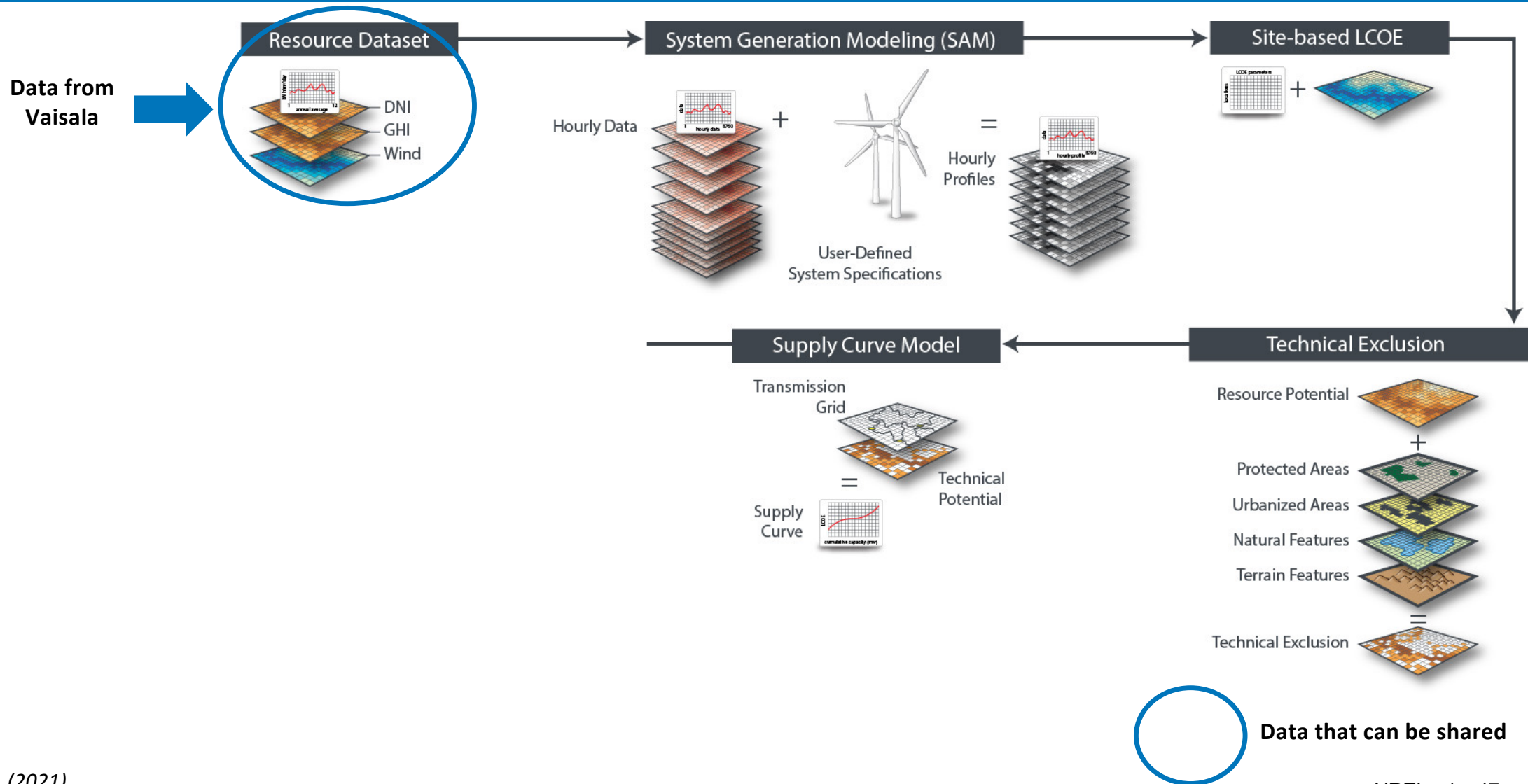


 **Data that can be shared**

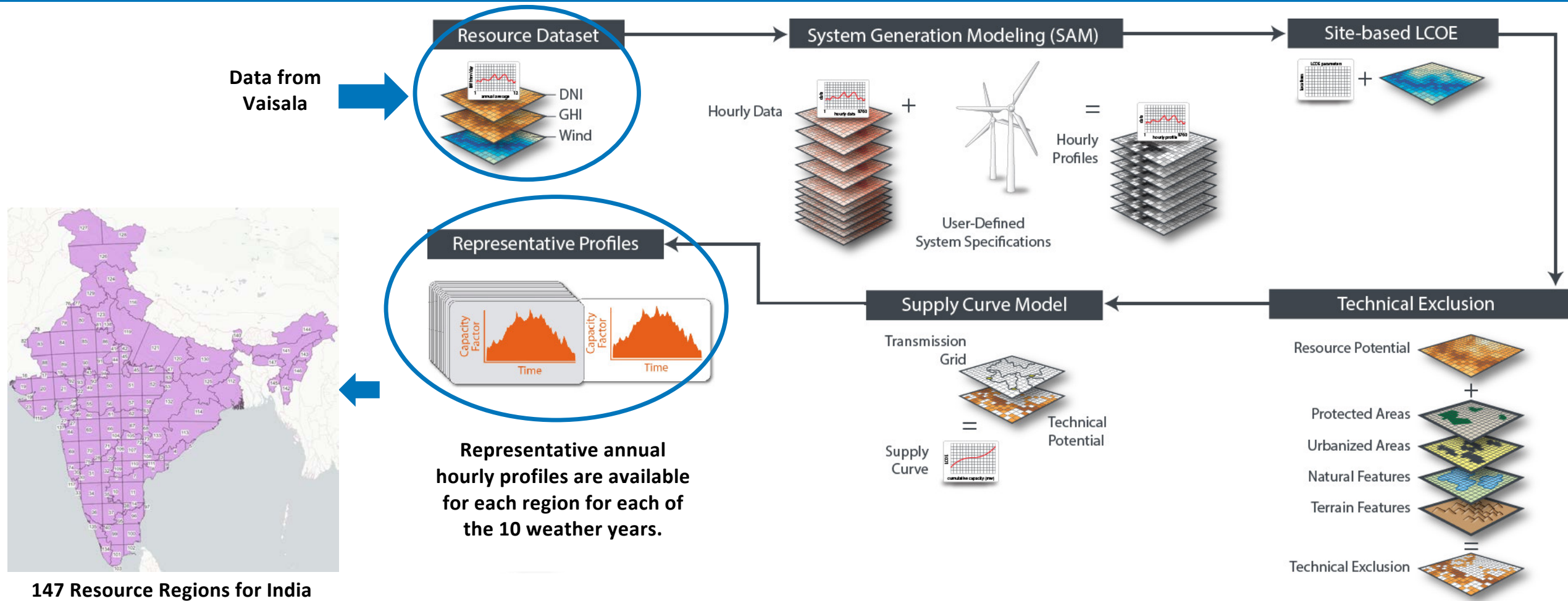
Renewable Energy Potential (reV) Model Workflow



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Output Datasets for Use in Power System Planning

For each technology, weather year, and resource region:

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For each technology, weather year, and resource region:

- ❑ Regional Summary
 - ❑ The technical potential capacity (i.e., AC and/or DC MW) of the technology (accounting for land-use exclusions) and its average capacity factor (accounting for the weather year) for each resource region

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- ☐ Hourly Profiles

- ☐ The hourly capacity factor profile of the technology, accounting for the weather year, that is most representative of each resource region

Output Datasets for Use in Power System Planning

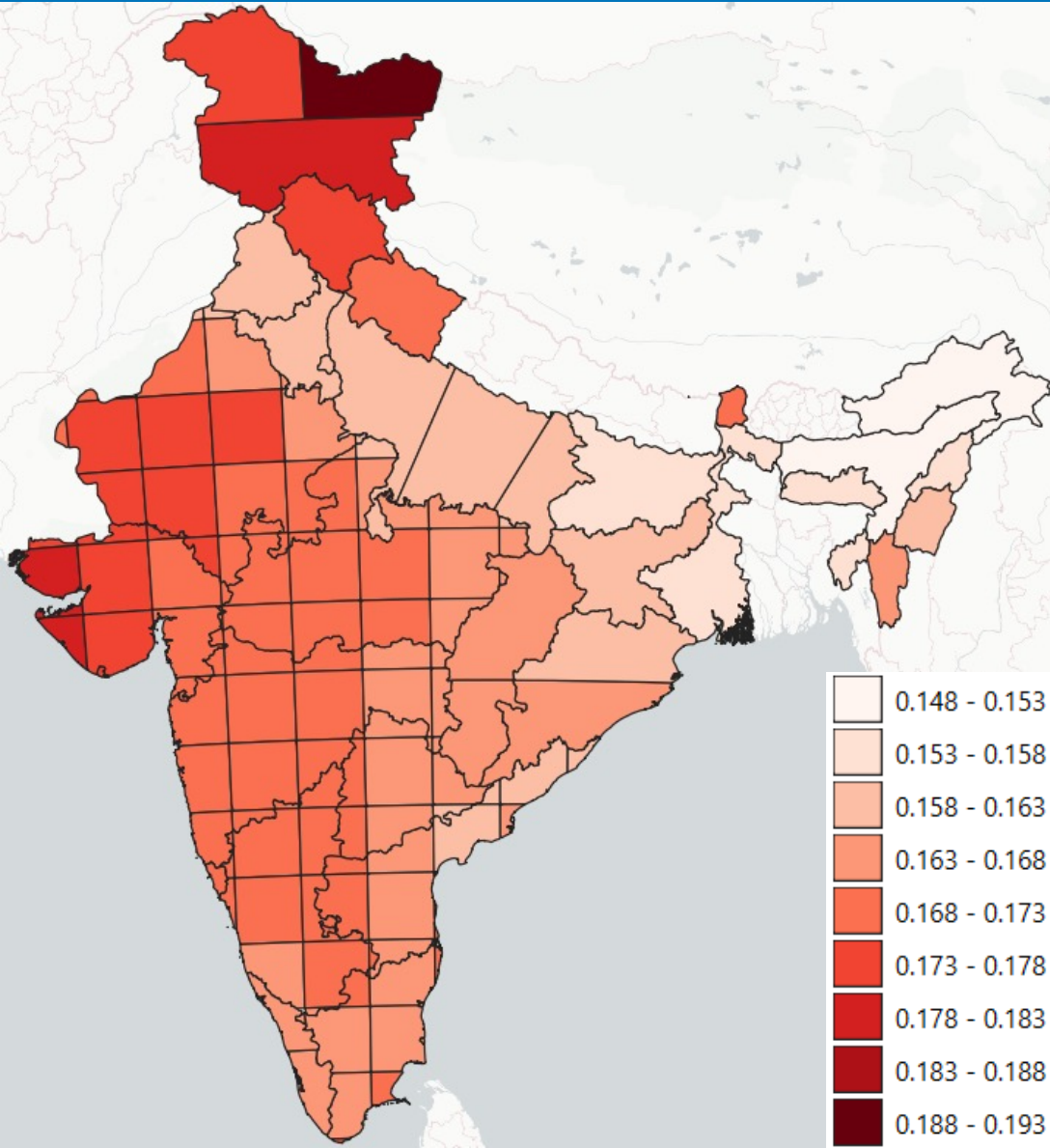
For each technology, weather year, and resource region:

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- ☐ Hourly Profiles
 - ☐ The hourly capacity factor profile of the technology, accounting for the weather year, that is most representative of each resource region
- ☐ Supply Curves
 - ☐ The technical potential capacity (i.e., AC and/or DC MW) of the technology (accounting for land-use exclusions) and its average levelized cost of electricity (LCOE) (accounting for grid interconnection costs)

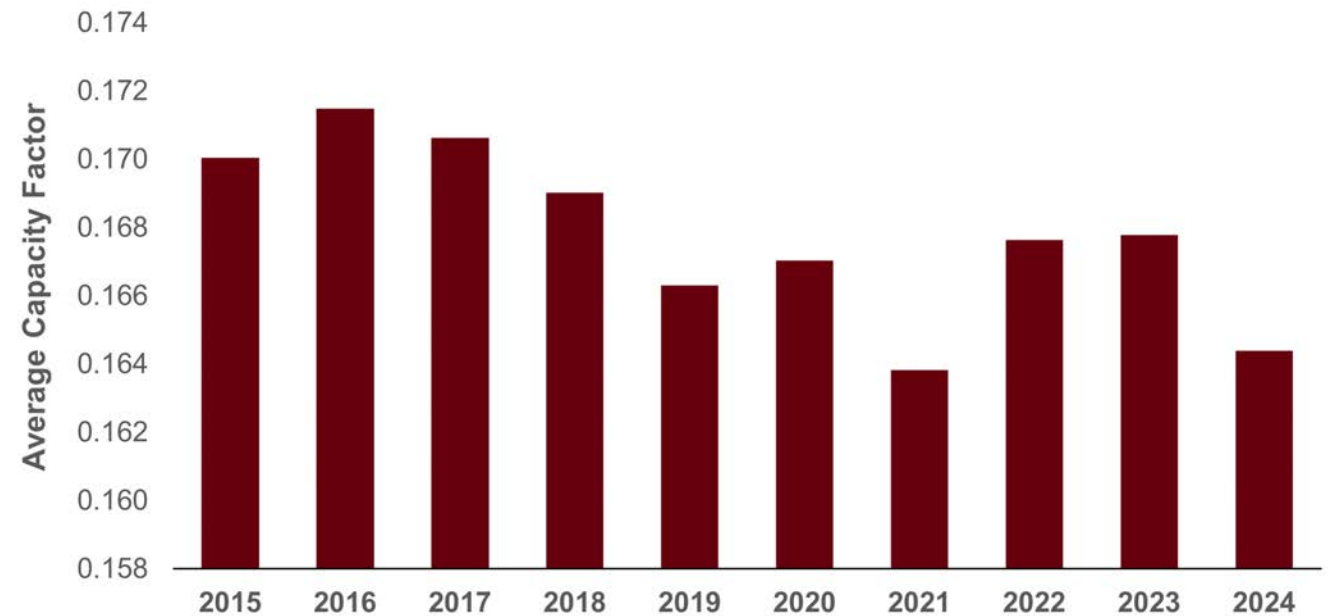
We are working with Tata Power to validate this data for specific sites

Results

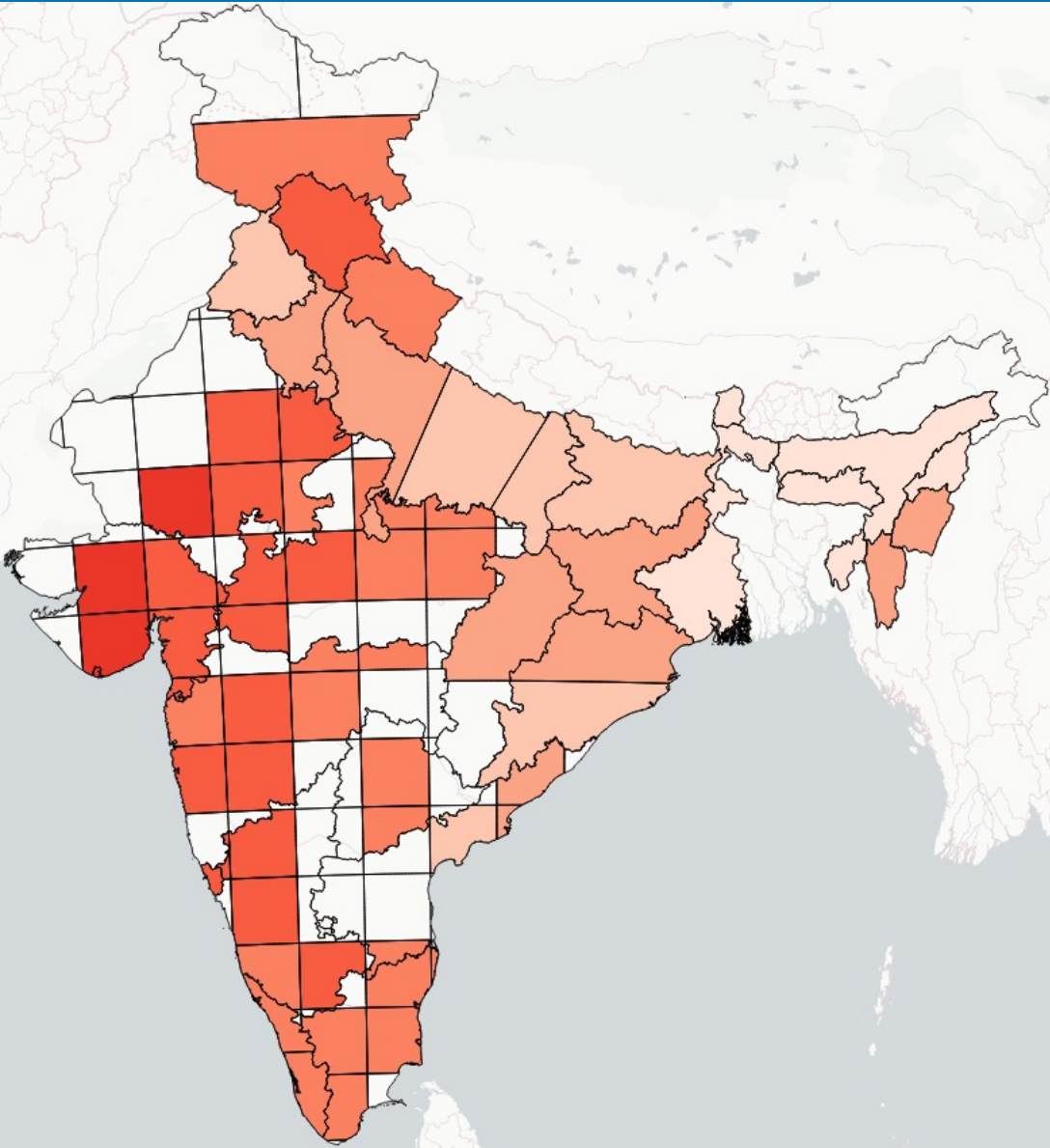
Utility-Scale Solar PV



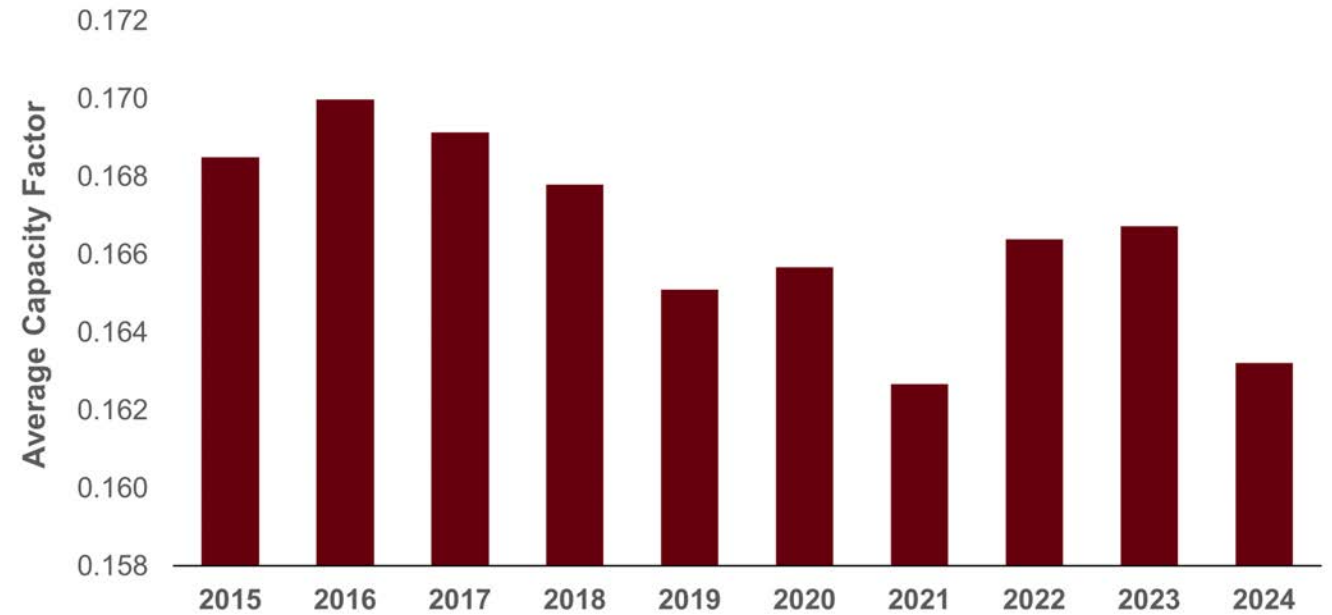
← **2015-2024 Average Capacity Factors (all years)**



Distributed Solar PV

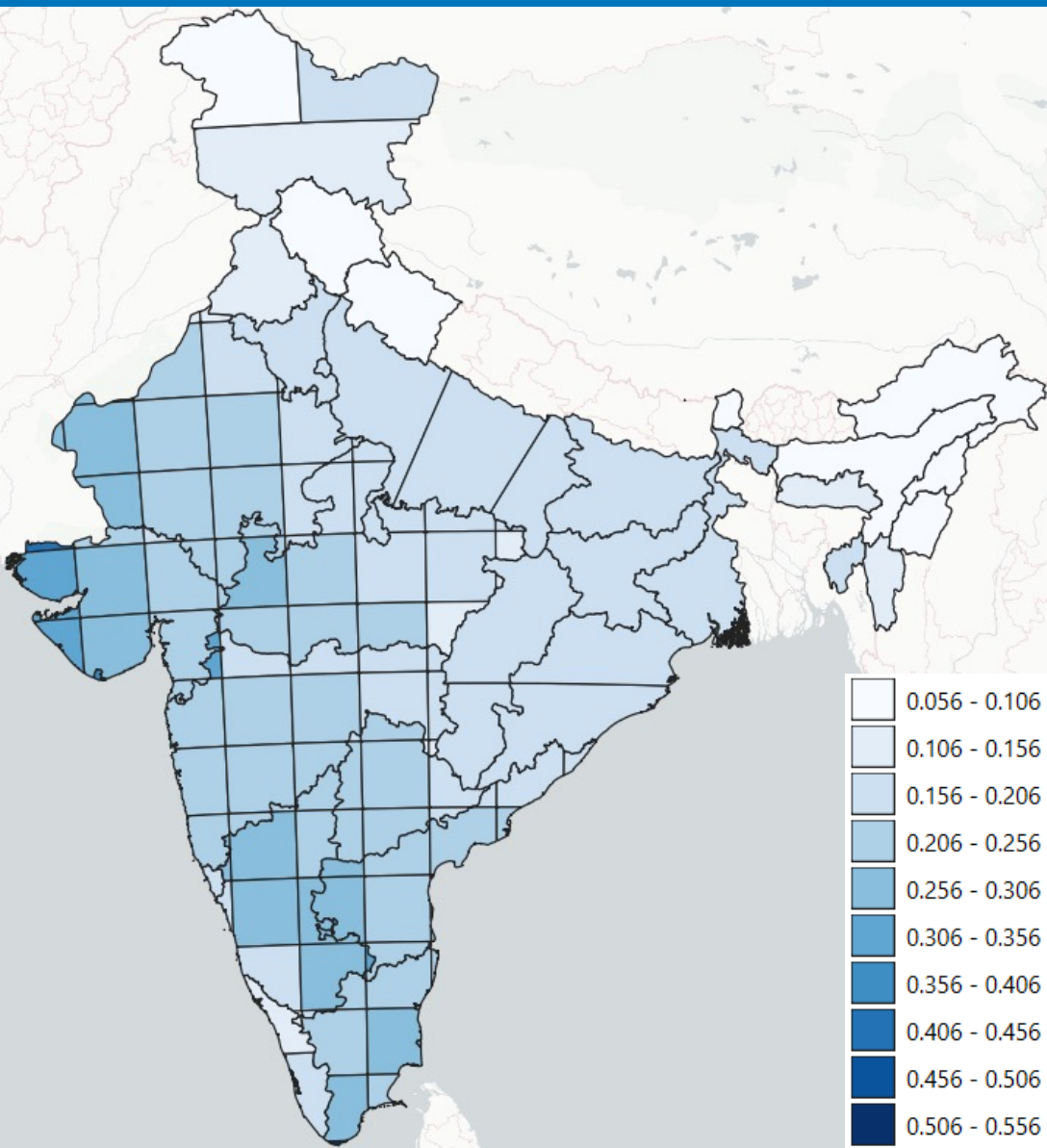


← **2015-2024 Average Capacity Factors (all years)**

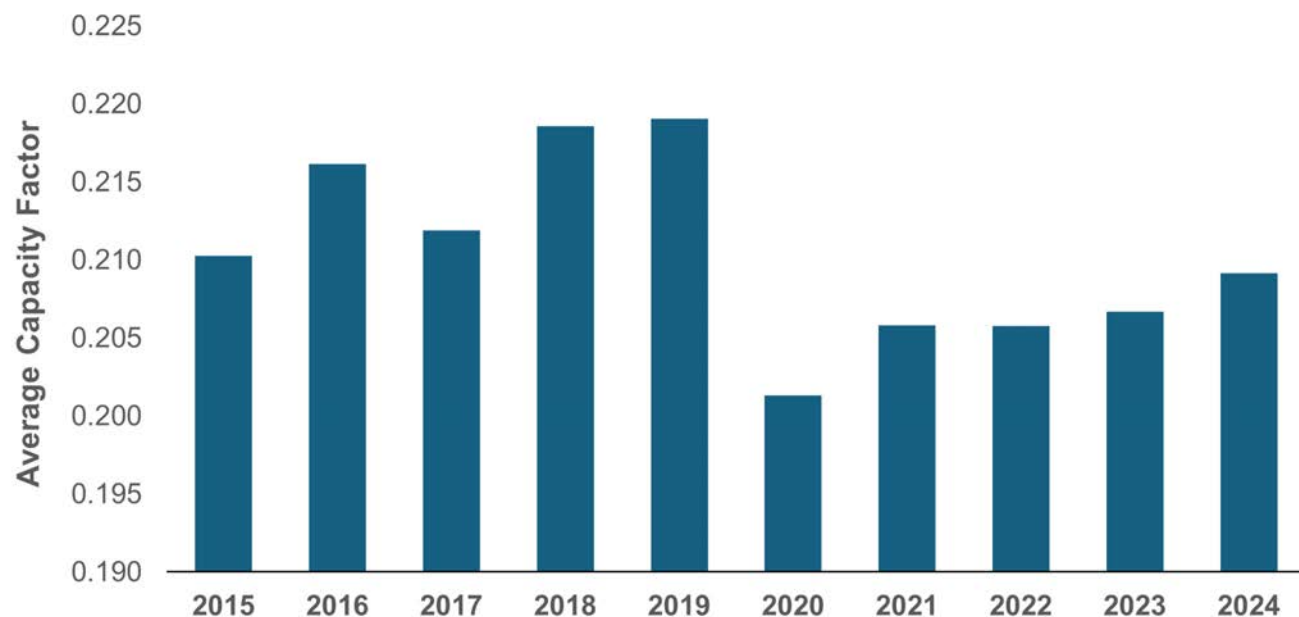


Based on metropolitan areas with a population greater than 1 million and the methodology outlined in Das et al. (2022).

Onshore Wind

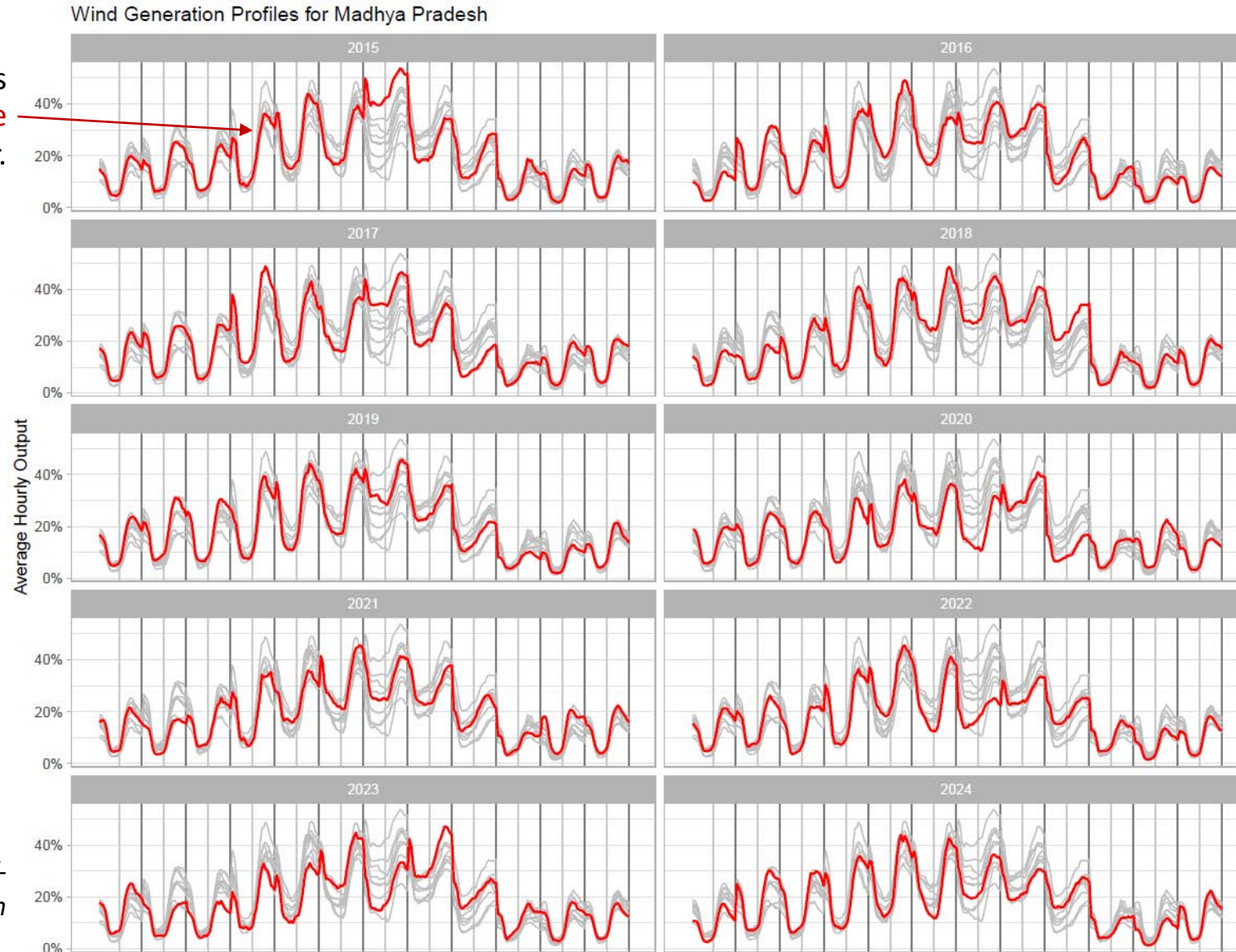


← **2015-2024 Average Capacity Factors (all years)**



Example: Wind Generation Profiles for Madhya Pradesh

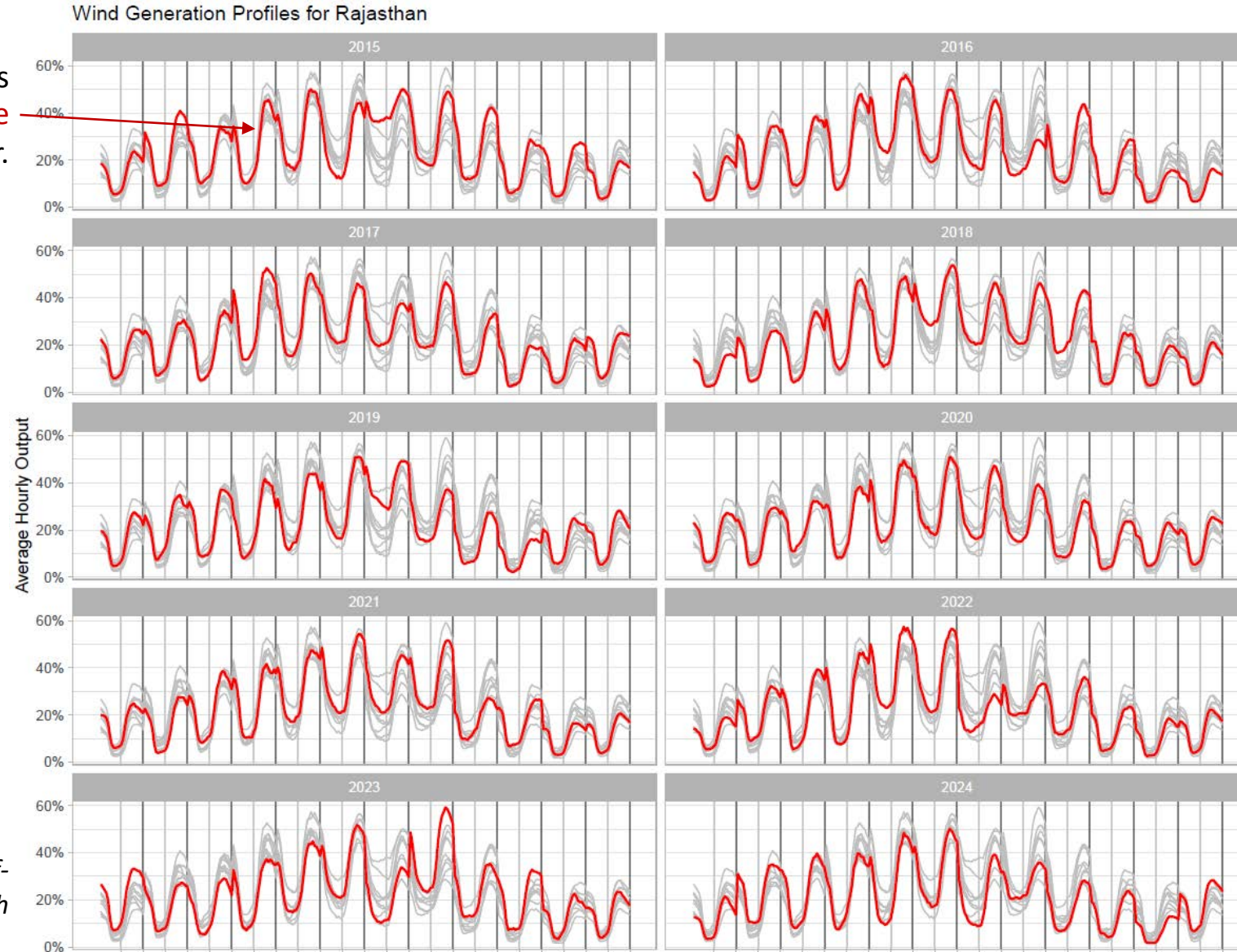
Grey lines represent all years (2015-2024), and red line represents the particular year.



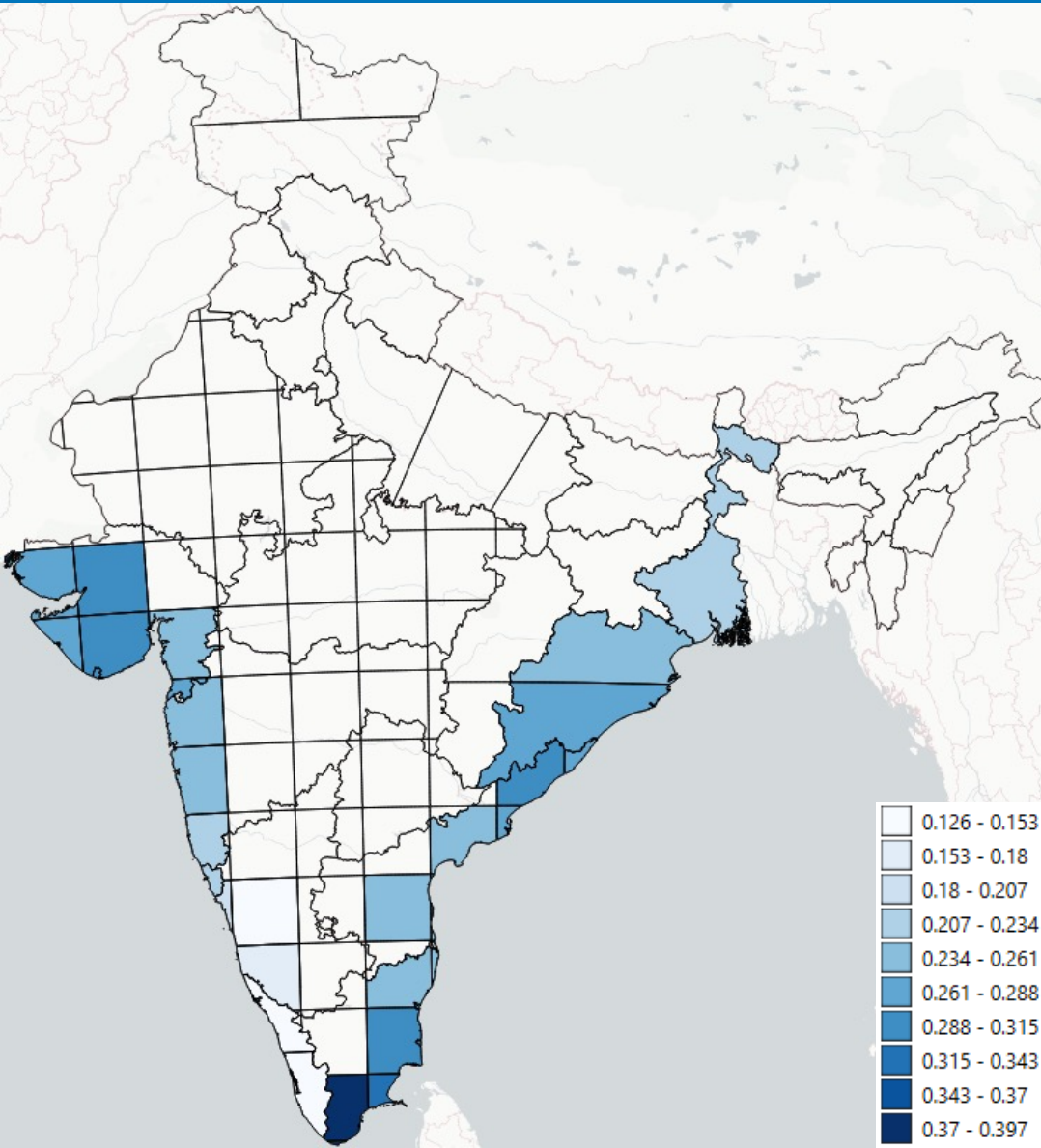
Note: x-axis represents hour-of-day averages for each month

Example: Wind Generation Profiles for Rajasthan

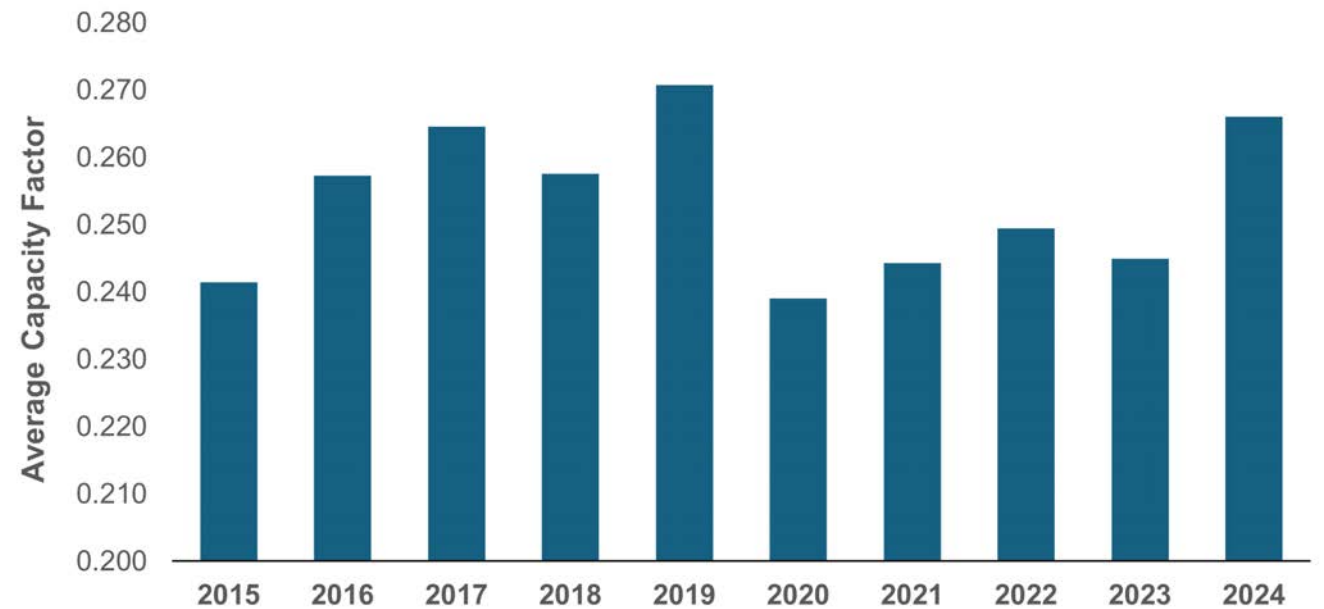
Grey lines represent all years (2015-2024), and red line represents the particular year.



Offshore Wind

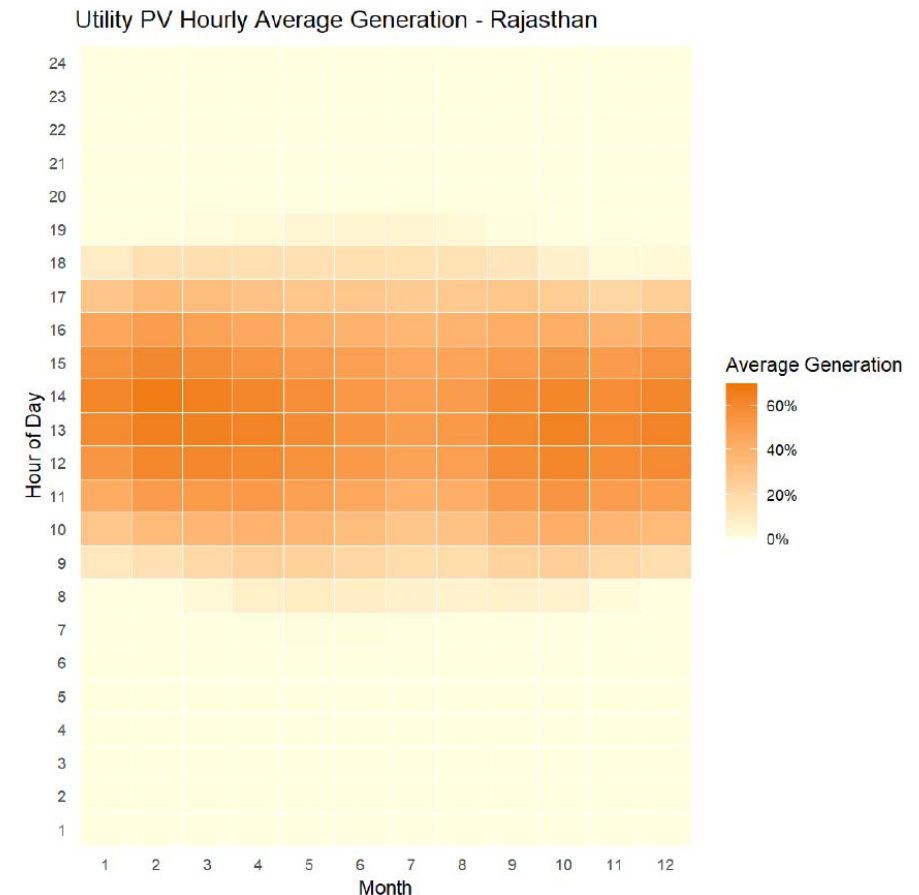
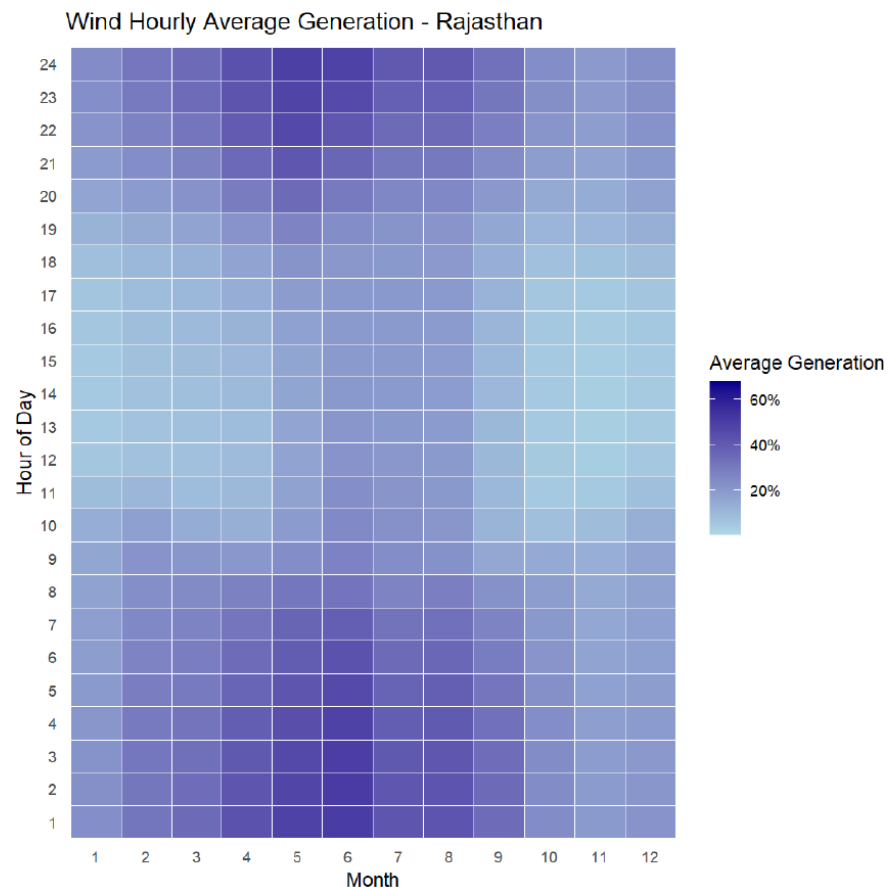


← **2015-2024 Average Capacity Factors (all years)**



General Observations

- Wind tends to have higher generation during monsoon months and nighttime, while solar has higher generation during non-monsoon months and daytime
- Diurnal variation is more important for solar, whereas seasonal variation is more important for wind



Thank You

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This work was authored by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by GridLab and World Resources Institute. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.



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Thank you!

Gridlab.org/india_weatherdata

