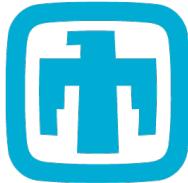


# Solar Forecast Arbiter

## An open source evaluation framework for solar forecasting



Sandia  
National  
Laboratories



ELECTRIC POWER  
RESEARCH INSTITUTE



William F. Holmgren, Clifford W. Hansen, Aidan Tuohy, Justin Sharp, Antonio T. Lorenzo, Leland J. Boeman, Adam Wigington, David P. Larson, Qin Wang, Anastasios Golnas



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# Evaluation Problems Identified by Stakeholders

- **Researcher** wants to analyze new solar forecasts in a variety of climate regions.
- **Funding manager** wants a neutral quantification of improvement over a meaningful reference.
- **Forecast provider** wants to standardize evaluations and ensure its forecasts are fairly assessed by end users.
- **Forecast user** wants to compare accuracy of forecasts from many providers in an operational setting.



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# Solar Forecast Arbiter

## Tool for analyzing accuracy of solar forecasts

- Web-based user interface
- Web-based API for scripting
- Python software package for analysis
- Scripts to redeploy entire software stack
- Detailed supporting documents
- Supported by stakeholder input, feedback

The screenshot shows the GitHub repository page for the Solar Forecast Arbiter project. It features three main repository cards:

- solarforecastarbiter-core**: Core data gathering, validation, processing, and reporting package for the Solar Forecast Arbiter. Details: Python, MIT license, 8 stars, 51 forks, 3 issues, updated 19 hours ago.
- solarforecastarbiter-api**: HTTP API and database schema for the Solar Forecast Arbiter. Details: TSQL, MIT license, 3 stars, 27 forks, 1 issue, updated 5 days ago.
- solarforecastarbiter\_dashboard**: Templates and code for rendering the Solar Forecast Arbiter dashboard. Details: HTML, MIT license, 3 stars, 23 forks, 4 issues, updated 19 days ago.

On the right side, there are sections for "Top languages" (Jupyter Notebook, Python, HTML, Dockerfile, TSQL) and "People" (a grid of profile pictures). A "Customize pins" button and a "New" button are also visible at the top right.

Open source. Transparently developed on GitHub



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# How do I use the Solar Forecast Arbiter?

- 1. Define site, observation and/or forecast metadata**
- 2. Upload observation and/or forecast data**
- 3. Optional: grant another user access to your metadata/data**
- 4. Run analysis report**

## Create New Forecast

### Site Metadata

Name: Power Plant 1  
Latitude: 43.73401 °N  
Longitude: -96.62328 °E  
Timezone: Etc/GMT+6  
Elevation: 786.0 m

Modeling Parameters:  
AC Capacity: 0.015 MW  
DC Capacity: 0.015 MW  
AC Loss Factor: 0.0 %  
DC Loss Factor: 0.0 %  
Temperature Coefficient: -0.002 1/C  
Tracking Type: fixed  
Surface Tilt: 45.0 °  
Surface Azimuth: 180.0 °

Name

Variable

 GHI (W/m<sup>2</sup>)

Issue time of day

 00 : 00 UTC

Lead time to start

 Minute

Run length/Issue frequency

 Minute

Interval length

 Minute

Interval Label

 Beginning

Interval Value Type

 Mean

# How do I use the Solar Forecast Arbiter?

1. Define site, observation and/or forecast metadata
2. **Upload observation and/or forecast data**
3. Optional: grant another user access to your metadata/data
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My data is formatted in:

CSV  JSON

Forecast data in CSV format should follow the formatting of the example below.

```
# optional header, ignored by Solar Forecast Arbiter  
timestamp,value  
2018-11-22T12:00:00Z,10.23  
2018-11-22T12:05:00Z,10.67
```

No file selected.

Solar Forecast Arbiter API (1.0beta3+1.g)

Download OpenAPI specification: [Download](#)

Solar Forecast Arbiter Team: [info@solarforecastarbiter.org](mailto:info@solarforecastarbiter.org)

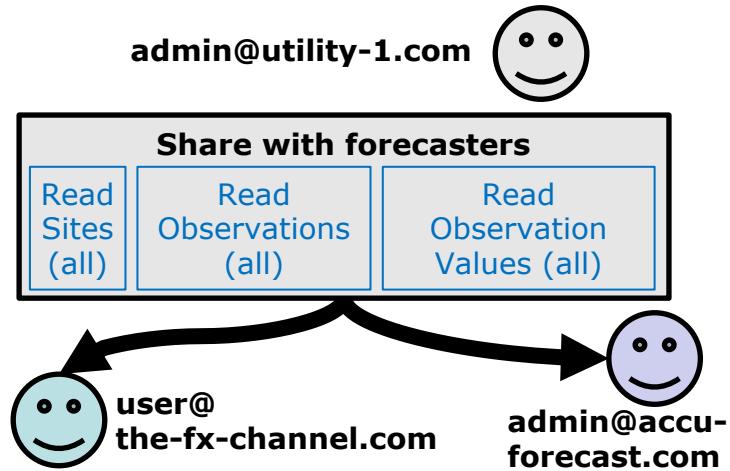
URL: <https://github.com/solararbiter/solarforecastarbiter-api> | License: [MIT](#)

The backend RESTful API for Solar Forecast Arbiter.



# How do I use the Solar Forecast Arbiter?

1. Define site, observation and/or forecast metadata
2. Upload observation and/or forecast data
3. **Optional: grant another user access to your metadata/data**
4. Run analysis report



# How do I use the Solar Forecast Arbiter?

1. Define site, observation and/or forecast metadata
2. Upload observation and/or forecast data
3. Optional: grant another user access to your metadata/data
4. Run analysis report

## Create New Report

### Name

### Start (UTC):

### End (UTC)

### Observation, Forecast pairs

#### Forecasts

 Table Mountain Boulder CO Day Ahead GFS ghi Desert Rock NV Day Ahead GFS ghi[Create Forecast Evaluation pairs ▾](#)

#### Observations/Aggregates

 Table Mountain Boulder CO ghi Desert Rock NV ghi

### Metrics

- MAE
- MBE
- RMSE
- MAPE
- NMAE
- NMSE
- NRMSE
- r
- R^2
- CRMSE
- KSI
- OVER
- CPI

### Categories

- Total
- Year
- Month of the year
- Hour of the day
- Date
- Day of the week

# Example Report

## surfrad ghi hrrr gfs    Intro/Metadata

This report of solar forecast accuracy was automatically generated using the [Solar Forecast Arbiter](#).

Download as [html](#) or [pdf](#) (coming soon). The download is a ZIP archive that includes checksums for the report file and a PGP signature that can be used to verify the authenticity of the report. The Solar Forecast Arbiter PC key ID is `0x22bd497c0930f8b0`.

Please see our GitHub repository for [known issues](#) with the reports or to create a new issue.

Contents:

- Report metadata
- Data
  - Observations and forecasts
  - Data validation
- Metrics
  - Total analysis
  - Year analysis
  - Month of the year analysis
  - Hour of the day analysis
  - Date analysis
- Versions

### Report metadata

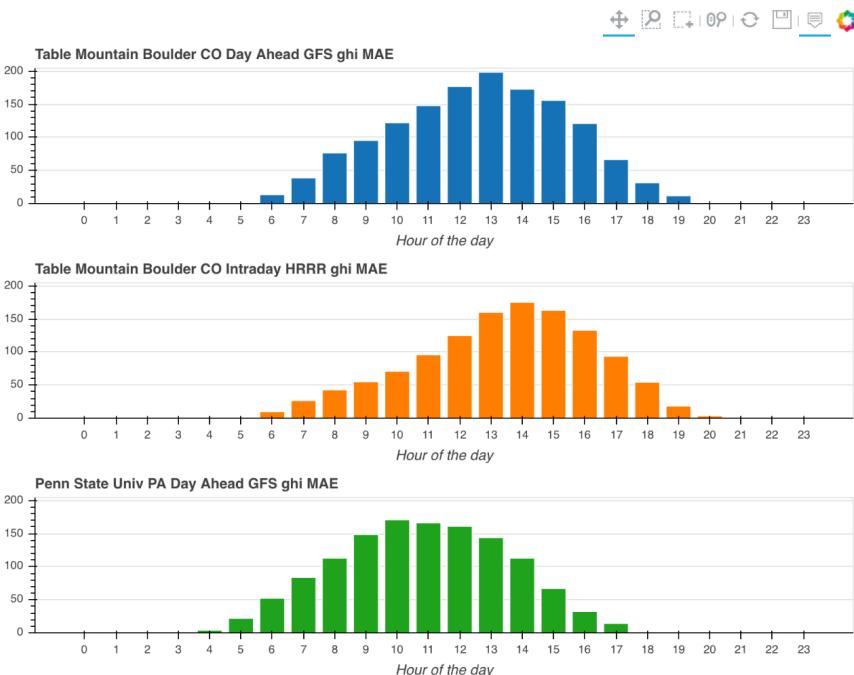
- Name: surfrad ghi hrrr gfs
- Start: 2019-04-01 05:00:00 +0000
- End: 2019-12-31 03:00:00 +0000
- Generated at: 2019-12-16 22:57:19 +0000

## Time series and scatter plots

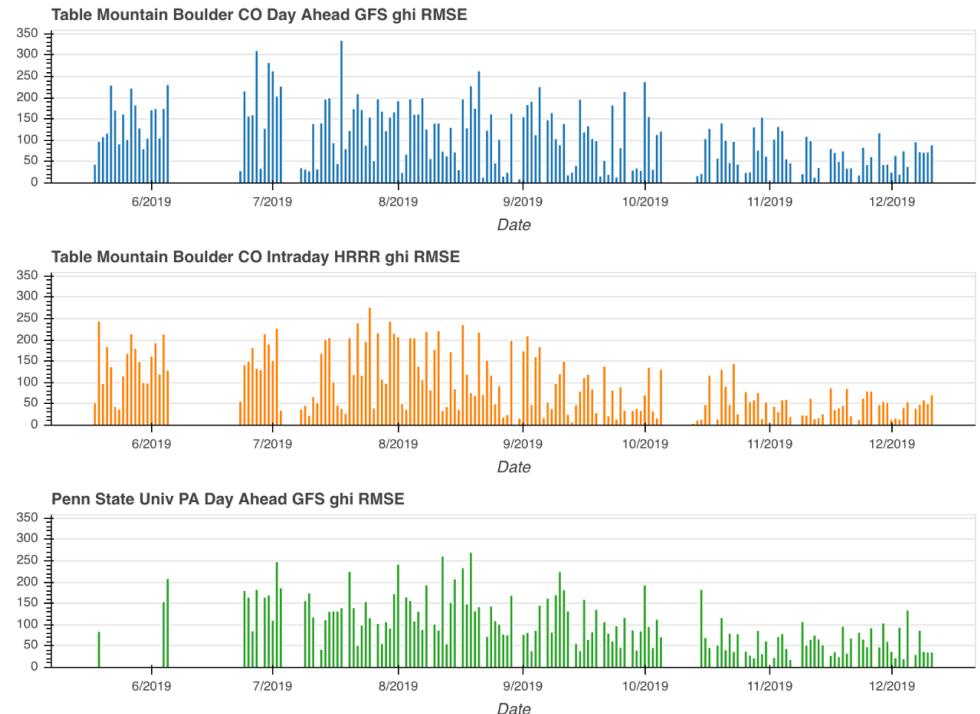


# Example Report

## Metrics by hour



## Metrics by date



# Reference Data Sources

## Public, Open Reference Data

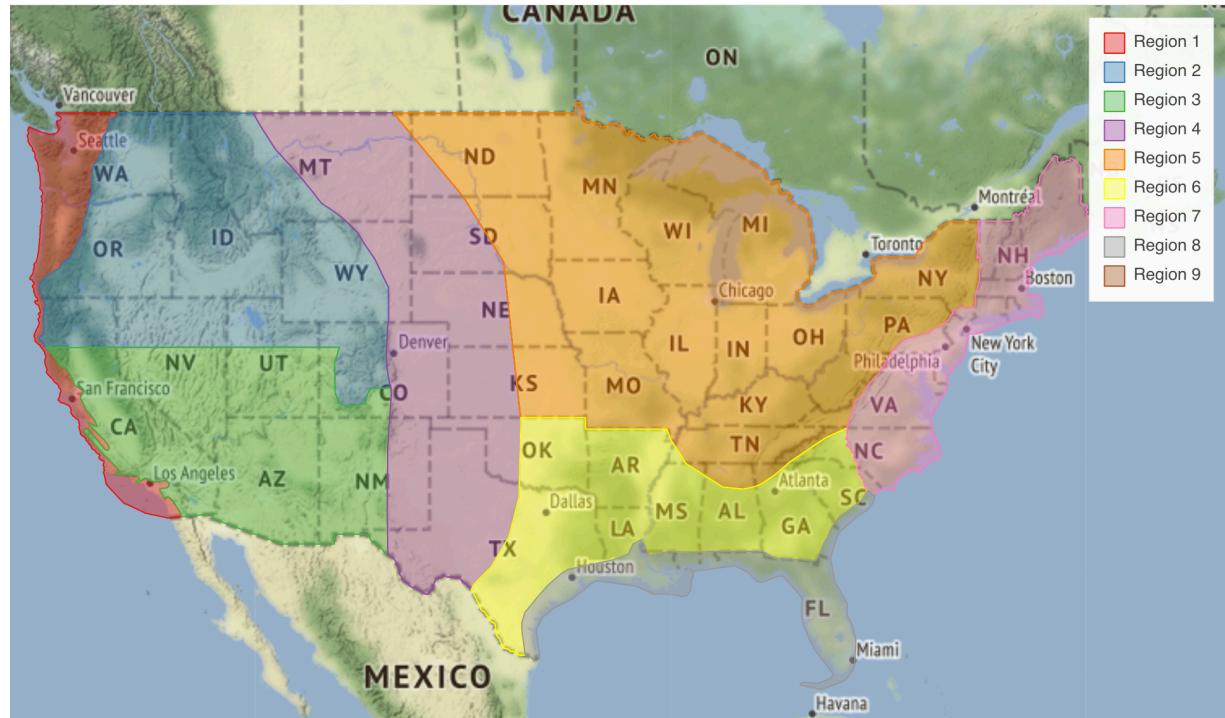
- NOAA SURFRAD
- NOAA SOLRAD
- NOAA CRN
- NREL MIDC
- DOE RTC
- U. Oregon network
- Contribute public reference data, get benchmark forecasts at that site



[solarforecastarbiter.org/  
referencedata](http://solarforecastarbiter.org/referencedata)

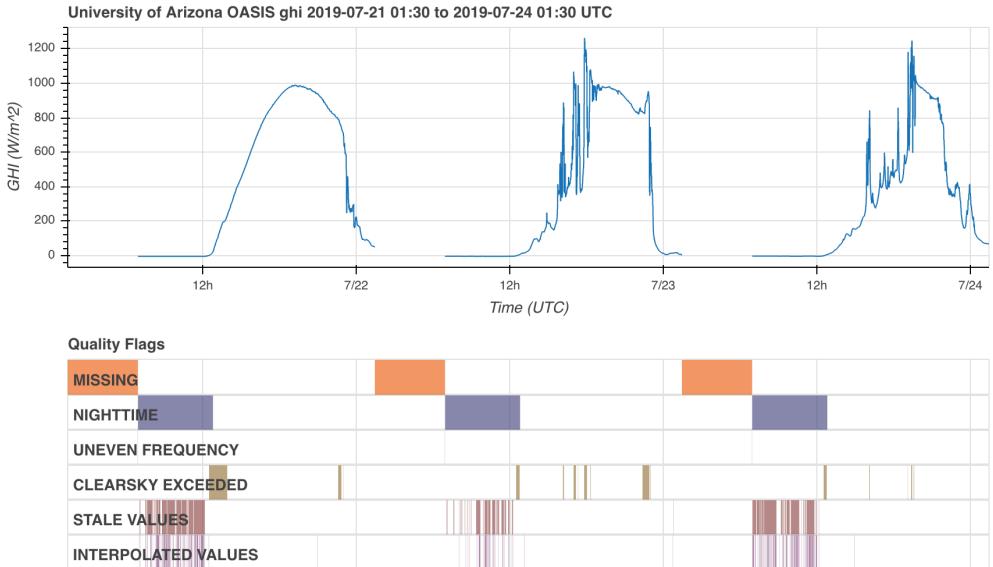
# Climate Regions

- Regions support broader analyses of forecast performance
- “This forecast performs well/poorly on the West Coast”
- Interactive map, shapefiles, kmz



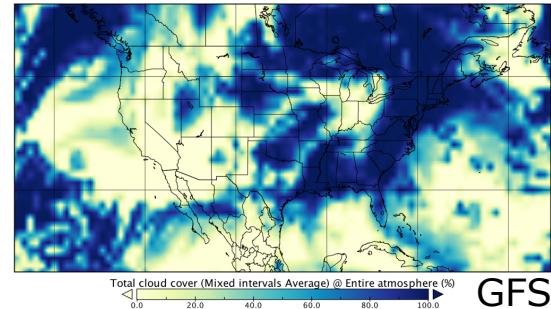
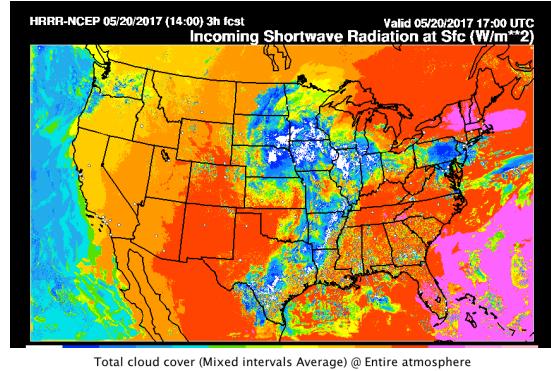
# Data Validation Toolkit

- Flags potential problems with user and reference data
- Automatically applied
- Report options control how flags should be used (e.g. exclude data, fill with 0)
- Open source, available for reuse



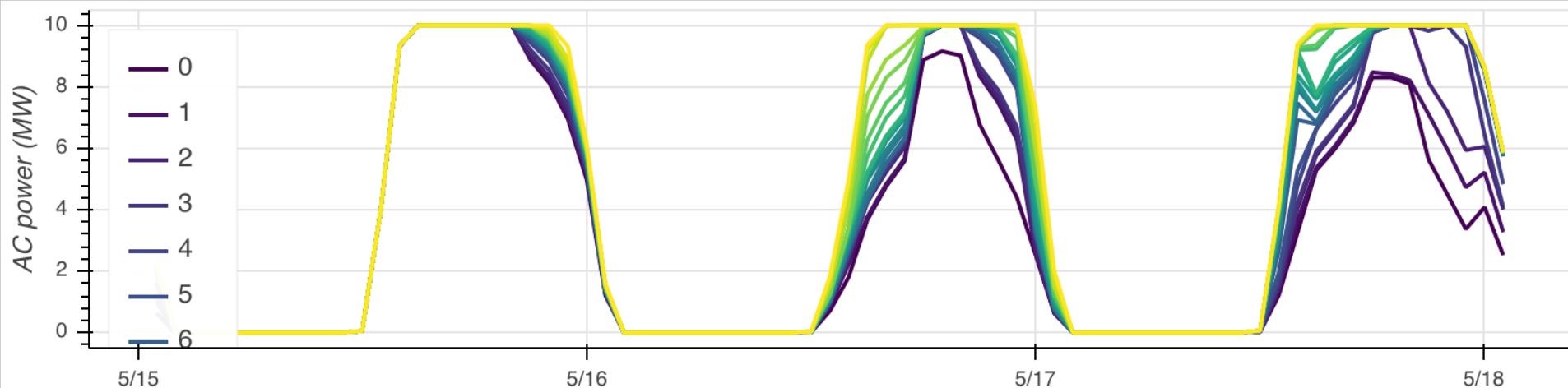
# Benchmark Forecasts

- Benchmark forecasts provided for:
  - Public reference data (automatic, standardized)
  - Forecast trials (designed in consultation with SFA admins)
- NWP options:
  - GFS, GEFS, NAM, RAP, HRRR processing supported
  - GFS, NAM, RAP irradiance forecasts have serious limitations, so derive irradiance or PV power from cloud cover.
  - Directly use HRRR subhourly irradiance
- Persistence options:
  - Persistence
  - Persistence of clear sky index
  - Day ahead persistence



# Probabilistic GEFS Benchmark Forecasts

- 21 member GEFS 3/6 hr mixed interval average cloud cover processed into hourly, hour-ending AC power percentiles (0, 5, ...95, 100)



Open source, reference implementation, available for reuse



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# Metrics

Stakeholder selections of:

- Deterministic Forecasts
- Event Forecasts
- Probabilistic Forecasts
- Cost metrics

Open source implementation



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## Contents

Introduction  
Metrics for Deterministic Forecasts  
A. Mean Absolute Error (MAE)  
B. Mean Bias Error (MBE)  
C. Root Mean Square Error (RMSE)  
D. Forecast Skill  
E. Mean Absolute Percentage Error (MAPE)  
F. Normalized Root Mean Square Error (NRMSE)  
G. Centered (unbiased) Root Mean Square Error (CRMSE)  
H. Pearson Correlation Coefficient  
I. Coefficient of Determination  
J. Kolmogorov-Smirnov Test Integral (KSI)  
K. OVER  
L. Combined Performance Index (CPI)  
Metrics for Deterministic Forecast Events  
A. Probability of Detection (POD)  
B. False Alarm Ratio (FAR)  
C. Probability of False Detection (POFD)  
D. Critical Success Index (CSI)  
E. Event Bias (EBIAS)  
F. Event Accuracy (EA)  
Metrics for Probabilistic Forecasts  
A. ROC Score (ROC)  
B. Brier Skill Score (BSS)  
C. Reliability (REL)  
D. Resolution (RES)  
E. Uncertainty (UNC)  
F. Sharpness (SH)  
G. Continuous Ranked Probability Score (CRPS)

## Metrics

The Solar Forecast Arbiter evaluation framework provides a suite of metrics for evaluating deterministic and probabilistic solar forecasts. These metrics are used for different purposes, e.g., comparing the forecast and the measurement, comparing the performance of multiple forecasts, and evaluating an event forecast.

### Metrics for Deterministic Forecasts

The following metrics provide measures of the performance of deterministic forecasts. Each metric is computed from a set of  $n$  forecasts ( $F_1, F_2, \dots, F_n$ ) and corresponding observations ( $O_1, O_2, \dots, O_n$ ).

In the metrics below, we adopt the following nomenclature:

- $n$  : number of samples
- $F$  : forecasted value
- $O$  : observed (actual) value
- norm : normalizing factor (with the same units as the forecasted and observed values)
- $\bar{F}, \bar{O}$  : the mean of the forecasted and observed values, respectively

#### Mean Absolute Error (MAE)

The absolute error is the absolute value of the difference between the forecasted and observed values. The MAE is defined as:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |F_i - O_i|$$

#### Mean Bias Error (MBE)

The bias is the difference between the forecasted and observed values. The MBE is defined as:

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (F_i - O_i)$$

[solarforecastarbiter.org/metrics/](http://solarforecastarbiter.org/metrics/)



## Data policies summary

1. Organization must sign non-negotiable Data Use Agreement before given access to do anything but view reference data.
2. Signing agreement does **not** obligate organizations to upload data or share data.
3. Organizations retain ownership of the data they upload to the framework.
4. Organization admins have complete control over how their data may be accessed by other users. Default: no sharing, private analysis only.
5. Organization admins may delete data from the framework.
6. Uploading data does **not** give SFA team ability to study data.
7. All non-public data will be securely deleted at the termination of the project (2021).

# How to get started

1. Make free user account at [dashboard.solarforecastarbiter.org](https://dashboard.solarforecastarbiter.org)
  - Browse reference data, forecasts
2. If you like it
  - Get your organization to sign the Data Use Agreement
  - Experiment with a small problem, upload some test data
3. If you love it
  - Help us beta test the operational forecast trial feature
  - Contribute data to the public reference data set
  - Spread the word
  - Contribute to the open source code development on GitHub



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# Summary

- Open source, reproducible, transparent evaluation framework
- Stakeholder feedback guides project – speak up!
- Use cases tailored to needs of solar forecast stakeholders
- Reference datasets and forecasts
- Secure, private data upload. Sharing optional
- Automated reports including bulk metrics, analysis filters
- Sign up for project updates, web dashboard at:

[solarforecastarbiter.org](http://solarforecastarbiter.org)

[holmgren@email.arizona.edu](mailto:holmgren@email.arizona.edu)

Find me in the poster session this afternoon for demo, Q/A



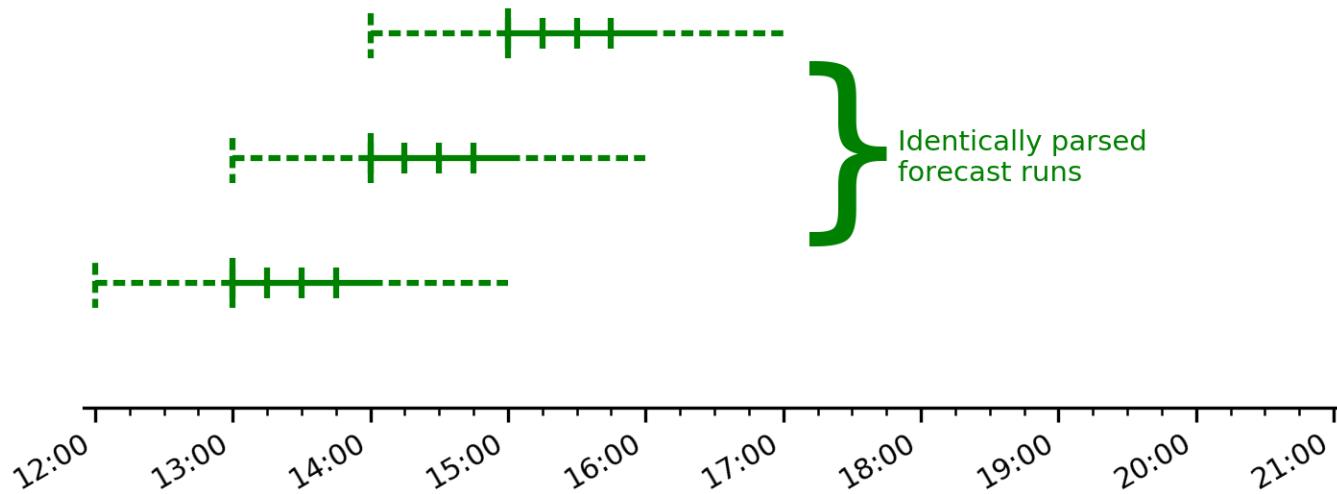
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Forecast runs concatenated into a forecast evaluation timeseries

Application: short term market

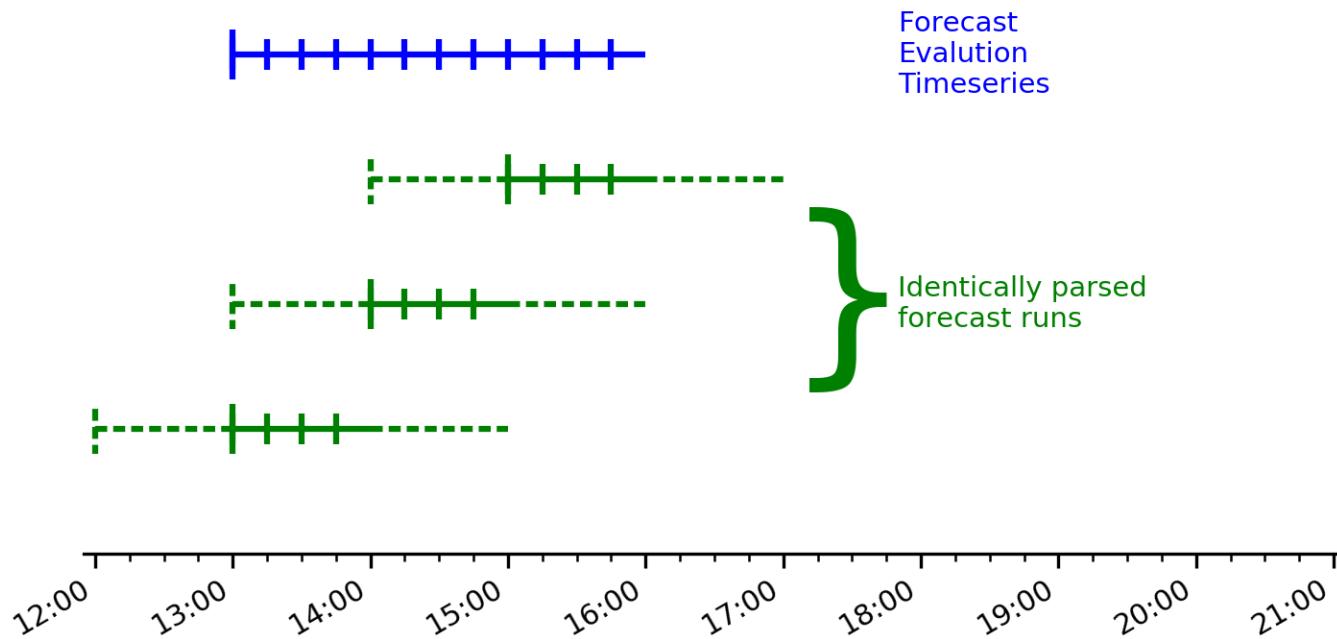
Requirement: hour ahead forecast



Forecast runs concatenated into a forecast evaluation timeseries

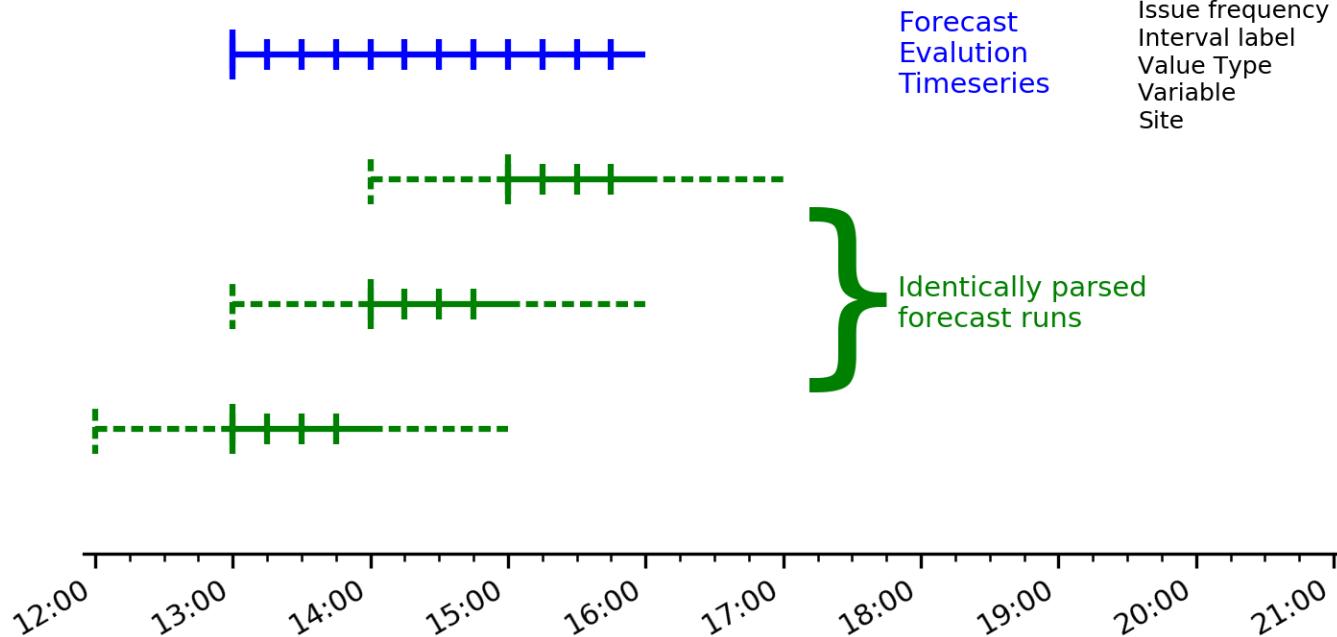
Application: short term market

Requirement: hour ahead forecast



## Forecast runs concatenated into a forecast evaluation timeseries

Application: short term market  
Requirement: hour ahead forecast



## Forecast taxonomy

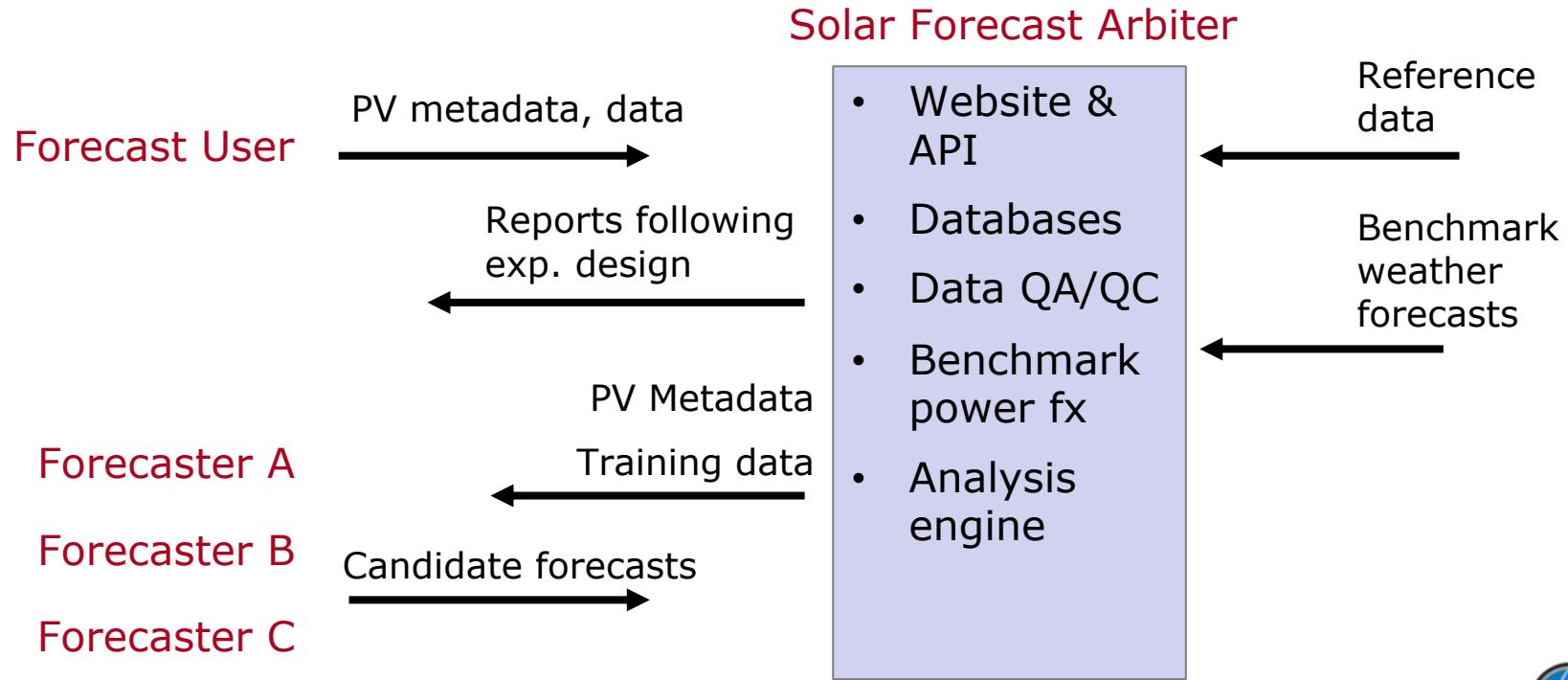
Lead time to start	1h	1h
Interval duration	15min	15min
Intervals / sub.	4	12
Issue frequency	1h	1h
Interval label	left	left
Value Type	mean	mean
Variable	Power	Power
Site	Plant X	Plant X

# Use Cases

## 1D time series – no gridded data

- A. Compare a forecast to measurements**
- B. Compare a probabilistic forecast to measurements (Feb.)
- C. Compare multiple forecasts to measurements**
- D. Compare forecasts to measurements for sites and aggregates**
- E. Evaluate an event forecast (Mar.)
- F. Conduct a forecast trial (Jan.)
- G. (*stretch*) Compare multiple overlapping forecast runs to measurements
- H. (*stretch*) Establish long-term performance baseline of state-of-the-art operational forecasts

# Sketch of Forecast Trial Use Case



# Data Upload/Download

## Dashboard

### Create New Site

Name

Latitude  Longitude

Elevation  Timezone

Site Type  
 Weather Station  Power Plant

Network (Optional)

Extra Parameters  
This field will store any ASCII text. We recommend using it to store other parameters you have collected in a format such as YAML or JSON.

[solarforecastarbiter.org/  
dashboarddoc](https://solarforecastarbiter.org/dashboarddoc)

## API

### Solar Forecast Arbiter API (0.1.0)

Download OpenAPI specification: [Download](#)

Solar Forecast Arbiter Team: [info@solarforecastarbiter.org](mailto:info@solarforecastarbiter.org)

URL: <https://github.com/solararbiter/solarforecastarbiter-api> | License: MIT

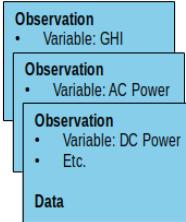
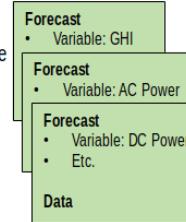
The backend RESTful API for Solar Forecast Arbiter.

[api.solarforecastarbiter.org](https://api.solarforecastarbiter.org)

## Data Model

### Site

- Latitude
- Longitude
- Etc.



[solarforecastarbiter.org/  
datamodel](https://solarforecastarbiter.org/datamodel)

# Project goal

Open-source framework for solar forecast evaluations that are impartial, repeatable, and auditable.

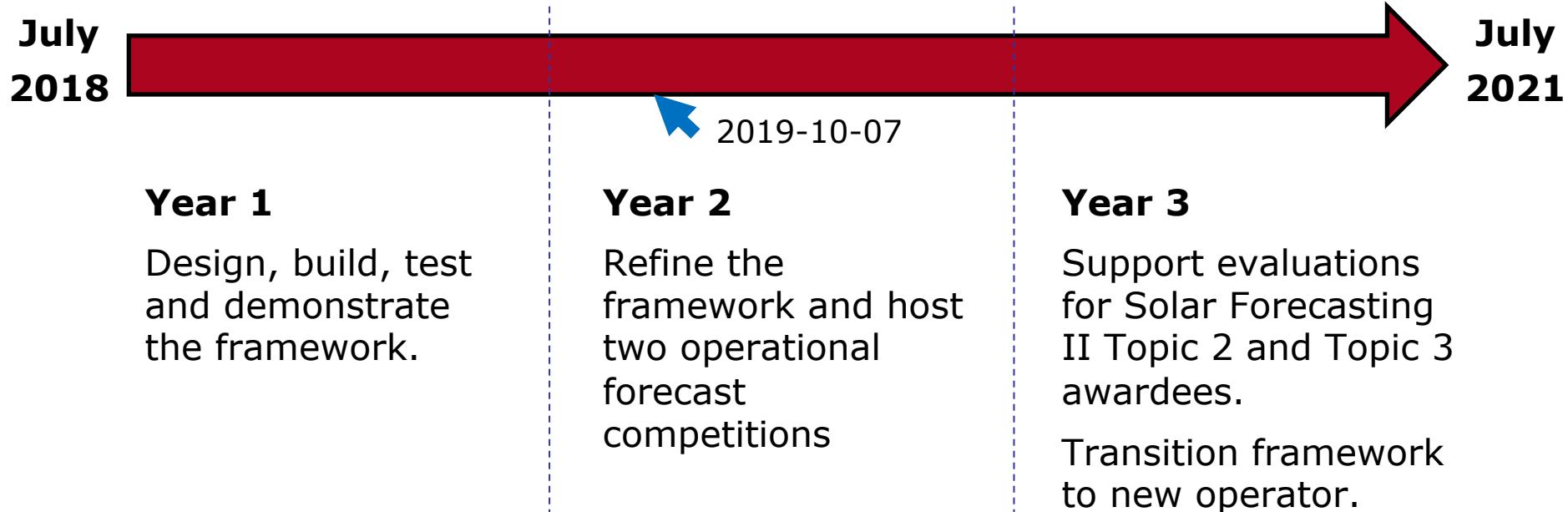
- Implement objective, consistent evaluation scenarios and metrics → better solar forecasts
- Develop user confidence in solar forecasts → system integration
- Standardize evaluations → reduce provider and user costs
- Easily extend to wind power and load forecasting



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# Project Timeline/Milestones



# Stakeholder Engagement

## 5 primary topics

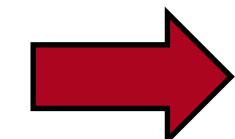
- Use cases
- Data format/API
- Data policies
- Benchmark forecasts
- Evaluation metrics

Please join the Stakeholder Committee! (open to all)

[solarforecastarbiter.org/  
stakeholdercommittee](http://solarforecastarbiter.org/stakeholdercommittee)

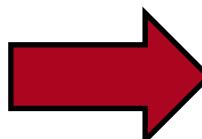
## Typical engagement process

Stakeholder  
Workshop  
St. Paul,  
June 2018



Team  
discussions

Proposal  
documents



Stakeholder  
feedback

Revised  
documents



Stakeholder  
consensus

Final  
documents  
Implement

# How do I use the Solar Forecast Arbiter?

- Option 1: Use the web dashboard, web API
  - most users, focus of this talk
- Option 2: Install python package for local use
  - researchers with python experience, PB of data
- Option 3: Stand up your own deployment of the full software stack
  - promotes reproducibility and reuse



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# Benchmark Forecasts

## Required Attributes

- Available throughout the US
- Freely accessible or easily implemented
- Provide quantities of interest to both forecast users and providers
- Stakeholder buy-in



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# Benchmark Forecast Configuration

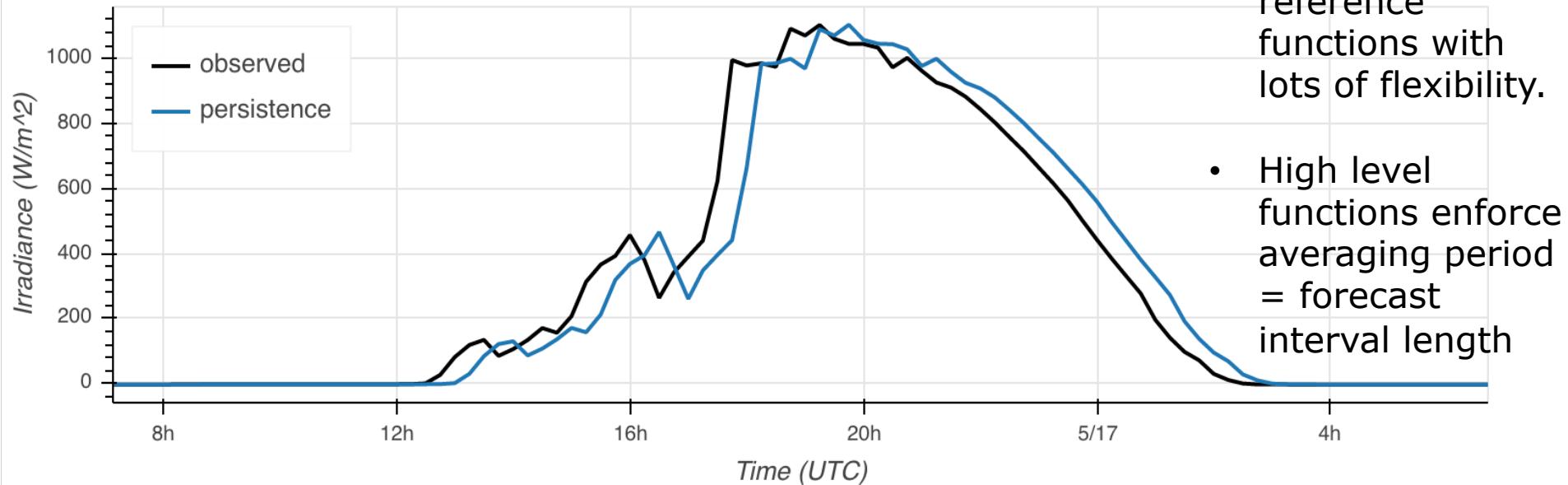
- Current operational NWP processing configuration
  - Based on time zone. Example for site in MST (UTC-0700):

Model	Issue time of day	Run length / Issue frequency	Lead time to start
GFS day ahead	7Z	1 day	1 day
NAM current day	6Z	1 day	1 hour
HRRR intraday	0Z	6 hours	1 hour
RAP intraday	0Z	6 hours	1 hour

- Persistence not yet configured. One idea: follow CAISO requirements
- Trials allow custom configuration

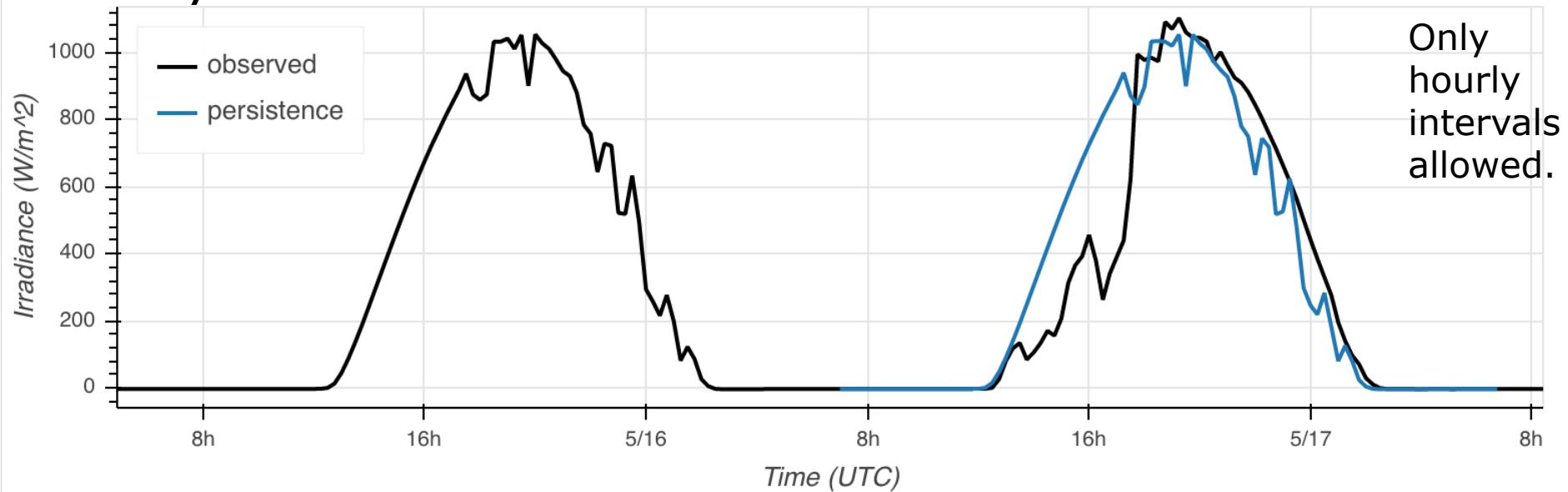
# Persistence Benchmark Forecasts

## Persistence



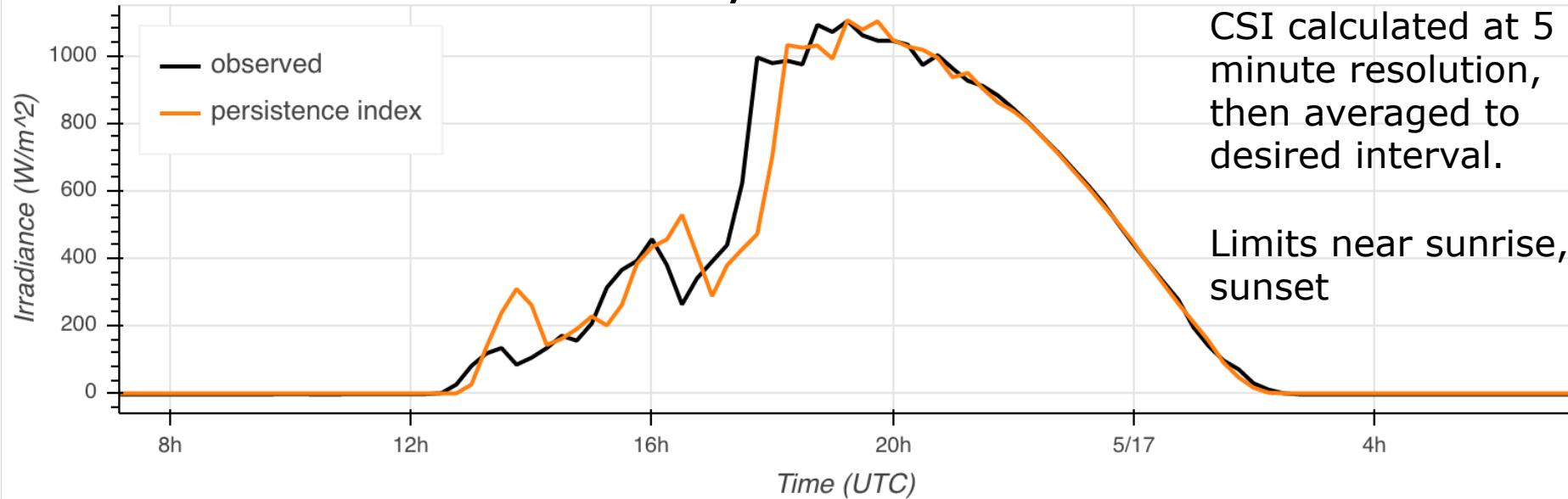
# Persistence Benchmark Forecasts

## Day Ahead Persistence



# Persistence Benchmark Forecasts

## Persistence of clear sky index



Open source, reference implementation, available for reuse



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# NWP Benchmark Forecasts Processing

- Our PV power model requires instantaneous input
  - Accurate hourly averages require many subhourly instantaneous points
1. Load hourly (or longer) interval data from the NWP grib files.
    - For GFS cloud cover, unmix the mixed-intervals average data.
  2. Resample data to 5 minute intervals.
    - For GFS cloud cover, backfill the data.
    - For all other NWP data, interpolate the data.
  3. Convert cloud cover to irradiance. Linear clear sky scaling Larson et. al.:
    - $\text{GHI} = (35\% + (100\% - \text{cloud cover})) * \text{GHI\_clear}$
  4. If PV, use site metadata to compute AC power using [pvlib-python](#) functions.
  5. Compute hourly averages with desired interval labels.

# Cost metrics

Built-in support for:

- Fixed \$/MW
- Fixed \$/MW for handful of error bins
- Time series of \$/MW

Also provide brief recommendations and references for how to conduct more detailed cost evaluations

# Evaluation with messy data

- Priority: clearly document the process and any user-configured options in each report
- Missing or bad forecast data
- Missing or bad observation data
  - Data validation toolkit flags most problems
- Research study
  - Options selected when report is created
- Operational forecast trial
  - Options selected when trial is created



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# Practical Time Series Issues

- Users specify start and end time for analysis report
- Rule: don't modify user-submitted forecasts
- Interval length consistency:
  - If measurements are higher resolution, Average the measurement data so that it has the same resolution as the forecast data (default)
  - If the forecast is higher resolution – comparison not allowed
- Interval label consistency:
  - Observations and forecasts have defined labels (beginning, ending, instant)
  - Arbiter accounts for observation intervals when resamples
- Nighttime data: Day/night filter based on solar zenith angle
- Ability to select certain periods: time of day, months of year, clear/cloudy, other weather variables, ramping periods

# Data Sharing Implementation: Role Based Access Control

admin@utility-1.com



**Share with forecasters**

Read  
Sites  
(all)

Read  
Observations  
(all)

Read  
Observation  
Values (all)

- Granular permissions by data type, grouped into a *role*
- Data shared with individual users
- Your IT staff can help
- We can help

user@  
the-fx-channel.com



admin@accu-forecast.com



user@accu-forecast.com

# Data Sharing Implementation: Role Based Access Control

