Funded by:

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

NREL/PR-5D00-80108

Pro2R: Procurement of Ramping Product and Regulation in CAISO Using Probabilistic Solar Power Forecasts

Benjamin F. Hobbs, bhobbs@jhu.edu

Theodore & Kay Schad Professor of Environmental Management
O'Connor Sustainable Research Institute, The Johns Hopkins University
Chair, CAISO Market Surveillance Committee

Venkat Krishnan, Venkat.Krishnan@nrel.gov

Senior Engineer, Sensing and Predictive Analytics
Power Systems Engineering Center
National Renewable Energy Laboratory

SETO Workshop on Solar Forecasting

May 5–6, 2021

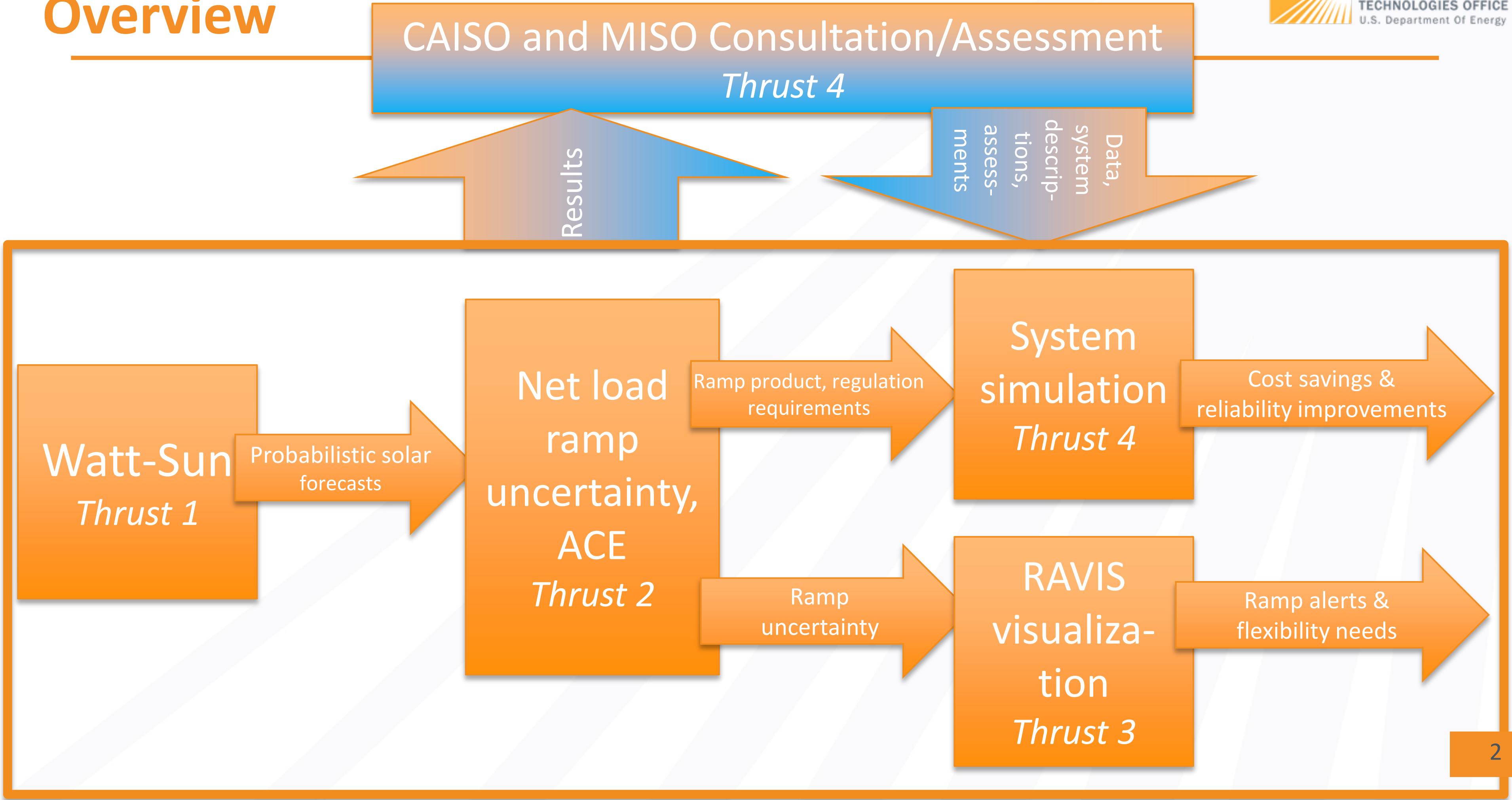
Team members:

Paul Edwards, Haiku Sky, and Ibrahim Krad (NREL)
Carlo Siebenschuh, Hendrik Hamann, and Rui Zhang (IBM)
Jie Zhang, Binghui Li, and Li He (University of Texas-Dallas)
Yijiao Wang, and Shu Zhang (JHU)

Thanks to staff from CAISO and MISO (especially A. Motley, G. Bautista, C. Loutan, R. Webb, S. Rose, and B. Borissov) and SETO for advice and data. Usual disclaimer applies.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number EE0008215. This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for DOE under Contract No. DE-AC36-08GO28308. The views expressed 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.

Overview

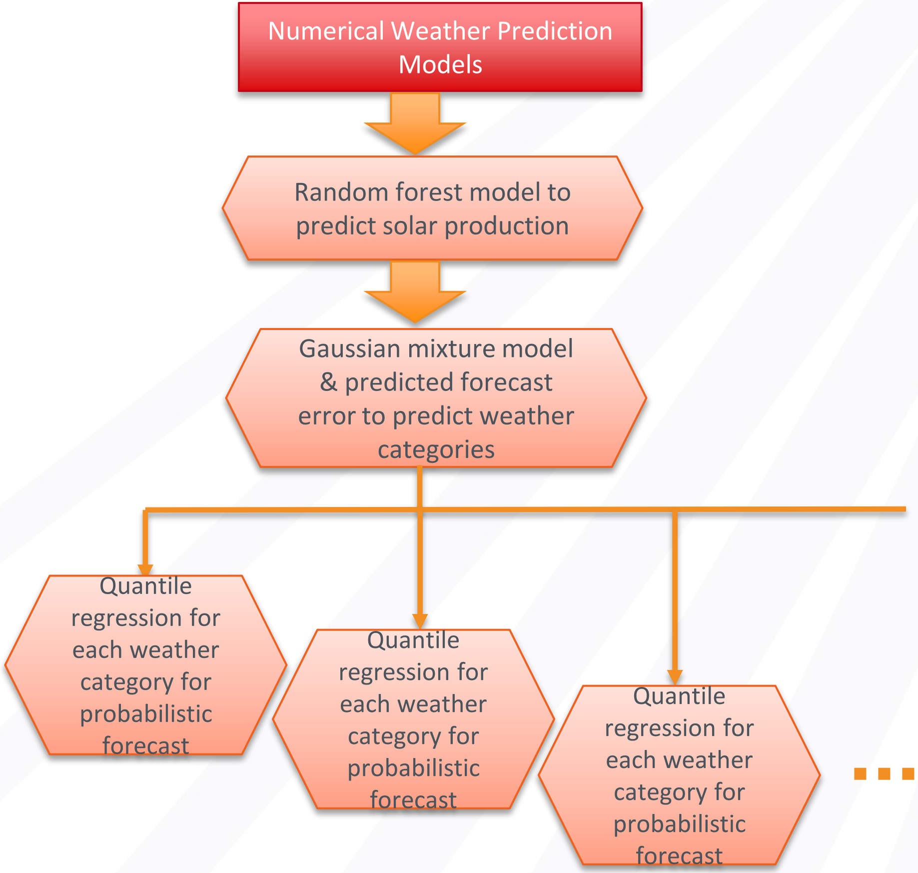

CAISO and MISO Consultation/Assessment
Thrust 4
Results
Data, system descrip- tions, assess- ments
Watt-Sun
Thrust 1
Probabilistic solar forecasts
Net load ramp uncertainty, ACE
Thrust 2
Ramp product, regulation requirements
Ramp uncertainty
System simulation
Thrust 4
Cost savings & reliability improvements
RAVIS visualiza- tion
Thrust 3
Ramp alerts & flexibility needs

Outline

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

1. Comparison of Watt-Sun to base method: P-P index
2. Using solar forecasting prediction intervals to predict ramp and regulation: the Pareto method
3. Simulation of cost-reliability effects of solar-conditioned ramp requirements on the California Independent System Operator (CAISO) system
4. Visualization: Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS).

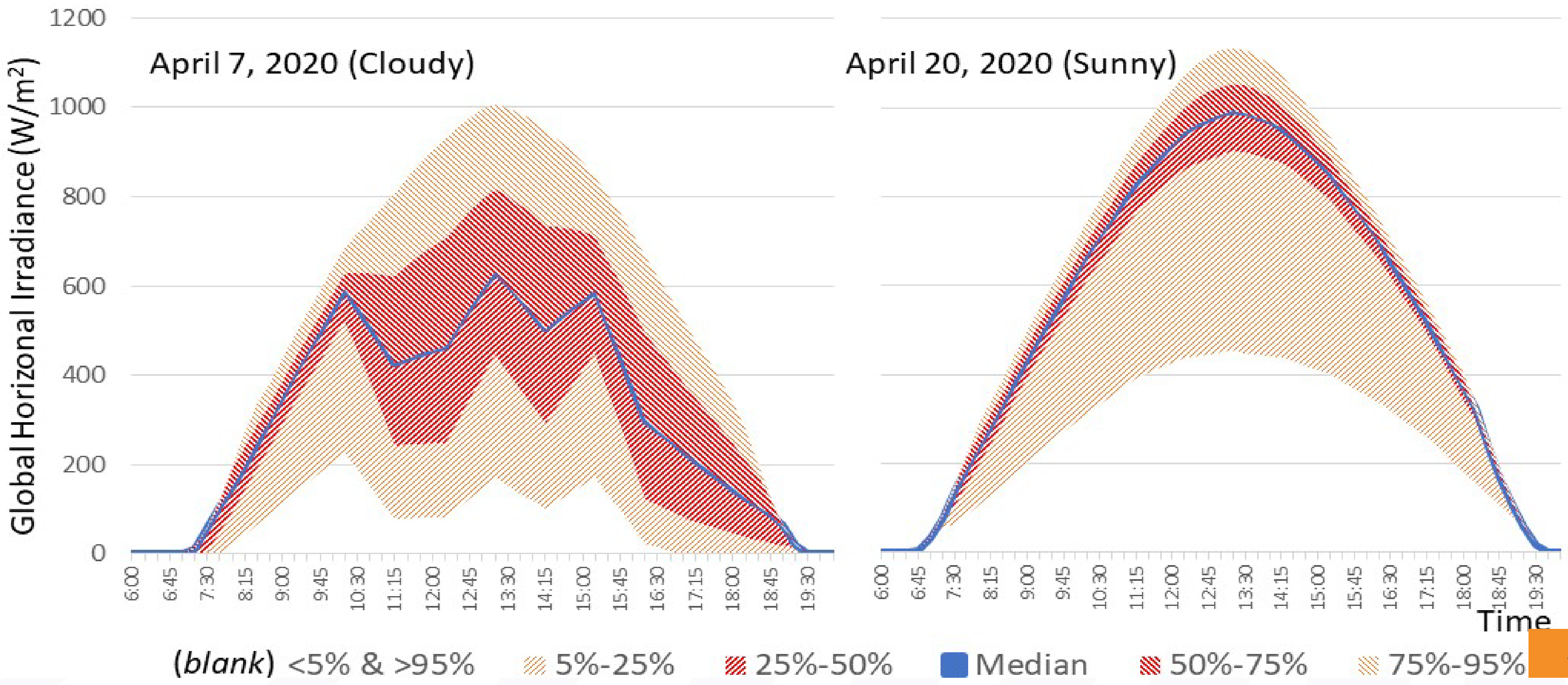
Probabilistic Watt-Sun Flowchart (IBM)



Used Quantile Regression to Deploy Probabilistic Forecast Models

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- Quantiles of solar as a function of independent variables
- Example results for 2-hour-ahead forecasts



Evaluation of Watt-Sun

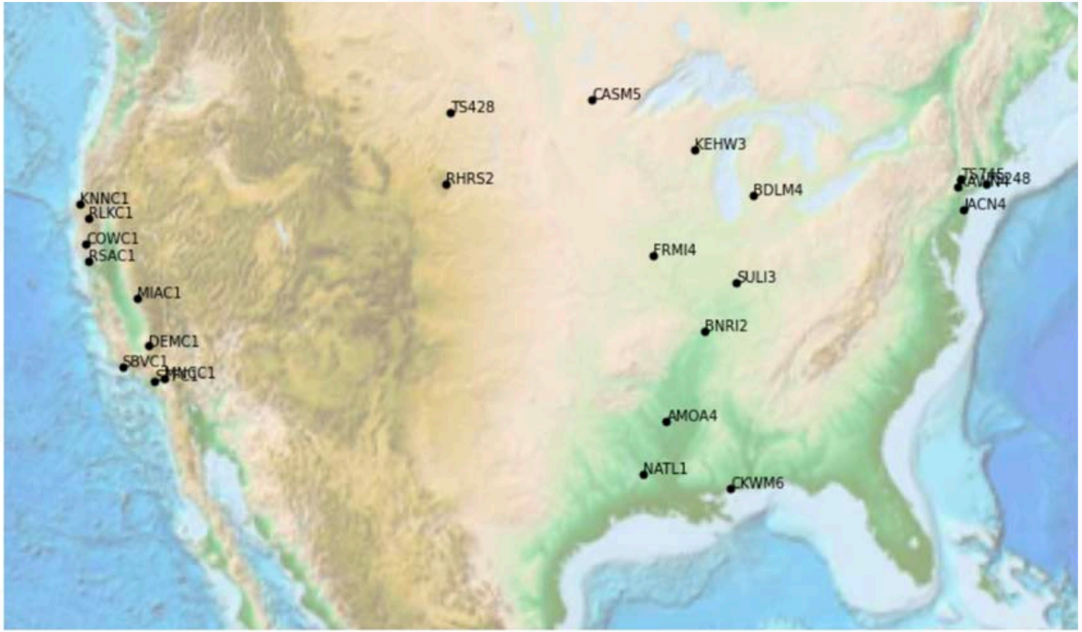
Assessment: Relative improvement of the PP-Plot metric

Temporal:

- Train: Sept. 1, 2018–Feb. 29, 2020
- Test: Mar. 1, 2020–June 1, 2020

Spatial:

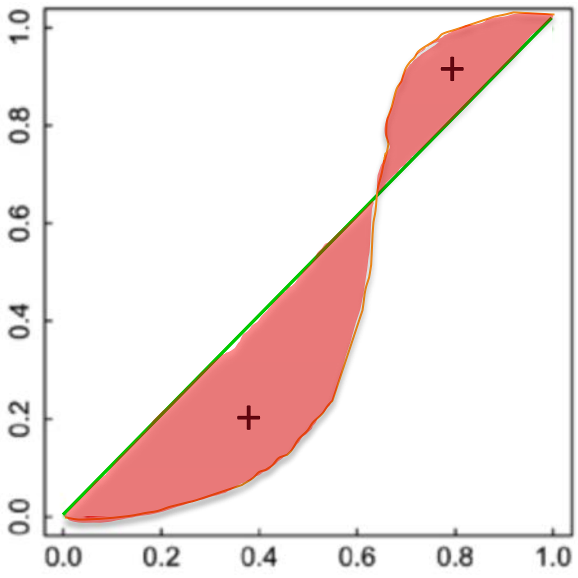
- 24 stations



Map: 24 reference stations

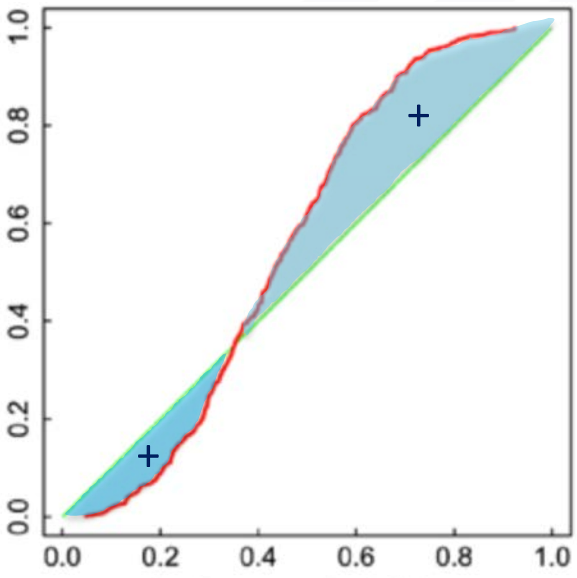
Calibration Quality of Watt-Sun vs. Persistence

Assessment: Relative improvement of the PP-Plot metric

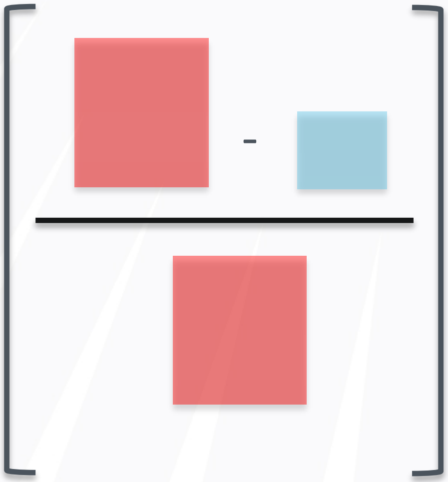


A. Baseline: PP-Plot

–



B. Watt-Sun: PP-Plot

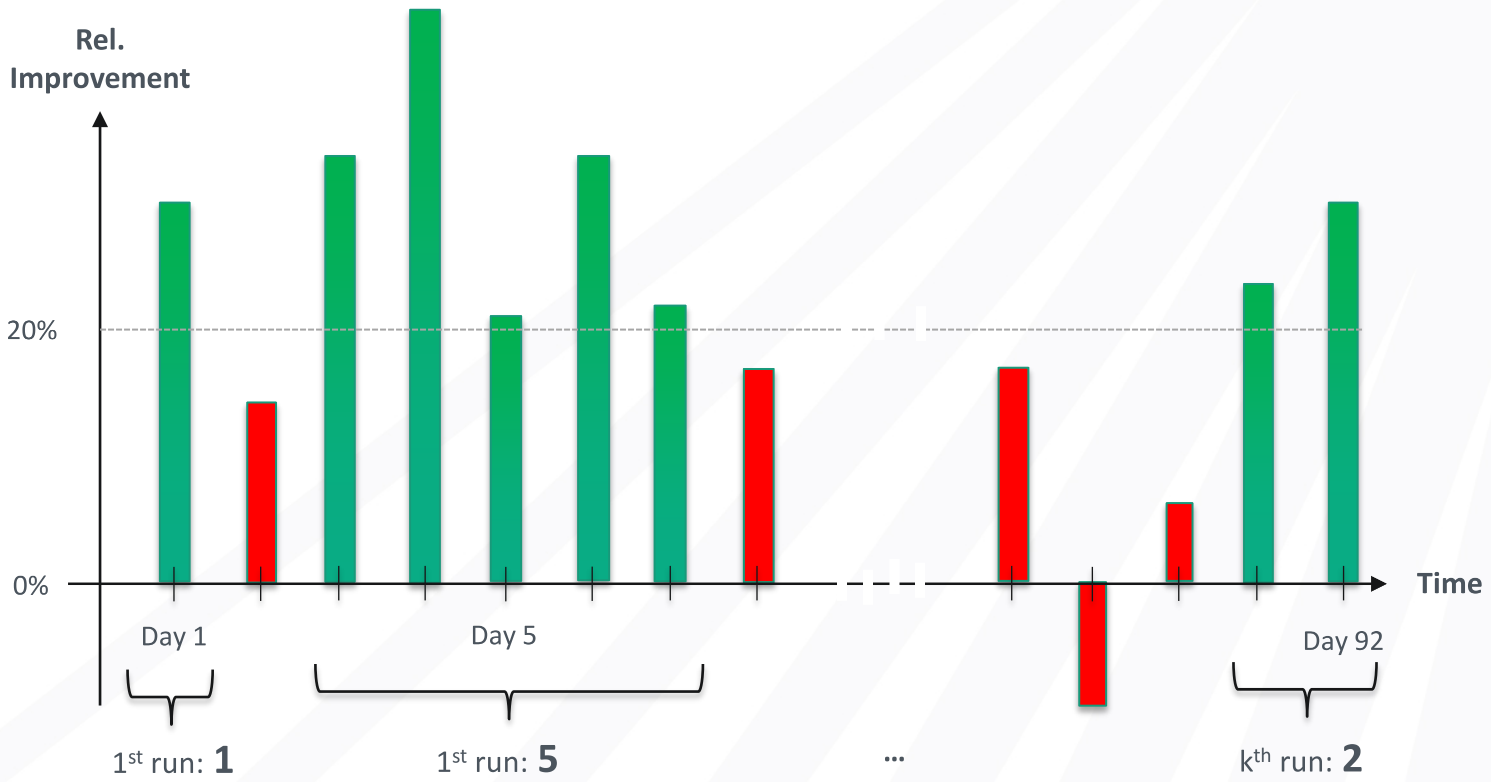


C. Relative PP-Plot metric improvement of Watt-Sun

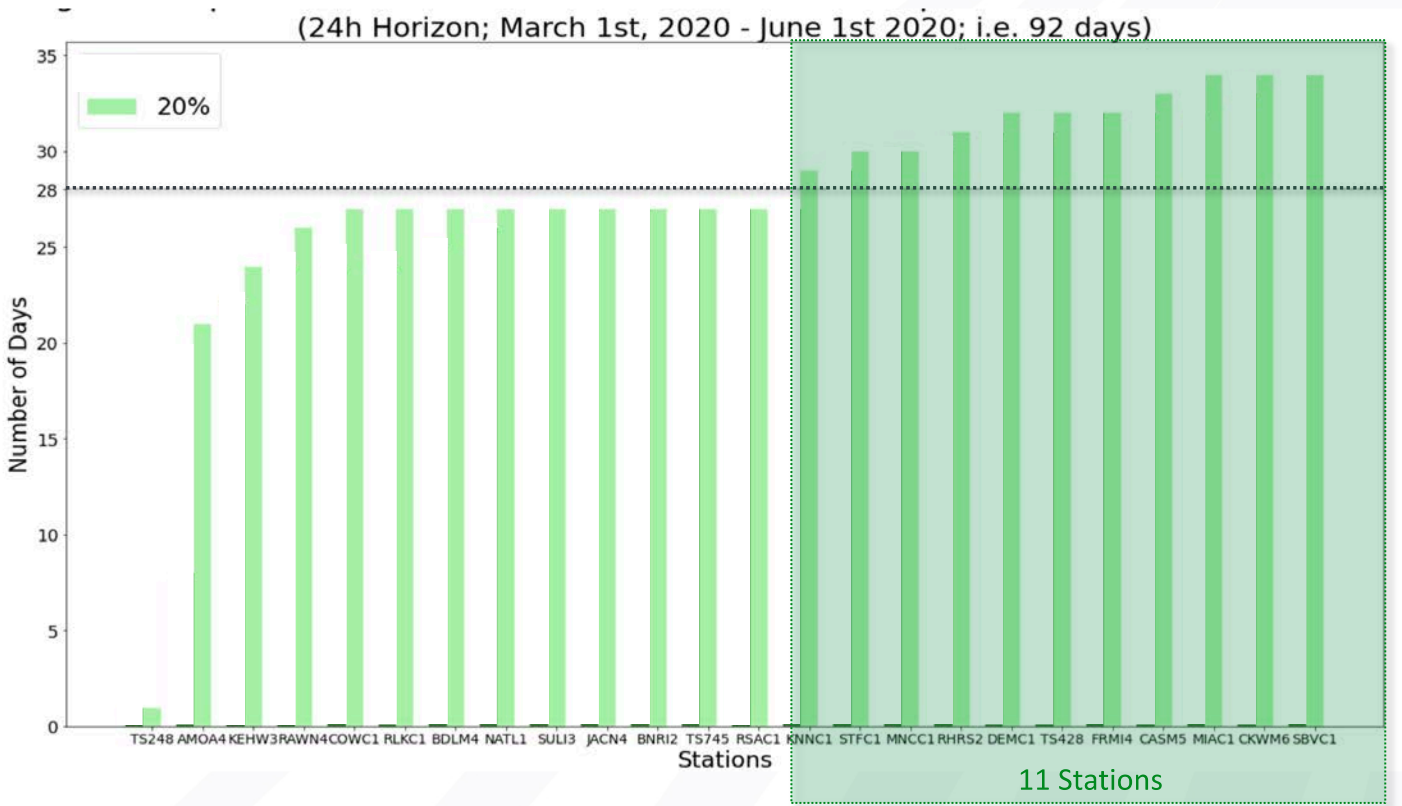
Daily Values of Metric

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Assessment: Relative improvement of the PP-Plot metric



Longest Run per Station with Metric Improvement >20%



Outline

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

1. Comparison of Watt-Sun to base method: P-P index
2. Using solar forecasting prediction intervals to predict ramp and regulation: the Pareto method
3. Simulation of cost-reliability effects of solar-conditioned ramp requirements on the California Independent System Operator (CAISO) system
4. Visualization: Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS)

Flexible Ramping Product: CAISO, MISO, SPP

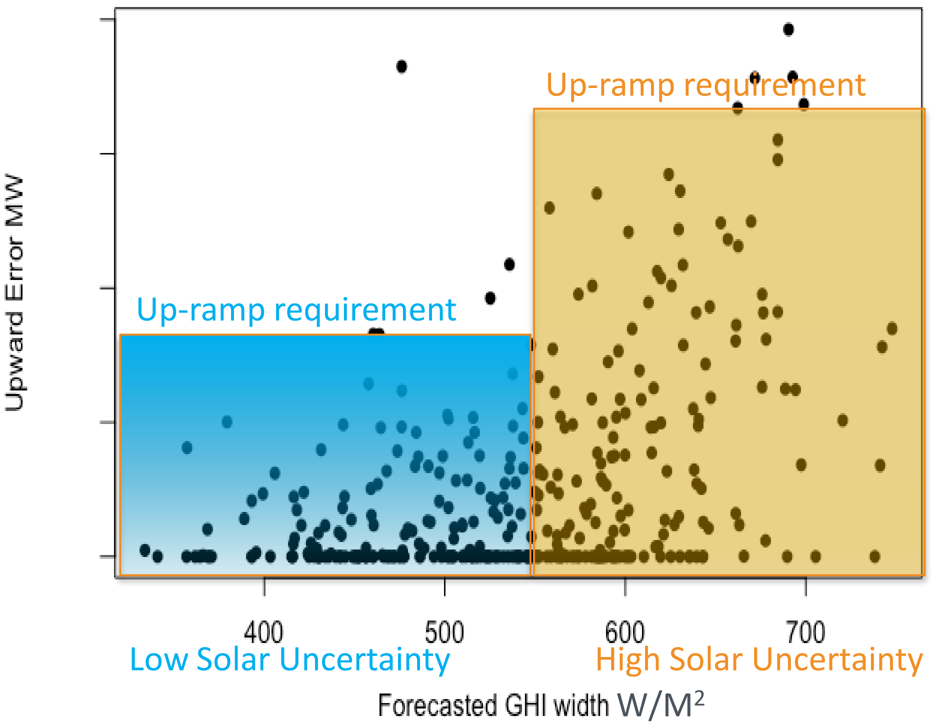
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- CAISO: Need to forecast three components in real-time:
  - Expected 5-minute ramp forecast
  - Uncertainty in up direction (97.5th percentile)
  - Uncertainty in down direction (2.5th percentile).
- Uncertainty distributions are presently unconditional.
  - CAISO is revising to condition requirements on wind, load, solar forecasts (www.caiso.com/StakeholderProcesses/ Flexible-ramping-product-refinements).

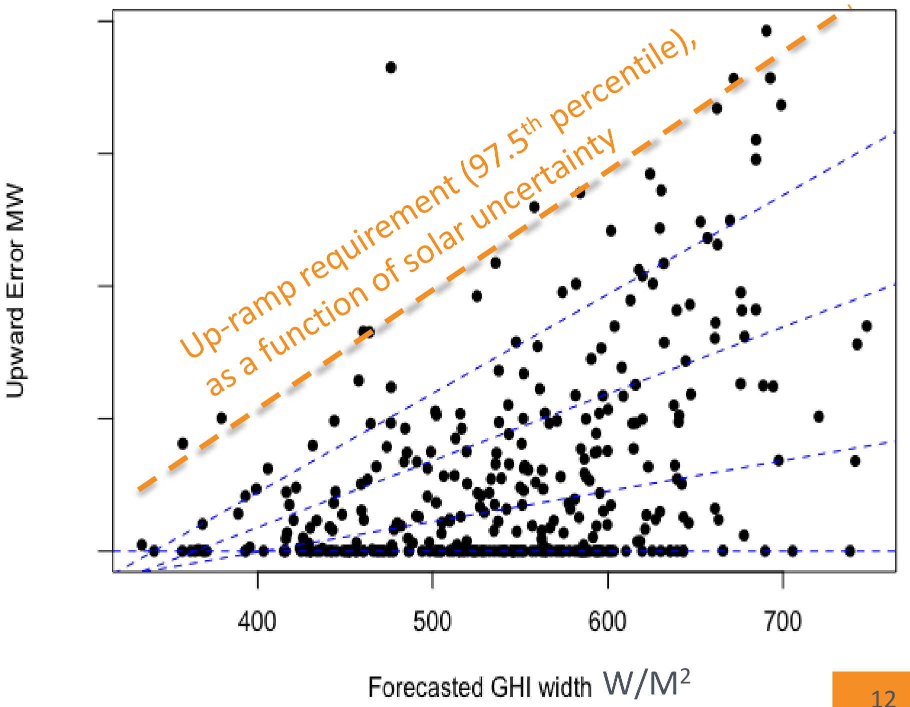
Quantile Analysis: Continuous Classifier Shows Potential to Adjust Net Load Ramp "Up Uncertainty" (JHU)

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Two-way classification results: 11 a.m.–2 p.m. May 2019— 97.5% cutoff (ramp requirement) for each day type



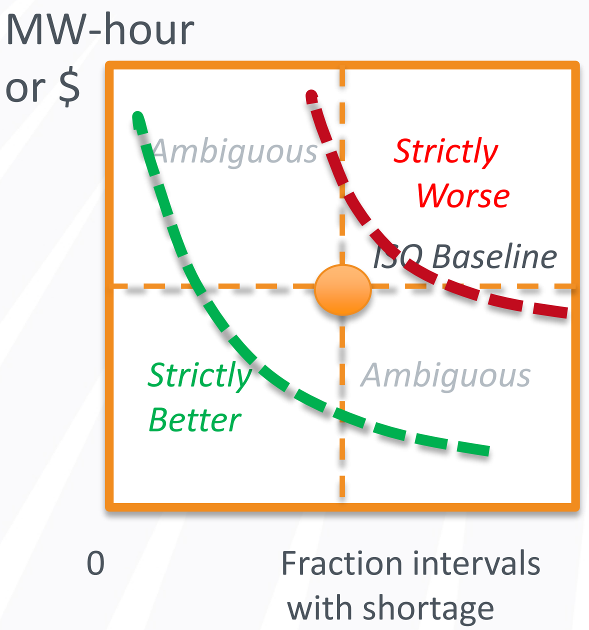
Upward error quantile regression results: 11 a.m.–2 p.m. May 2019 (dashed blue lines are, from top to bottom, respectively: 90th, 75th, 50th, 25th estimated percentiles)



Out-of-Sample Pareto Analysis of Requirements

Methods:

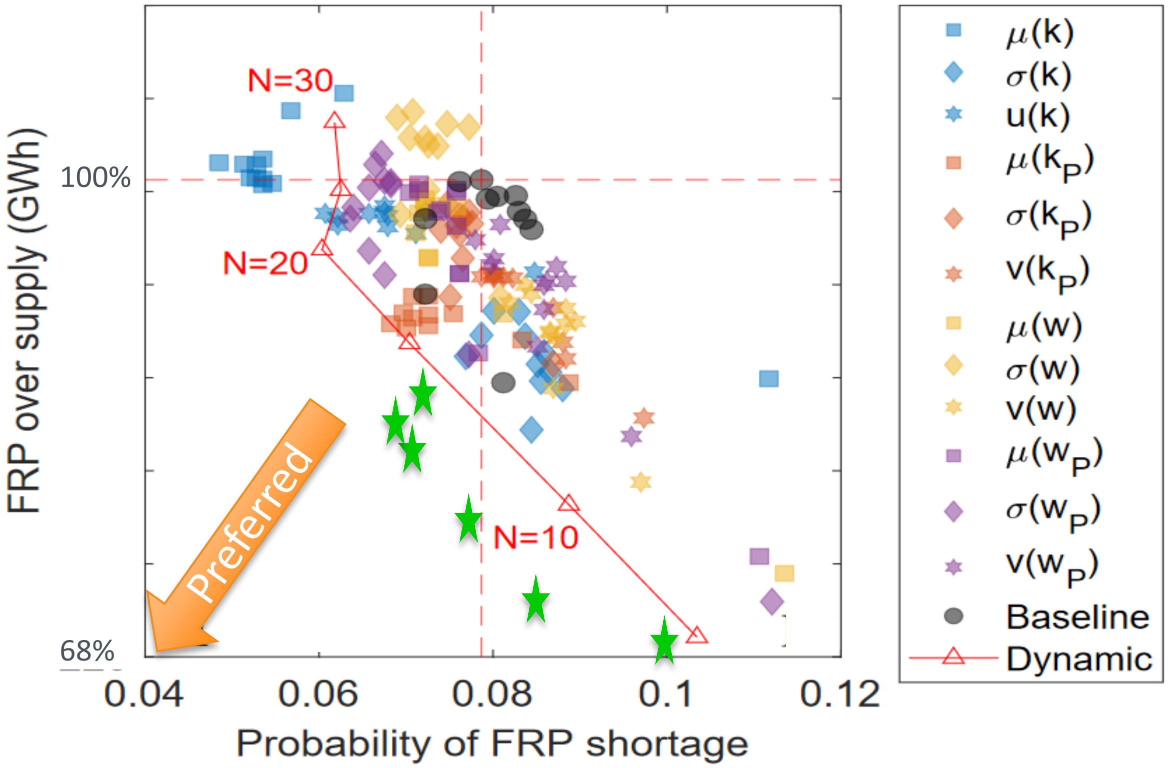
- Compare performance of ramp capacity (MW) requirement method relative to independent system operator (ISO) baseline method using multiple criteria
- Criteria:
  1. Reliability: Fraction of intervals in which ramp capacity (MW) need exceeds requirement ("shortage")
  2. Cost: Total MW-hour/$ cost of requirement.
- Assessment procedure:
  - Simulate rolling estimation method (out-of-sample test)
    - Baseline: Histograms of N previous days' realizations of MW need in that interval
    - Alternative: Statistical or machine learning-based estimate of MW need
  - All methods: Rescale amount or vary target reliability
    - Trade-off: More requirements → less shortage but more cost



kNN/PCA-Based Method for Flexible Ramp Requirements (UTD)

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

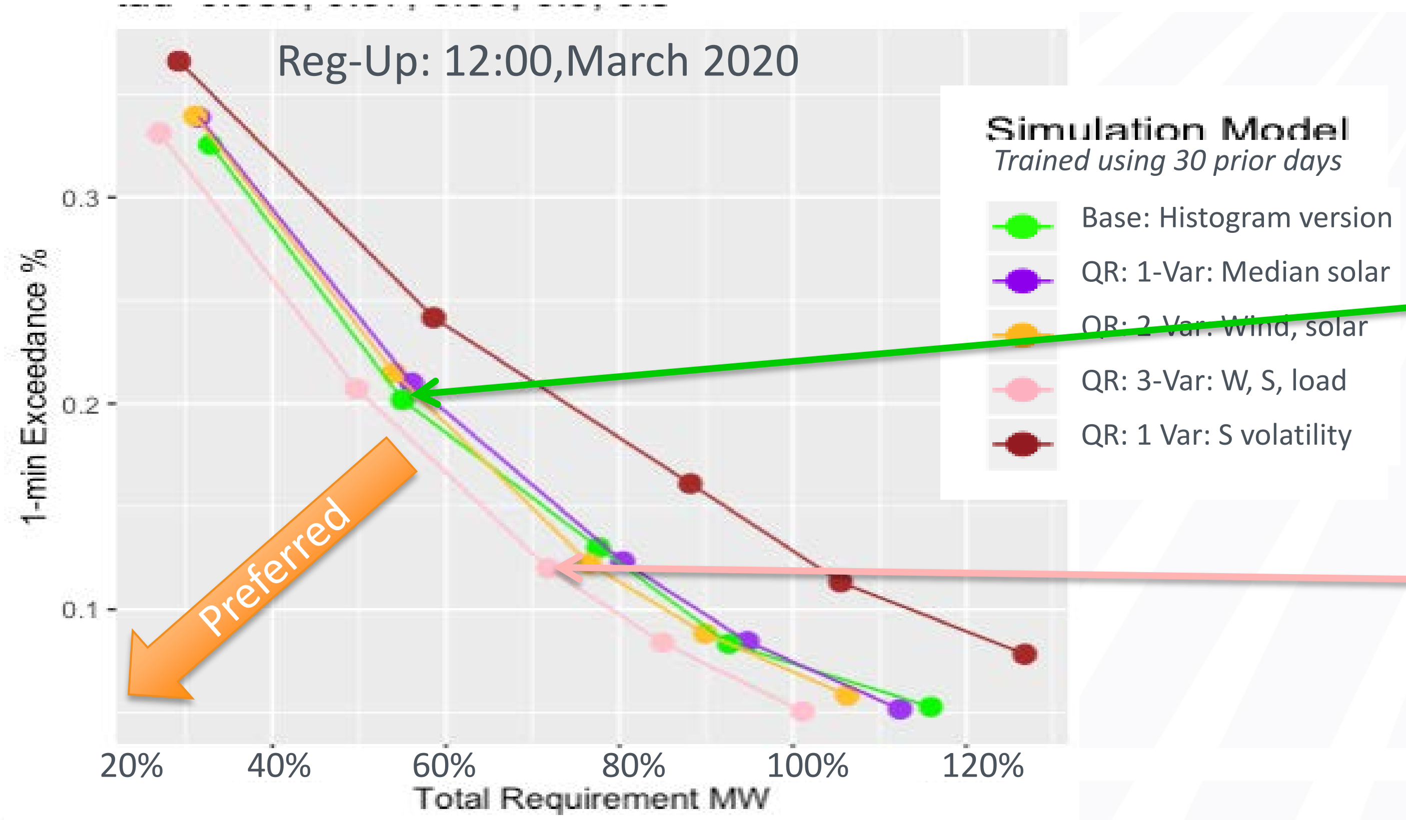
- Shown: kNN-based Flexible Ramping Product (FRP) requirements: Reliability-oversupply trade-offs Feb. 2020.
  - 1-D classifiers from solar site 2 using various predictors.
- Multisite/PCA classifiers perform even better.



Out-of-Sample Pareto Analysis of Weather-Aware *Regulation* Requirements Using Solar Forecasts (JHU)

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Quantile regression-based regulation requirements: Tradeoffs between **reliability** (fraction of 1-min average adjusted ACE > requirement) and **MW supply**. (Unconditional and 1- and 3-variable rolling regressions)



Preliminary results:

- *ISO baseline method performs well.*
- *Adding forecast variables sometimes improves.*

Outline

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

1. Comparison of Watt-Sun to base method: P-P index
2. Using solar forecasting prediction intervals to predict ramp & regulation: the Pareto method
3. Simulation of cost-reliability effects of solar-conditioned ramp requirements on the California Independent System Operator (CAISO) system
4. Visualization: Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS)

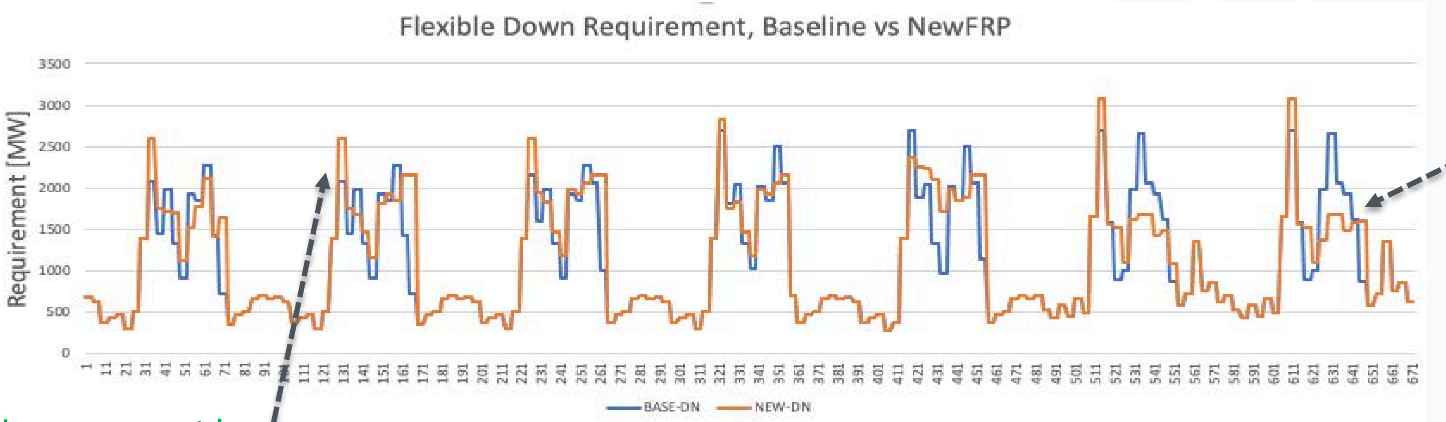
Other relevant materials for this simulation task:

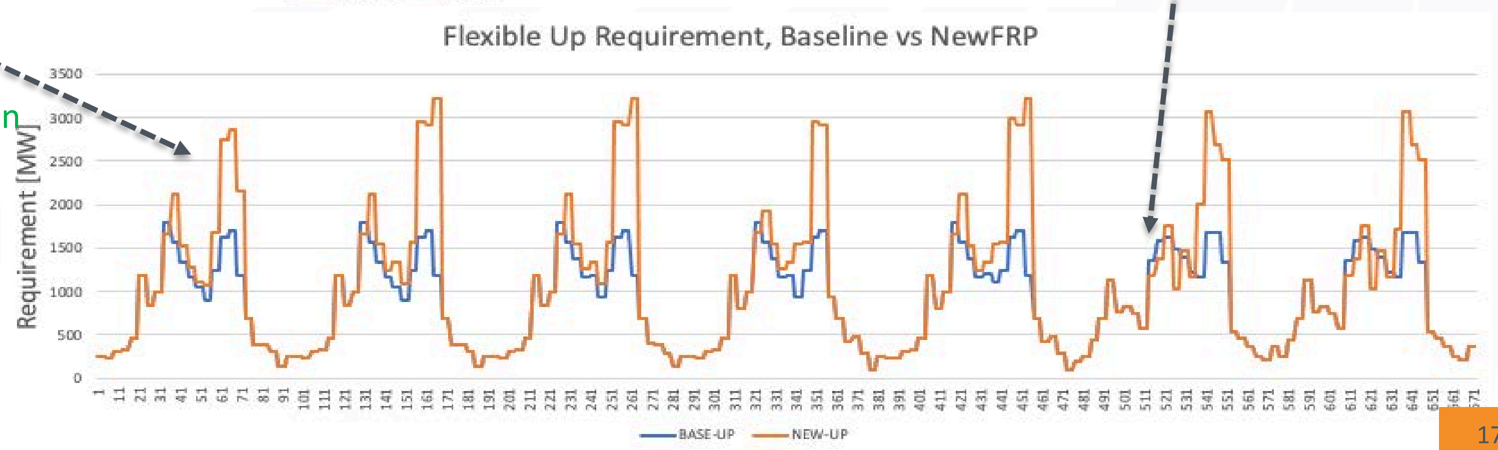
- Presentation 1: ESIG Spring Technical Workshop, 2019
- Presentation 2: Solar Forecasting 2 Annual Review and Workshop, 2019
- IEEE GreenTech 2020 conference paper: https://www.nrel.gov/docs/fy20osti/75544.pdf

Benefits Assessment Using Simulations (NREL)

FRP Analysis March 9–15: Baseline vs. New Flexible Ramp Requirements

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy





- Decrease in peaker units scheduling
- Reduction in production costs

- Improvement in reliability
- Expected reduction in generation scarcity and price spike!
- Reduction in renewable curtailment

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Experimental Setup for Economic Analysis from Simulation

- **Flexible Energy Scheduling Tool for Integrating Variable generation (FESTIV) tool modified with CAISO operating rules**
- **Three scenarios considered:**
  1. ***Baseline*—used historical FRP requirements obtained from the Open-Access Same-Time Information System**
  2. ***New FRP*—used new machine learning-based FRP requirements calculated by the team**
  3. ***Perfect*—perfect knowledge (i.e., forecasts) representing operations without netload uncertainty.**
     - Will be used to obtain uncertainty-induced costs under scenarios 1 and 2 by subtracting the total costs from the "*perfect*" run

Note: Another metric used in economic analysis will be *"total FRP procurement costs"* (total of "FRP procured" times the "FRP market clearing prices/duals" in various intervals). Only intervals with binding FRP constraints will have nonzero FRP marginals.

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Simulation Results – CAISO-Like IEEE 118-Bus System

- FESTIV market clearing process modified with CAISO operating rules
- IEEE 118 simulated for 3 weeks in March (9–29, 2020):

	Baseline (Scenario 1)	New FRP (Scenario 2)	Perfect NO uncertainty
Total Production Cost [$M]	23.45	23.05 *(1.7% savings)*	23.00
Total Uncertainty Cost [$M]	0.45	0.05 *(~90% savings)*	

- Uncertainty-induced costs reduced by a daily average of 44%
  - Savings in production cost from lower FRP (reduction in peaker units)
  - Higher FRP reduces generation scarcity events and real-time price spikes
  - More flexible generation, with lower min. gen → reduced curtailment.

Total VG Curtailment [GWh]	69.1	63.9 *(more VG)*

Simulation Results – Large 1,820-Node WECC/CAISO System

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

~1,820 buses: 1,782 buses for CAISO and 38 for other WECC regions and trading hubs

- **Copperplate analysis for 3 weeks in March (9–29, 2020):**

Total Production Cost ($M)	Baseline (Scenario 1)	New FRP (Scenario 2)	Savings in uncertainty costs (comparing with "perfect" run)
Week 1 (March 9-15)	70.72	70.56 *(0.3% savings)*	1.13%
Week 2 (March 16-22)	49.35	49.29 *(~0.09% savings)*	6.3%
Week 3 (March 23-29)	44.95	44.94 *(0.01% savings)*	0.27%
All weeks (March 9-29)	165.02	164.75 (0.16% savings)	~1.7% (~$270K)

$0.27M savings in uncertainty-induced costs **in 21 days ~ extrapolate to $4.7M/y***

*Note: Good annual estimations of cost savings will require longer-term simulations under myriads of scenarios

Simulation Results – Large 1,820-Node WECC/CAISO System

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Due to the computational burden of simulations with full network, few different days in March 2020 were simulated.

- With full network analysis: $0.43M savings in 8 days simulated

Total Production Cost ($M)	Baseline (Scenario 1)	New FRP (Scenario 2)	Savings in uncertainty costs (comparing with "perfect" run)
5 days: March 16-20	66.9	66.5 *(0.5% savings)*	2.34% (~$332K)
1 day: March 23	11.94	11.91 *(~0.23% savings)*	10.6% (~$28.3K)
3 days: March 23-25	39.74	39.65 *(0.24% savings)*	~1.7% (~$97K)

Total FRP procurement Cost ($K)	Baseline (Scenario 1)	New FRP (Scenario 2)
5 days: March 16-20	76.14	67.53 (11.3% savings ~ 8.6K)
3 days: March 23-25	60.38	28.9 (52.15% savings ~ 31.5K)

High solar penetration and conventional generation flexibility limited scenarios may further increase the cost benefits of using probabilistic forecasts based FRP procurements

Outline

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

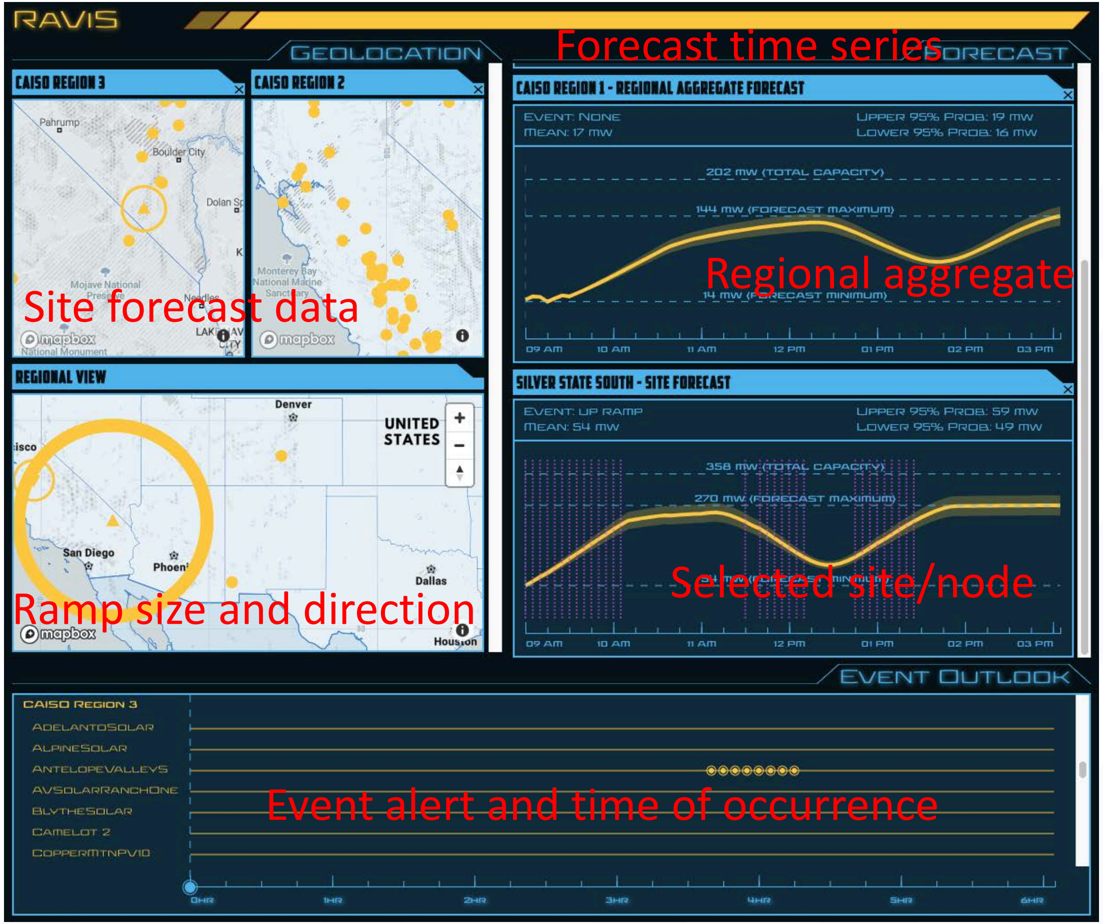
1. Comparison of Watt-Sun to base method: P-P index
2. Using solar forecasting prediction intervals to predict ramp & regulation: the Pareto method
3. Simulation of cost-reliability effects of solar-conditioned ramp requirements on CAISO system
4. Visualization: Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS)

Open-source link to the source code: https://github.com/ravis-nrel/ravis

Public-facing demo with past forecasts (2017 solar eclipse): https://maps.nrel.gov/ravis

Resource Forecasts and Ramp Visualization for Situational Awareness RAVIS

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy



RAVIS: A modular dashboard for viewing:

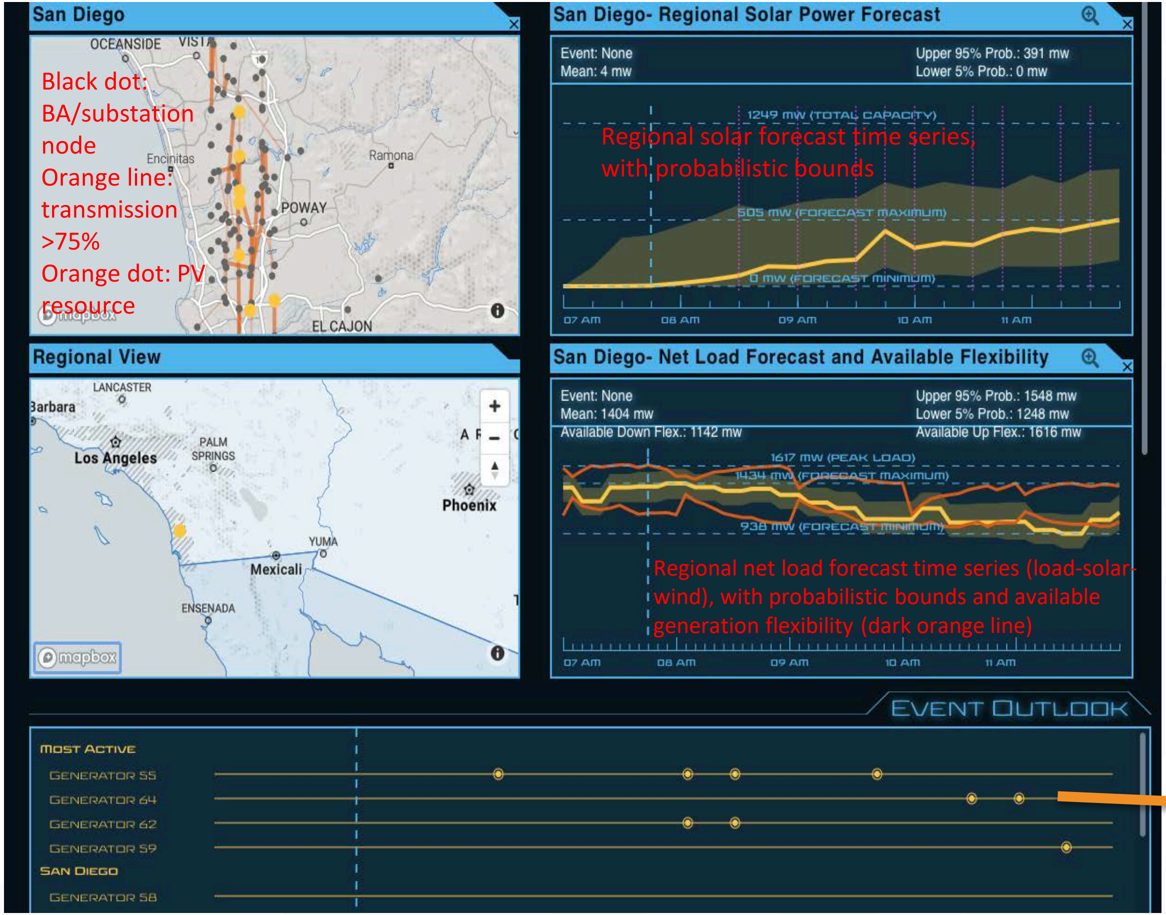
- Forecast timeline
- Spatially relevant forecasts and events
- Details of specific events as desired, including market data.

Design: RAVIS's technology suite is assembled to ***provide optimum visualization facility.***

- Takes ***advantage of web application technologies*** and tooling
- These technologies ***enable deployment in any environment***, using any operating system.

Can Also Show Net Load Time-Series Forecasts and Available Generation Headroom/Flexibility

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy



Flexible architecture to visualize more data:

- Net-load forecasts, or each component
- Available generation flexibility
- Network nodes
- Transmission
- Prices

Sorted ramp events: **"most active"** (e.g., most events in the next 5 hours)

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Summary of Features Visualized in RAVIS

1) **Site-specific probabilistic solar power forecasts**:

   Hovering reveals forecast data and other metadata; ramp size and direction are shown by circle and arrow.

2) **Time-series forecast data:** Clicking a site/region shows individual site-specific probabilistic forecast time series.

3) **Event alerts (e.g., ramp alerts)**, at site as well as regional level

4) **User can configure visualization parameters:**

   a) Specific sites or user-defined aggregate regions

   b) Ramp definition customizable by end user.

5) **Data from market clearing engine integrated with forecasts viewer:**

   a) **On map:** Network topology, nodal prices, transmission congestion

   b) **On time series:** Available generation flexibility, plotted against net load forecasts.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Open Source, Publicly Accessible/Extensions

1) **Open-source link to source code: https://github.com/ravis-nrel/ravis**
2) **Public-facing demo (2017 solar eclipse data): https://maps.nrel.gov/ravis**

3) Documentation published @ https://www.nrel.gov/docs/fy21osti/79746.pdf.

Edwards, Paul, Haiku Sky, and Venkat Krishnan. 2021. RAVIS: Resource Forecast and Ramp Visualization for Situational Awareness—An Introduction to the Open-Source Tool and Use Cases. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-79746.

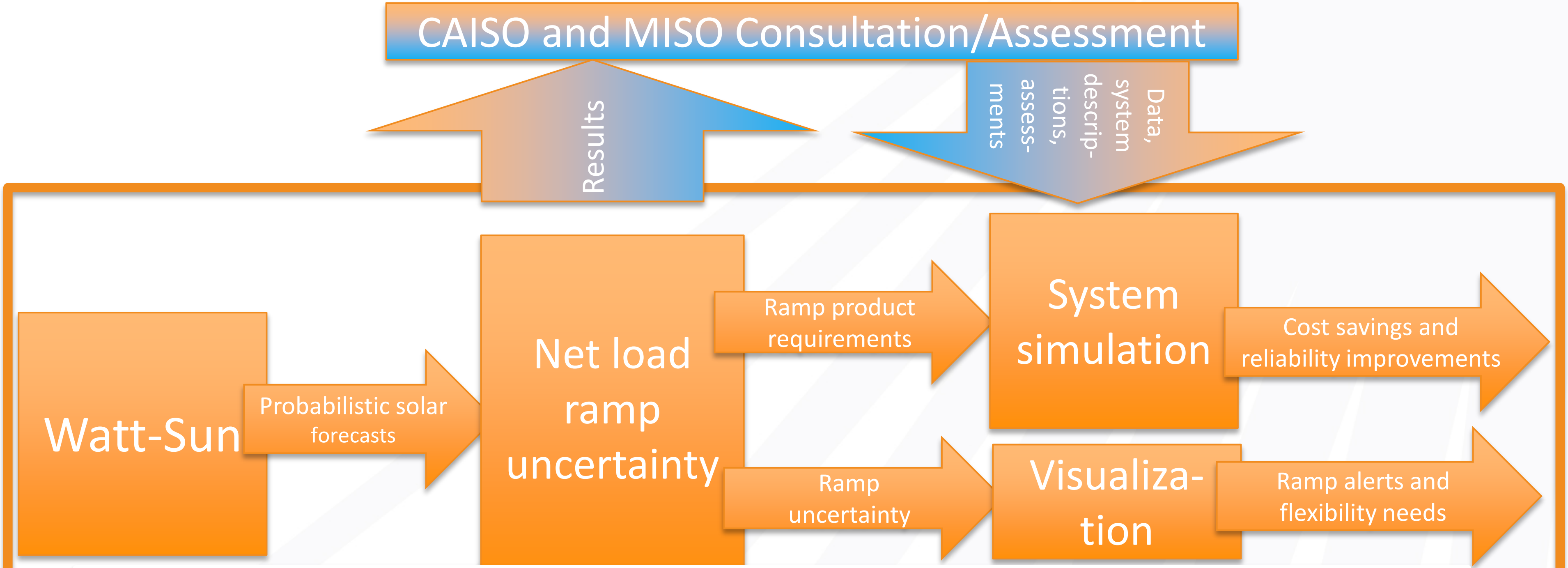
4) EnergyViz conference publication @ https://www.nrel.gov/docs/fy21osti/79786.pdf

Future extensions:

- Transmission and distribution grids with grid-edge visibility
- **Ongoing project:** Sensor data and cyber threat integration
  - (U.S. Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response (CESER) funded project Situational Awareness and Grid Analytics (SAGA) project at NREL.)

Conclusion

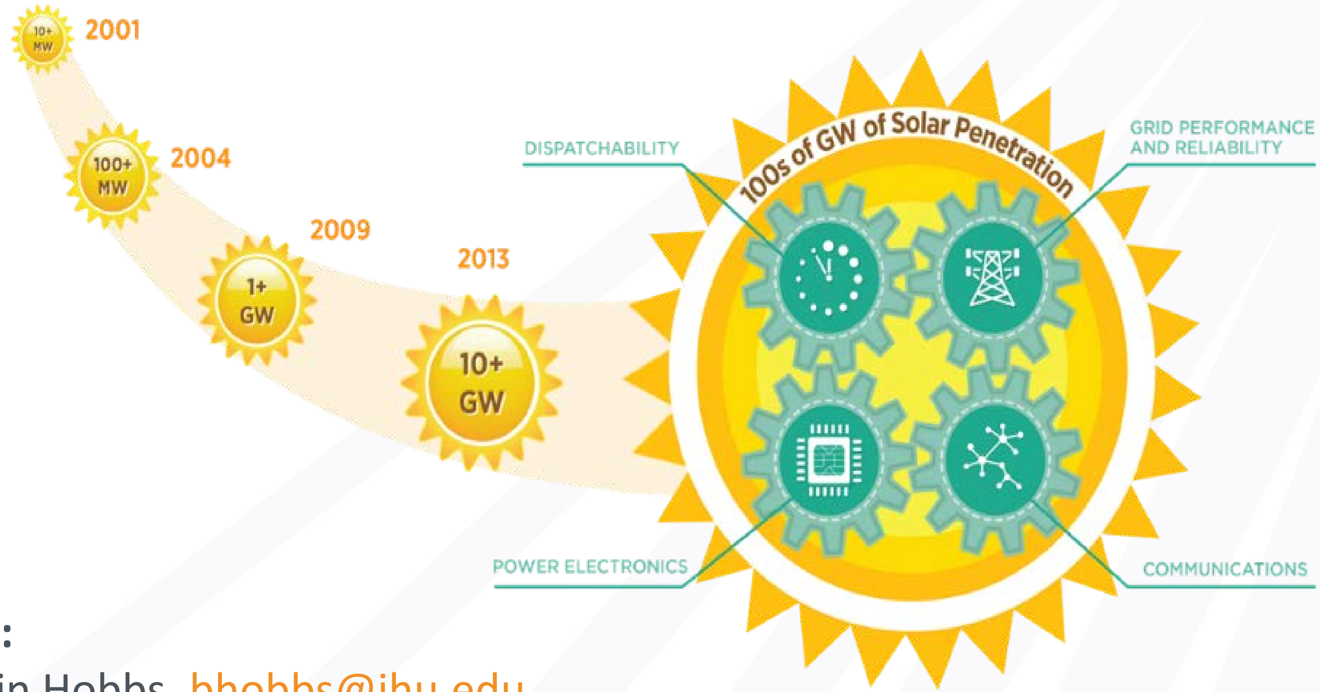
Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy



- We conclude that probabilistic forecasts are a highly promising way to condition ancillary service requirements on up-to-date weather forecasts.
- ***Future:*** Convolve wind, retail load, and solar forecasts for fuller picture.

Questions?

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy



Contact:

Benjamin Hobbs, bhobbs@jhu.edu

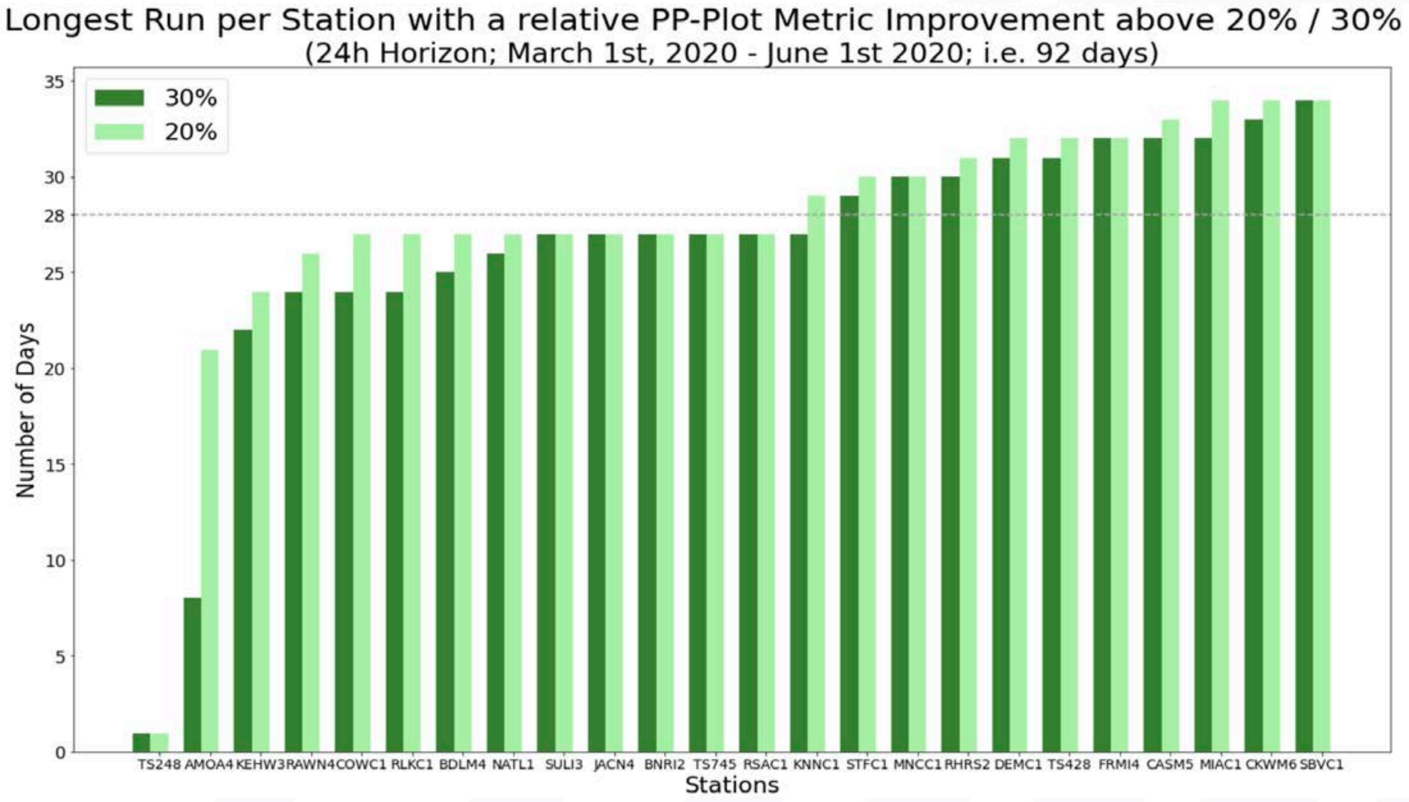
Venkat Krishnan, Venkat.Krishnan@nrel.gov

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Backup/Extra Slides

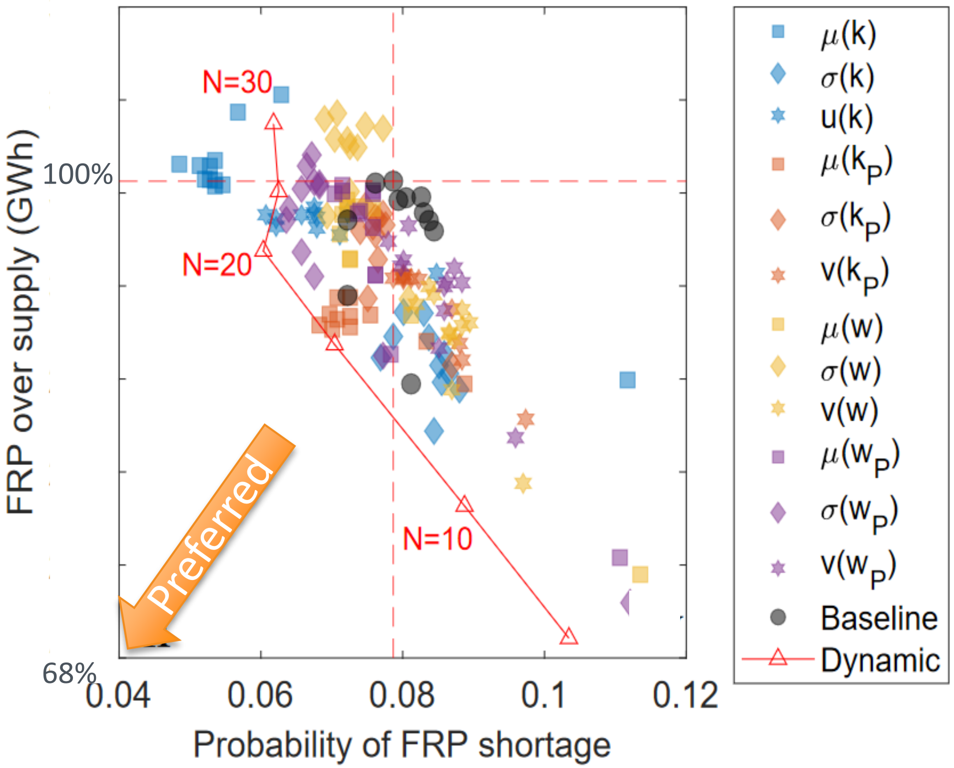
Continuous Improvements of Watt-Sun

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

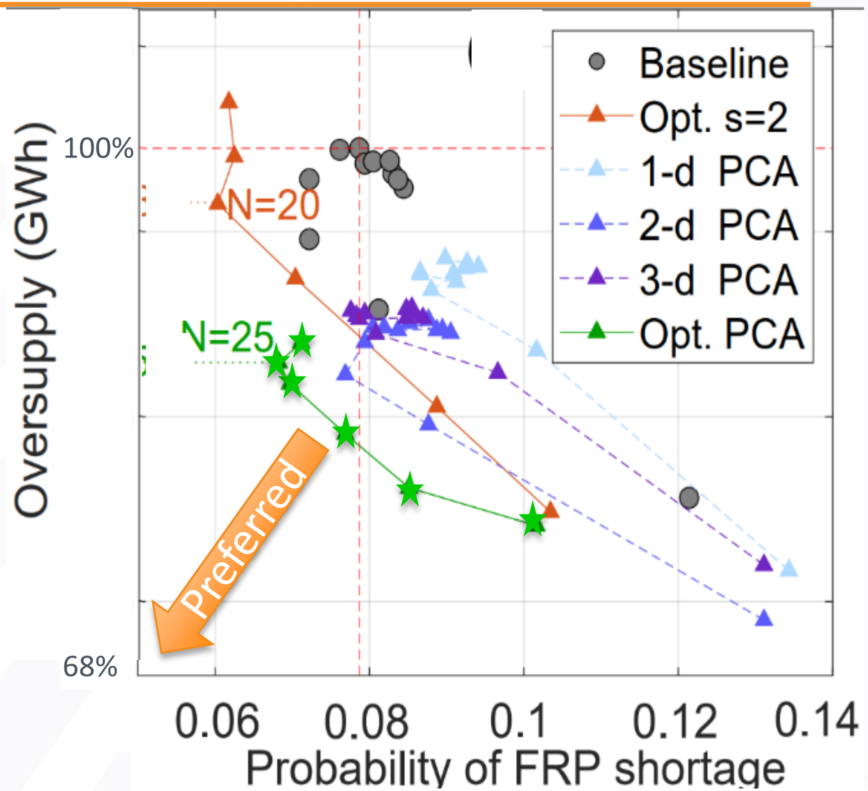


PCA/kNN-Based Method for FRP Estimation (UTD)

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy



kNN-based FRP requirements: Reliability-oversupply, trade-offs Feb. 2020. (1-D classifiers from solar site 2 using various predictors)



PCA-based kNN analysis of FRP requirements from multiple sites