

An Operational Evaluation of Modeled Uncertainties to Measured Solar Irradiance and Grid Energy

Halley Darling

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OUR VISION

Creating a world powered by renewable energy



AGENDA

1. Background and Motivation
2. Datasets and Processing
3. Results
4. Conclusions

Background and Motivation

Uncertainty for irradiance and energy modeling



Uncertainty Quantification and Communication

Standard Deviation and Root-Sum-Square:

- Root-sum-square (RSS) combination of different independent uncertainty parameters
- RSS assumes a normal distribution
- RSS should NOT be used when uncertainty parameters are interdependent
- Uncertainty usually reported as the uncertainty at 1 standard deviation (68% confidence interval) or 2 SD (95% confidence interval)

Probability of Exceedance:

- Both methods will typically communicate the relationship of the uncertainty to the long-term expected energy in P-values indicating the probability of exceedance (eg if P75, 75% of the time the energy is above that value annually)

Non-standard distributions and CDF:

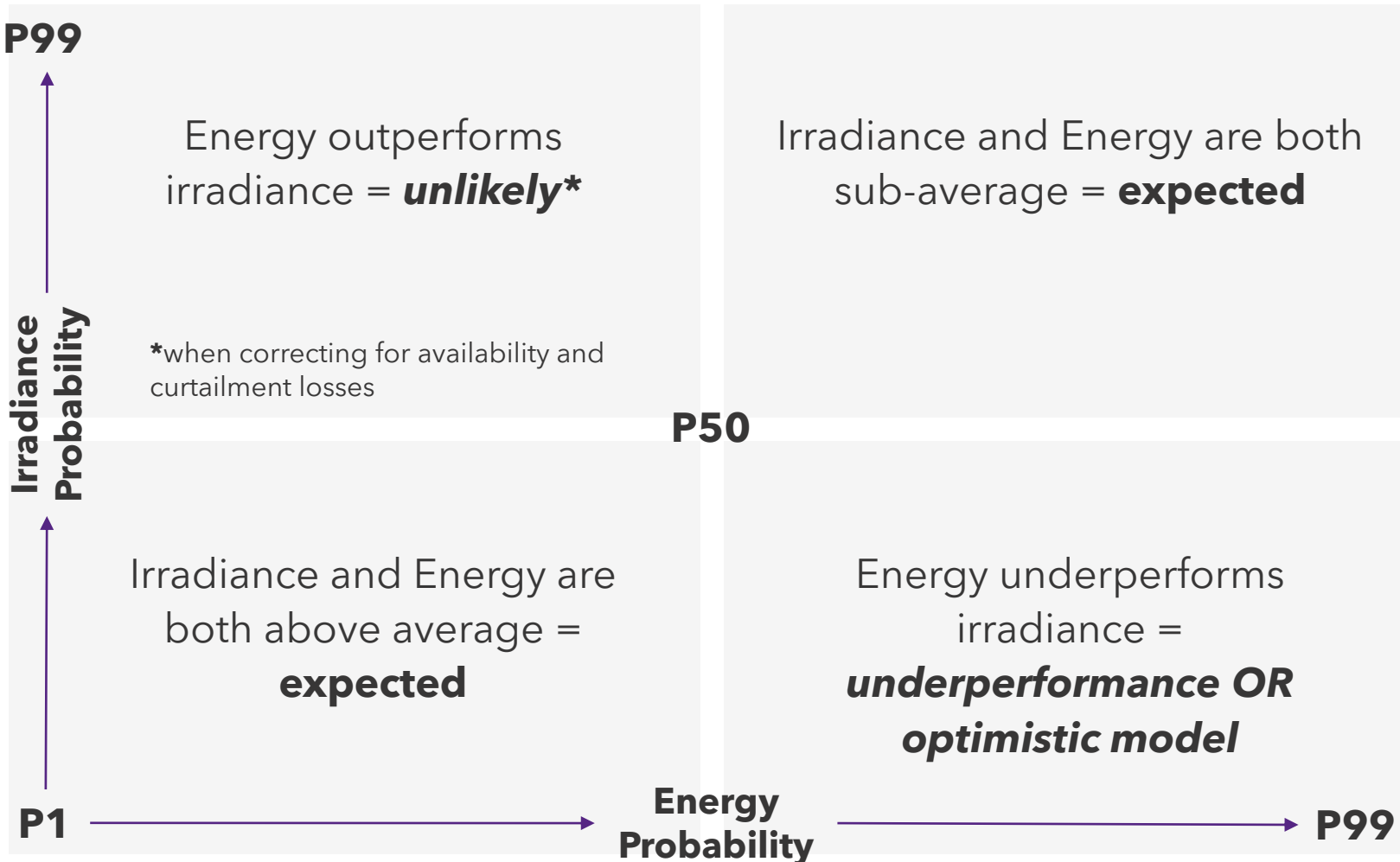
- Non-standard distributions of uncertainty may occur for various reasons, including interdependence of uncertainty variables
- A more refined combination technique may be required, such as Monte Carlo simulations
- May be evaluated as a Cumulative Distribution Function (CDF)
- Typically reported in probability of exceedance values

Motivation

Does annual P-XX irradiance interannual variability correspond to annual P-XX energy, either from the preconstruction energy assessment or from an operational assessment?

E.g., if you have P75 irradiance for a 12-month period, how close to P75 energy will the generation be?

Expected Probability Relationship by Quadrant



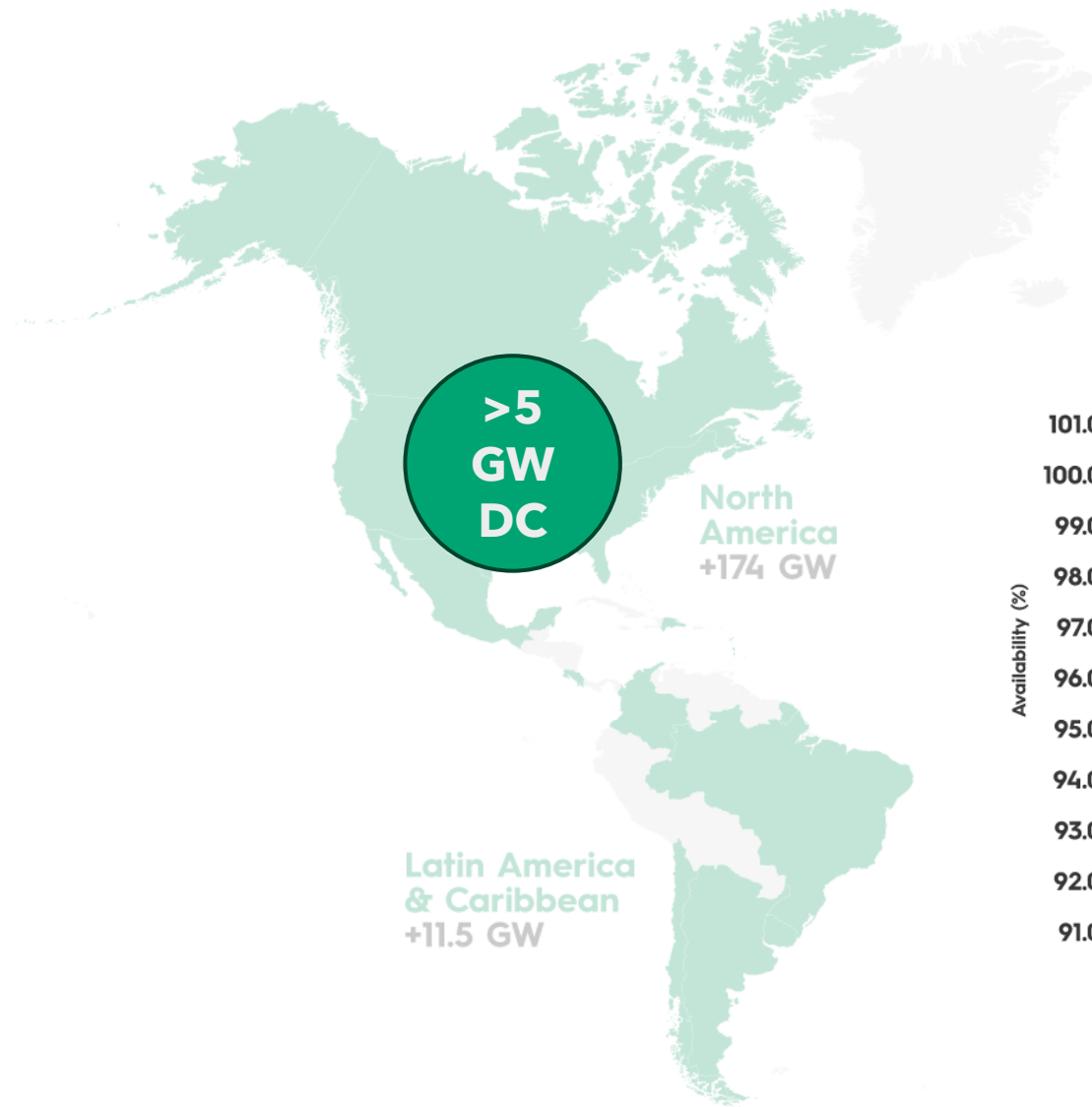
- When comparing directly, some scatter expected, so quadrant approach helps to clarify expectations
- Upper left quadrant is not expected to be densely populated as the irradiance probability is expected to “ceiling” the energy probability; data in this quadrant may be due to errors in modeling or reported generation values

Datasets and Processing

Modeled, operational and irradiance data

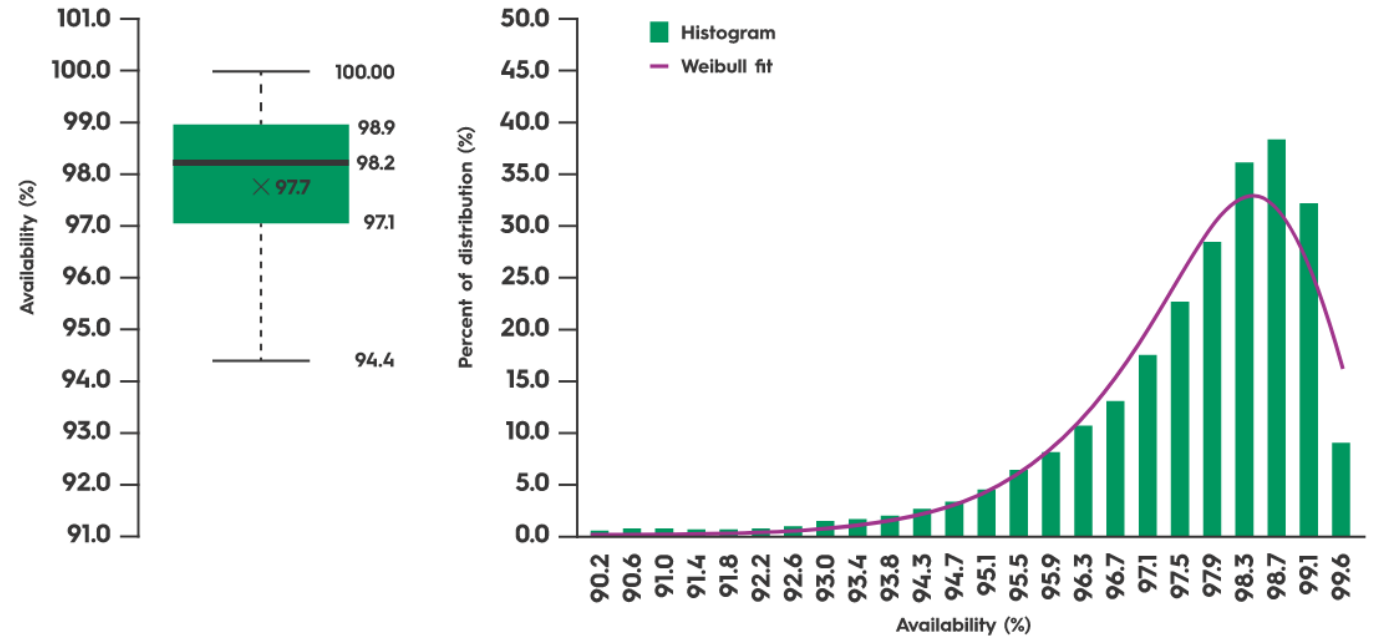


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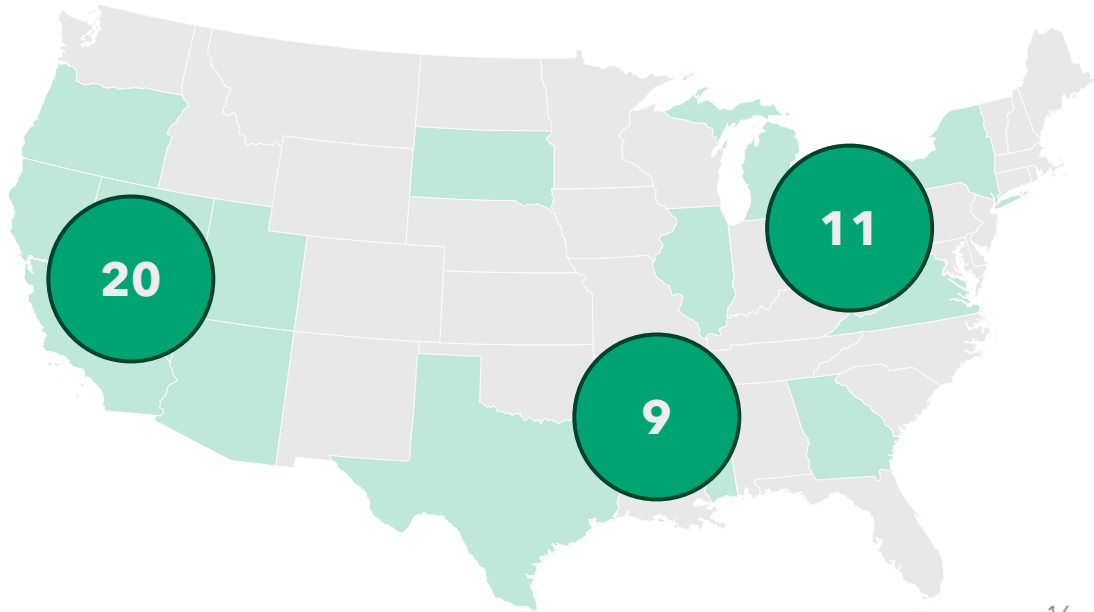
Global experience 1995-2025

71 Countries
+500 GW



A data based assessment of solar project availability in the United States, Natural Power, 2024

Demographics of Sample Data



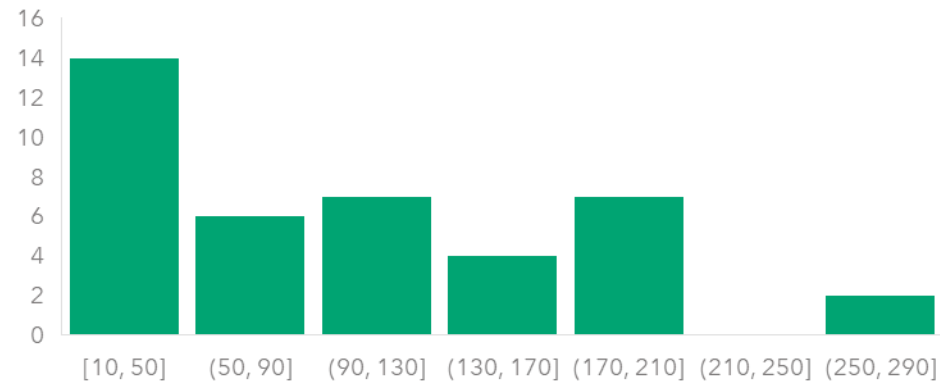
40 projects

20 West / Southwest
9 South / Southeast
11 Northeast / Midwest

>5 GWdc

4 GWac at POI across all projects

Distribution of Projects MWac at POI



Parameters for Study

1

Operational Data: Monthly generation data, including monthly availability and curtailment statistics to “gross” up the data to zero availability loss and zero curtailment loss.

2

Preconstruction Energy Estimate: P50 energy estimate with uncertainty statistics, availability and degradation assumptions.

3

Operational Energy Assessment: Correlation of long-term irradiance to availability- and curtailment-adjusted generation data (12 months or more) to determine P50 energy from operations, including uncertainty.

4

Long-Term Irradiance: Timeseries of long-term data used to derive interannual variability and determine probability of specific irradiance years.

Data Processing

Irradiance:

- Selected PSM GHI for consistency and independence
- At each site, irradiance was summed for each month-and-year, then 12-month rolling summed to evaluate specific 12-month periods for probability of exceedance
- P-values determined via two methods: traditional IAV standard distribution, and CDF from ranked rolling sums

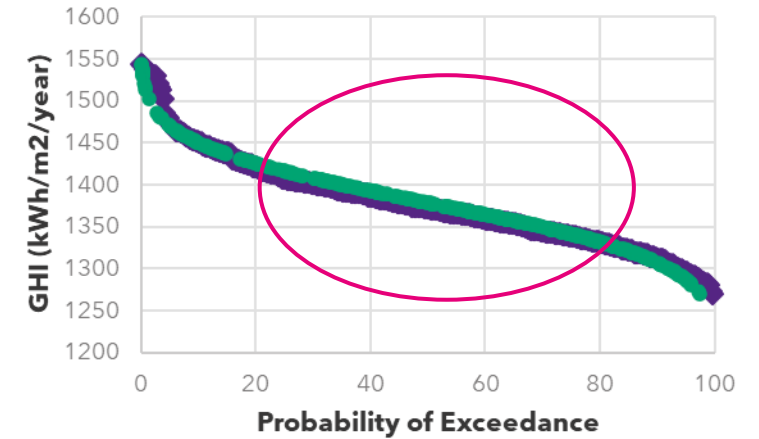
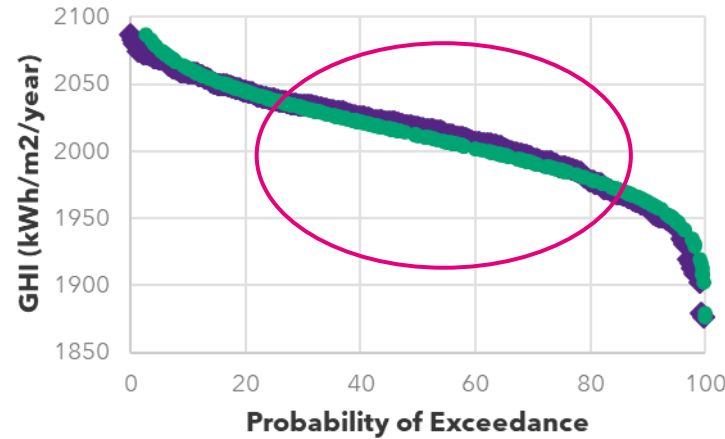
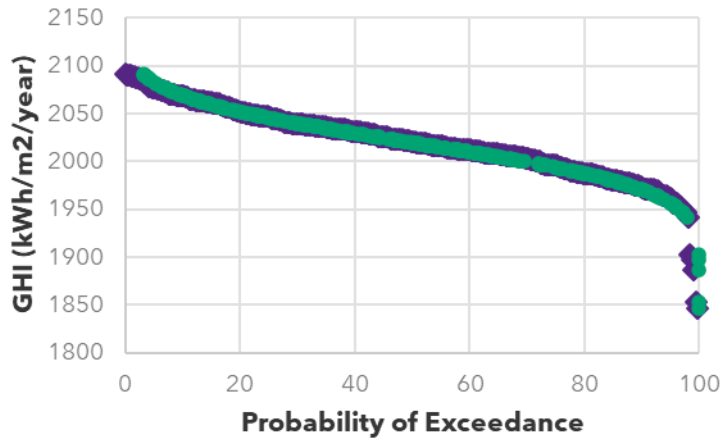
Operational Generation:

- Of 40 sites, 35 had >1 year prior to the end of 2024
- Generation data were adjusted to account for availability and curtailment losses
- 12-month periods were summed to evaluate 1-year periods of "gross" generation
- Gross generation compared to preconstruction and operational analyses to determine the probability of exceedance for that year respectively

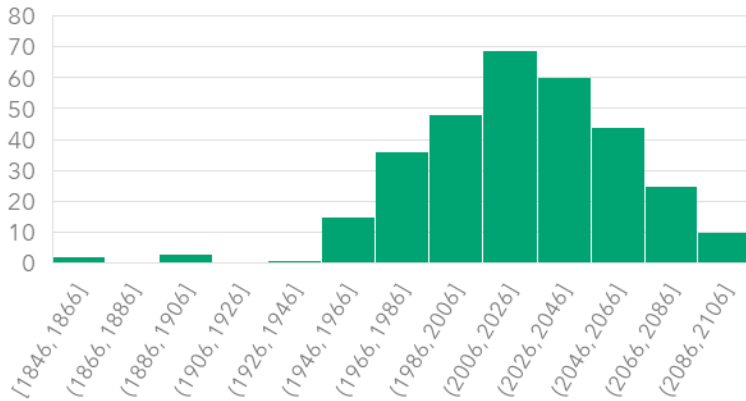
Modeled Generation:

- Two means, preconstruction and operational assessments
- Both corrected for availability assumptions and degradation to get expected P50 generation for each specific 12-month period
- Probability applied as standard deviation from single-year uncertainty evaluation for the respective assessment

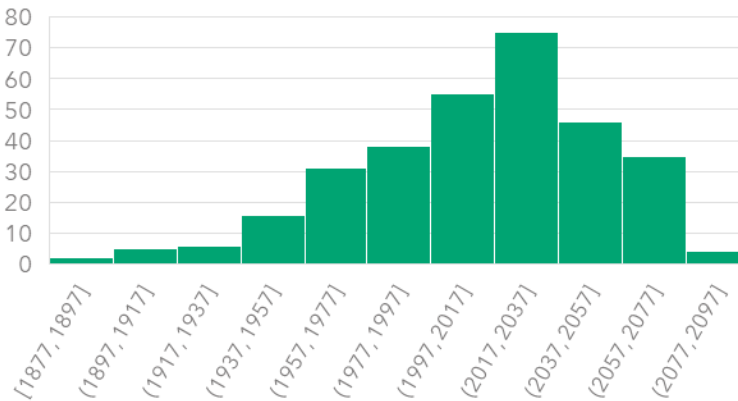
Rolling Sum CDF and Histograms for 3 Sites



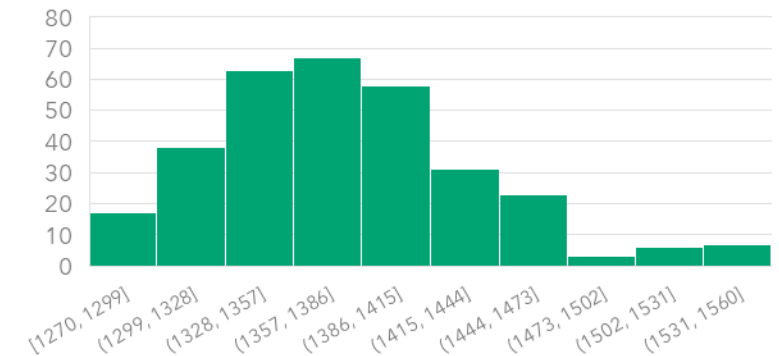
12-month Rolling Sum GHI 1998-2024 (CA-1)



12-month Rolling Sum GHI 1998-2024 (CA-2)



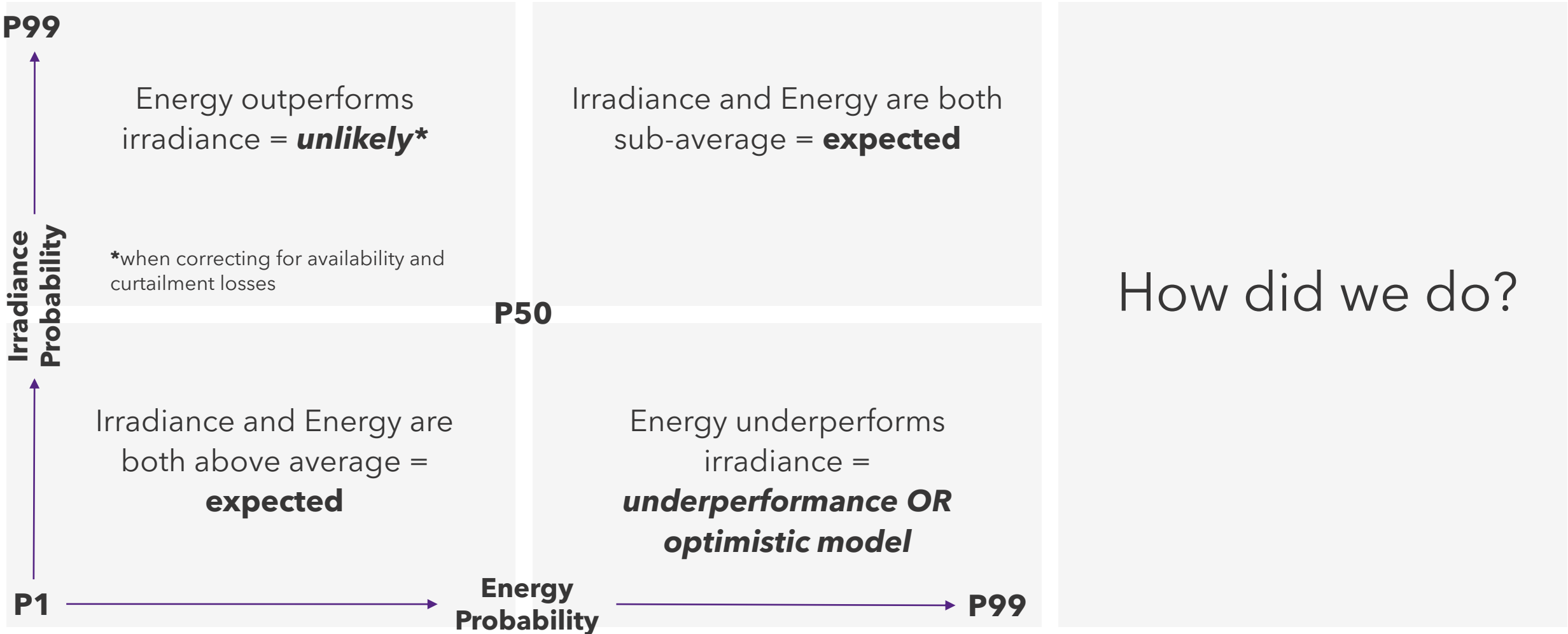
12-month Rolling Sum GHI 1998-2024 (Northeast)



Results

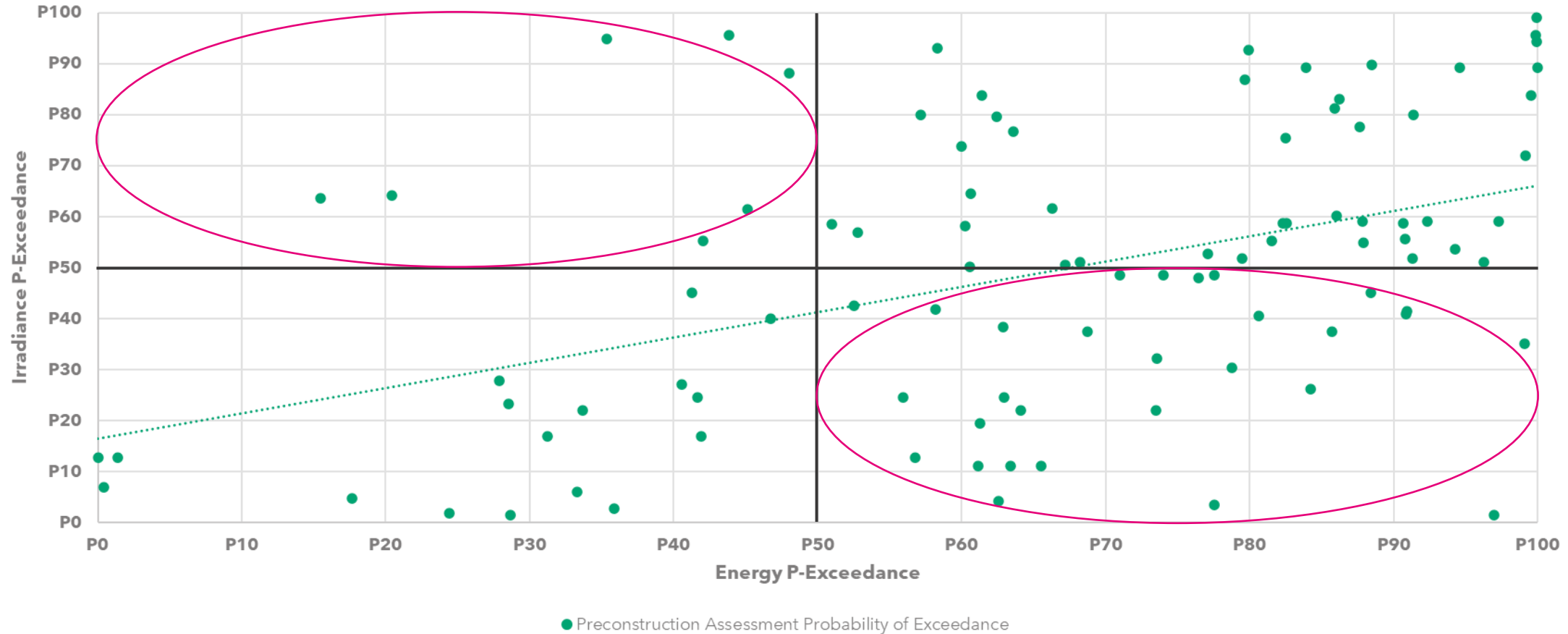


Expected Probability Relationship by Quadrant



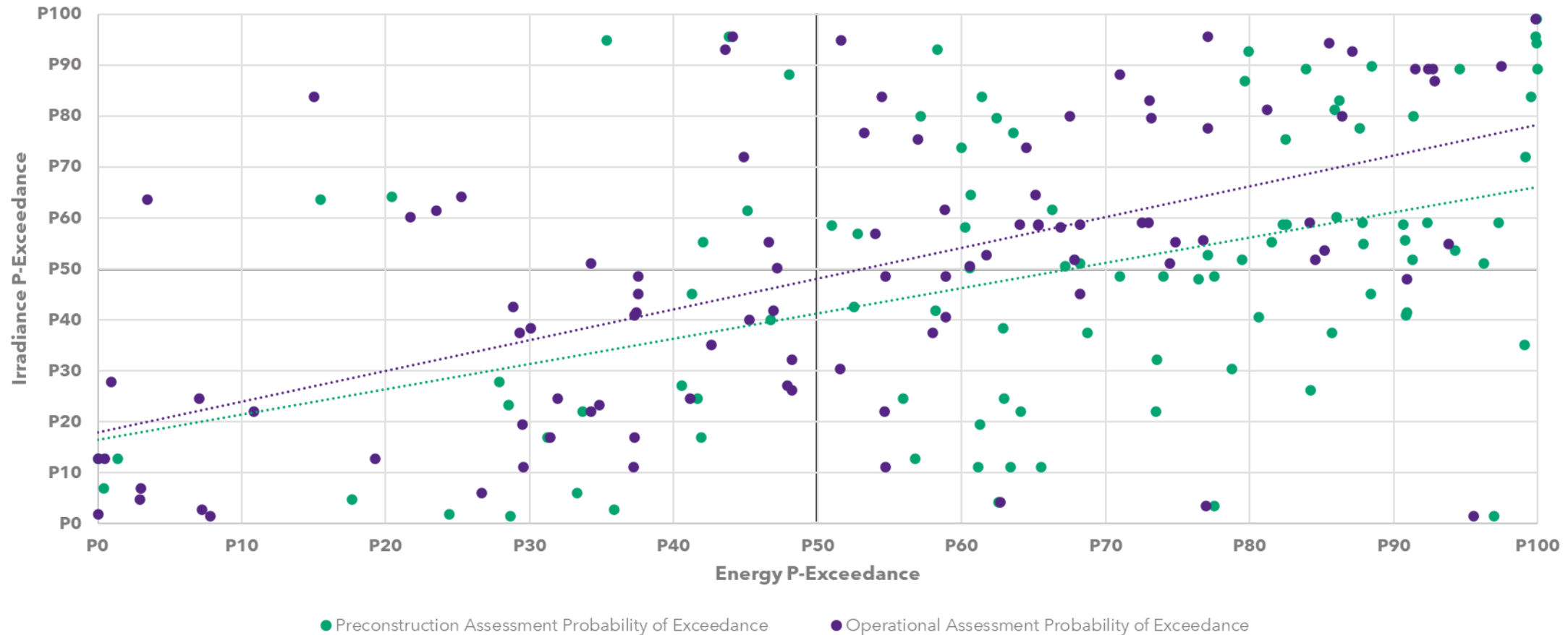
Preconstruction Energy Probability vs Irradiance

98 Discrete Years' Probability of Exceedance from 35 Sites



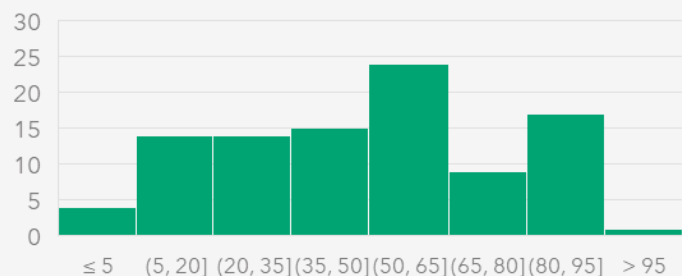
Precon and Operational Probabilities vs Irradiance

98 Discrete Years' Probability of Exceedance from 35 Sites

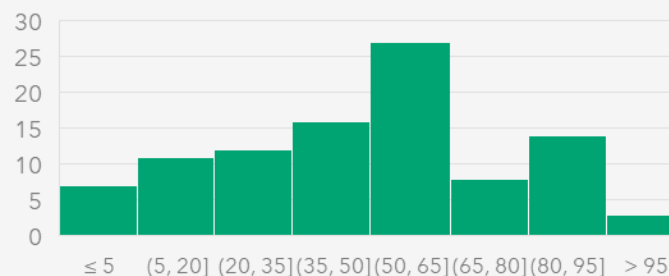


Histograms of Discrete Years Probability of Exceedance

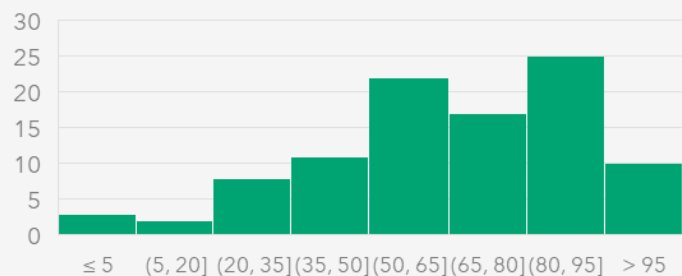
PSM GHI Standard Deviation
Probability of Exceedance



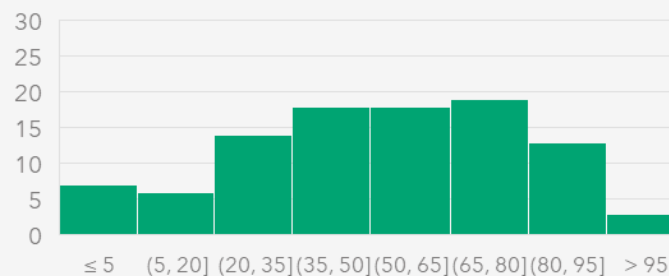
PSM GHI Cumulative Distribution
Probability of Exceedance



Preconstruction Assessment
Probability of Exceedance



Operational Assessment Probability
of Exceedance



- Irradiance distributions are relatively similar despite calculation differences; suggest a largely normally distributed sample of locations / years
- Preconstruction histogram is weighted towards lower production than expected
- Operational histogram is more evenly distributed, suggesting median is closer to P50 than the preconstruction analysis

Conclusions and Next Steps



Takeaways and Future Efforts

We found:

- Older energy modeling may have inconsistencies with operational data, likely due to modeling advancements made in the last several years regarding terrain, sub-hourly clipping, availability, etc.
- Operational assessments can help to better align gross P50 energy with P50 irradiance, especially when availability and curtailment are well defined.

Looking to further evaluate:

- Relationship between P50 irradiance and net energy; how does this effect typical year calculated energy?
- Improvements to uncertainty statistics calculations, including more refined approaches to uncertainty combinations for preconstruction estimates.

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