Validating Irradiance Models for High-Latitude Vertical Bifacial Photovoltaic Systems

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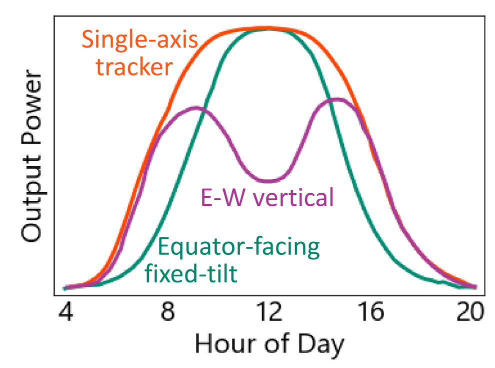
Introduction

- **Accurate modelling** of photovoltaic systems is **critical** for the **design, financial analysis, and monitoring** of solar PV plants
- **Bifacial** PV models must additionally offer robust **rear-side irradiance algorithms**
  - Especially true for:
    - Emerging E-W **vertically oriented** bifacial PV systems, where receiving direct beam solar irradiation swaps at solar noon
    - **High latitudes**, where there is an increased fraction of the year with high ground albedo

PV fences [1] | Agri-PV [2] | **The North** [3]

Morning & afternoon production can help with matching load demand

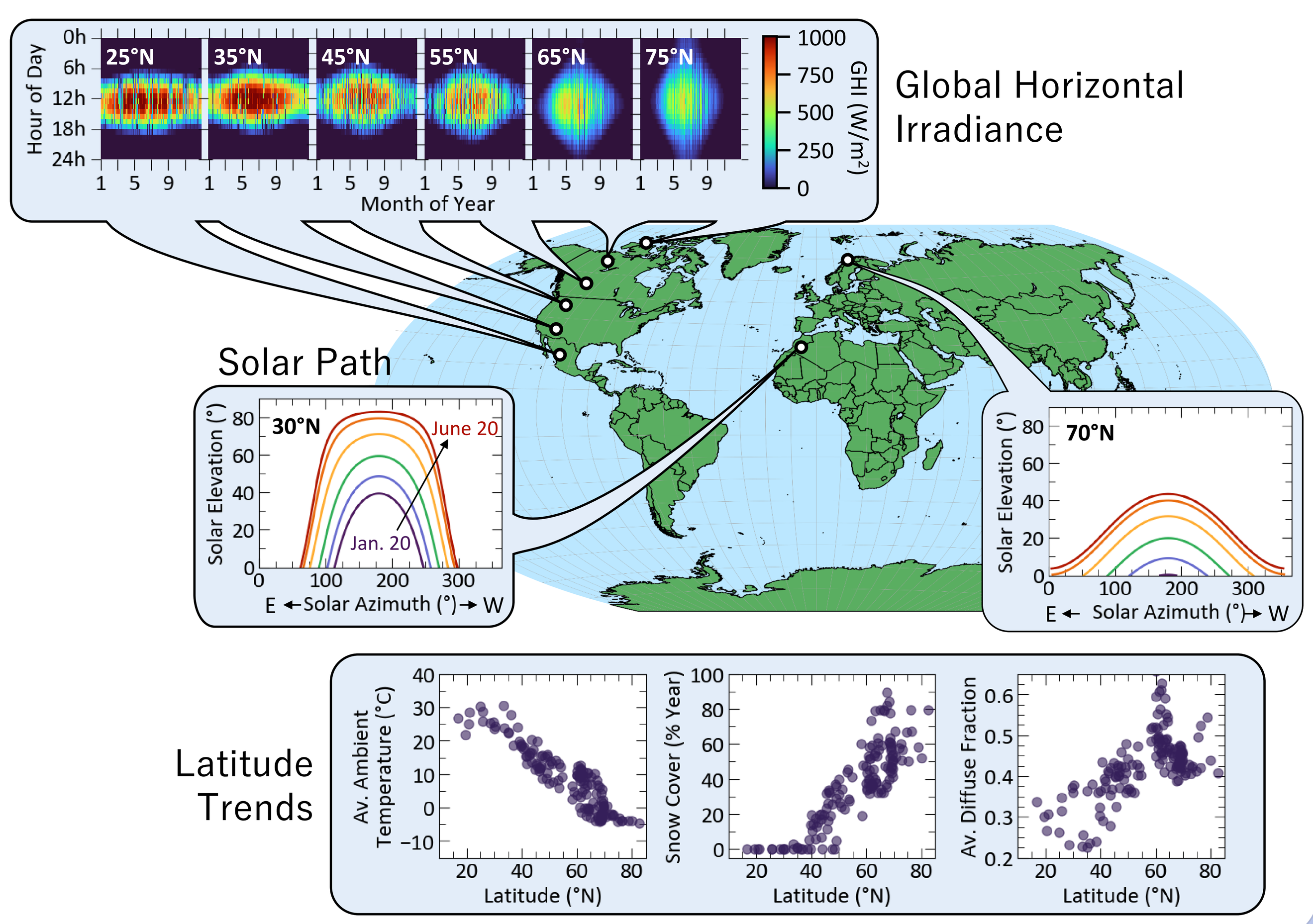


East-west **vertical** systems become **competitive** with traditional equator-facing tilted systems **at high latitude**

The Challenge:

Bifacial irradiance models have yet to be validated for vertical systems or at high latitude

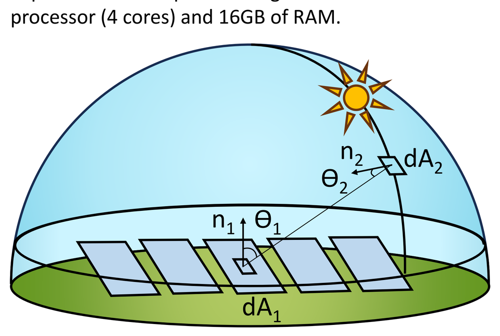
High Latitude Conditions



Bifacial Irradiance Models

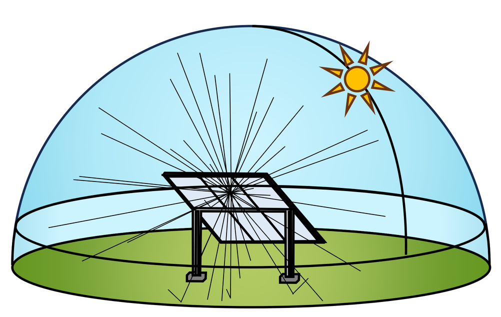
	bifacial_radiance [4]	bifacialVF [5]	System Advisor Model [6]	DUET SUNLAB [7]
Main algorithm	Ray tracing	2D view factor	2D view factor	3D finite element
Spectral albedo	✓	✗	✗	✗
Specular reflections	✓	✗	✗	✗
Rear-irradiance non-uniformity	✓	✗	✗	✓
Rack shading	✓	✗	✓	✓
Edge effects	✓	✗	✗	✓
Speed (time/timestamp)	6 s	3 s	< 1 s	6 s
Version used	v0.4.2	v0.1.8.1	v4.2.0	v0-research

*Speed test is completed using the Golden E-W vertical test-site on a Windows 10.0 Dell OptiPlex 7020 computer with an Intel Core i5-4690 processor (4 cores) and 16GB of RAM.



View Factor

- Simple geometry, computationally inexpensive
- Calculates the amount of sky & ground visible from a point on the panel, captures module and ground shading
- Commonly used in industry



Ray Tracing

- Custom geometry, computationally expensive
- Backwards ray-tracing: traces rays from a point on the module outwards to the ground, sky, other objects. Scattering properties of the materials are captured [4]

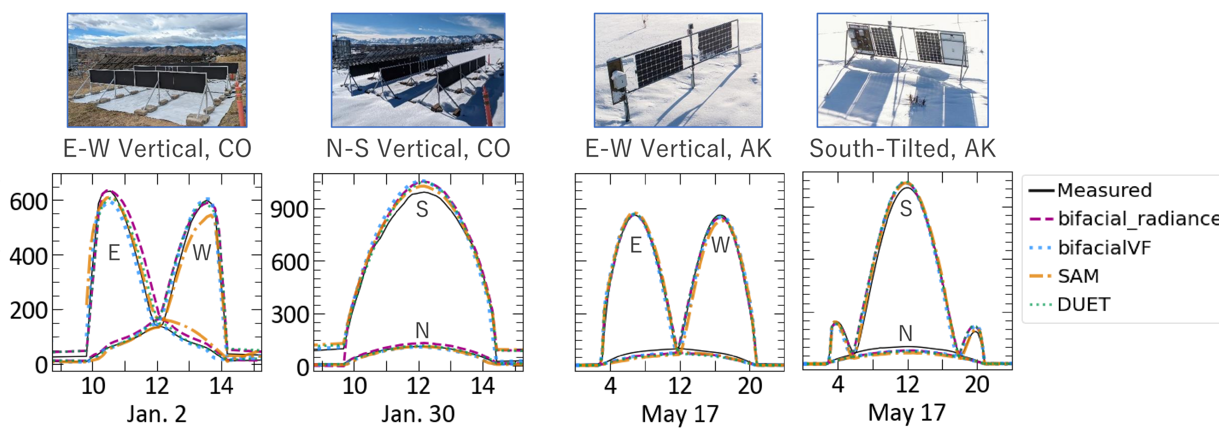
Model Validation

Ex) Clear Sky Day

Comparing modelled vs measured irradiance on example clear sky days

All models **over-estimate**: South-irradiance for N-S vertical

All models **under-estimate**: Diffuse irradiance in Alaska



All Data

Comparing modelled vs measured irradiance data, without filters. Colorado systems = ~3000 timestamps, Alaska systems = ~18,000 timestamps.

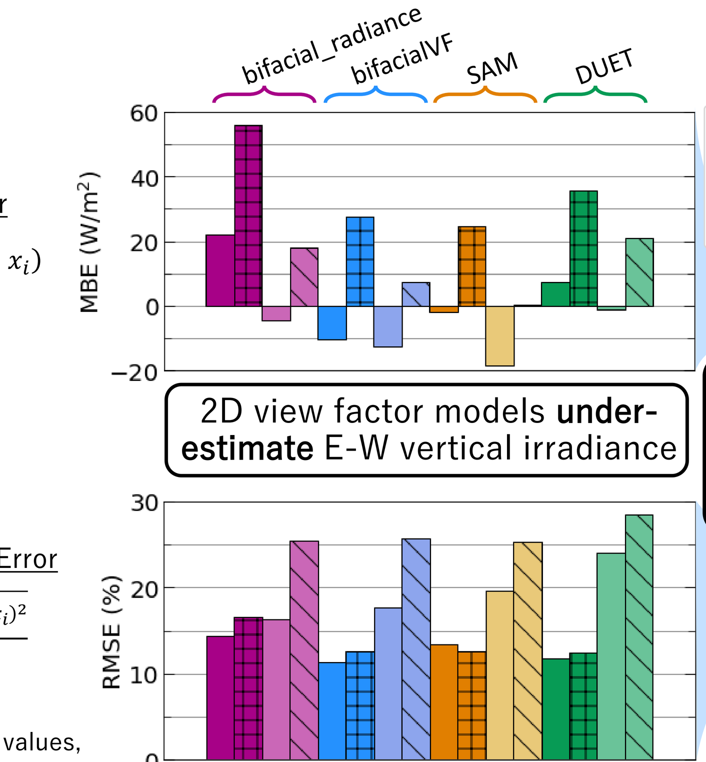
Mean Bias Error

$$MBE = (1/N)\sum(y_i - x_i)$$

Root Mean Square Error

$$RMSE = \frac{\sqrt{(1/N)\sum(y_i - x_i)^2}}{(1/N)\sum x_i}$$

with y_i modelled values, x_i measured values, N timestamps

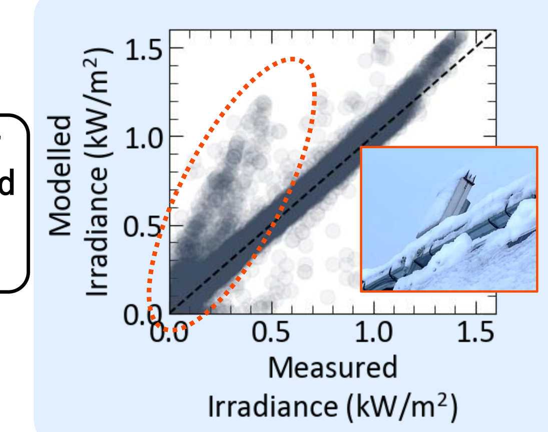


2D view factor models under-estimate E-W vertical irradiance

RMSE varies between **11-28%**

Highest error for south-tilted Alaskan testbed

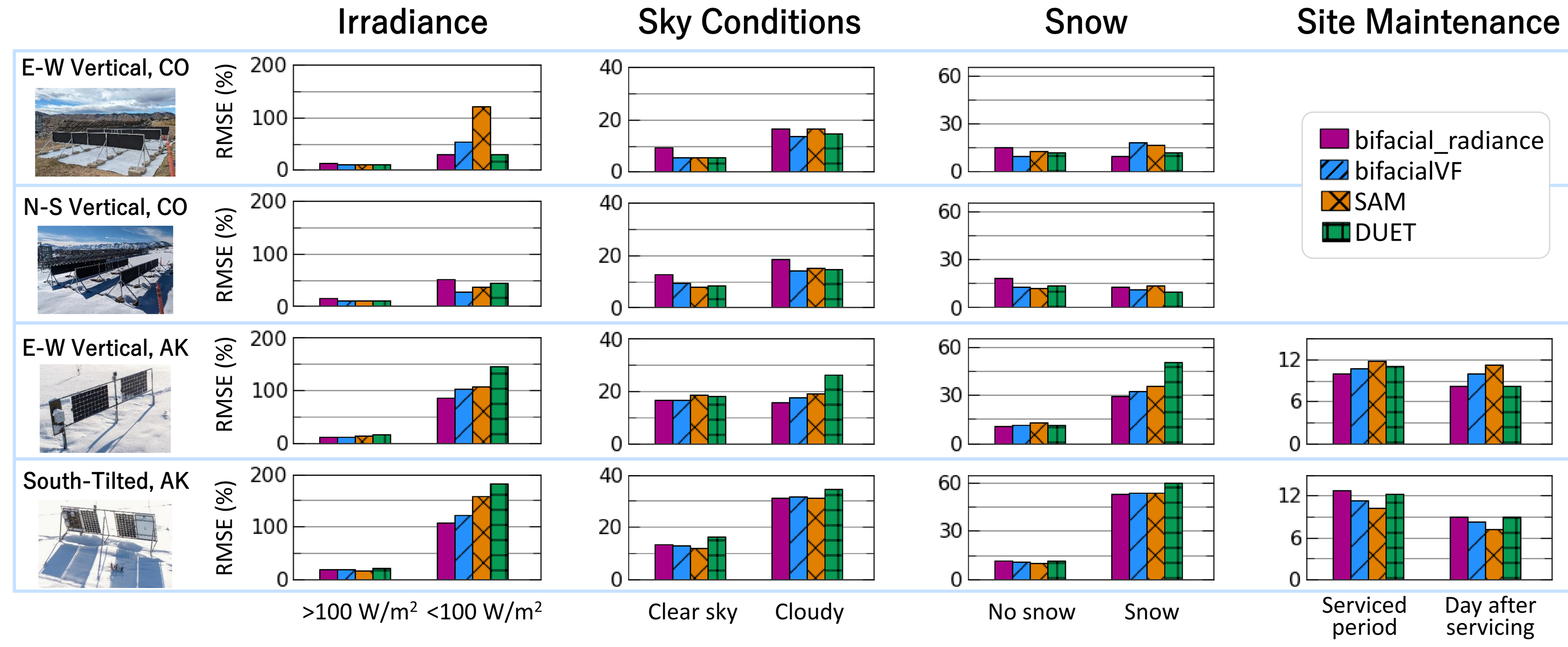
All 18,000 timestamps
All models show the same feature



Snow on ref. cells → **models over-estimate**

Model Error Trends

Comparing modelled vs measured irradiance data, with filters



Highest error for **low irrad.** **≤5%** of insolation

More error associated with cloudy conditions

High snow error in Alaska **17% of annual insolation**

Av. **error drops 14% rel.** (vertical), **29% rel.** (S-tilted)

Insolation included in filter (%)

		< 100 W/m²	Clear sky	Snow	Winter
Colorado	EW	3	30	14	-
	NS	1	57	30	-
Alaska		5	33	17	10

(Nov. – March)

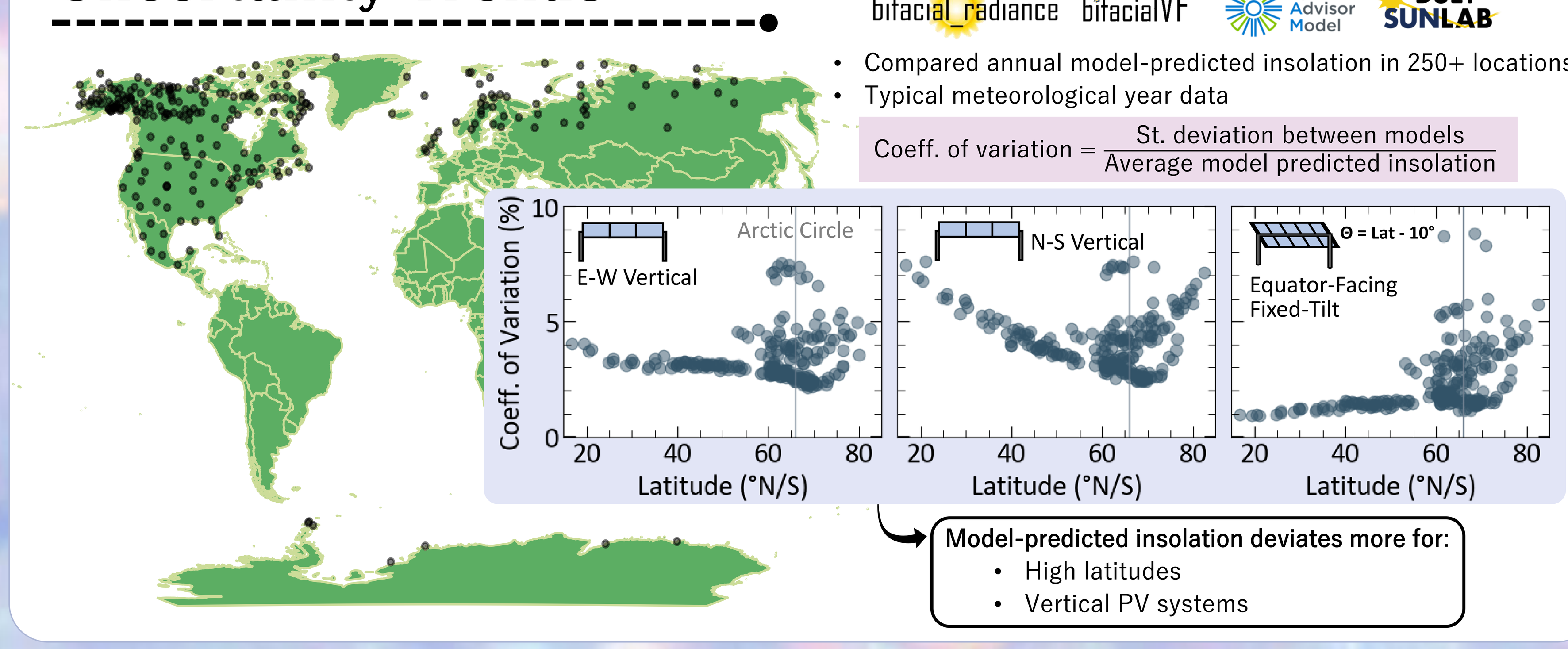
Best case filtering: RMSE varies between **5-13%**

>100 W/m², clear sky, no snow

Uncertainty Trends

- Compared annual model-predicted insolation in 250+ locations
- Typical meteorological year data

$$\text{Coeff. of variation} = \frac{\text{St. deviation between models}}{\text{Average model predicted insolation}}$$



Model-predicted insolation deviates more for:

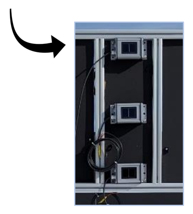
- High latitudes
- Vertical PV systems

Testbeds

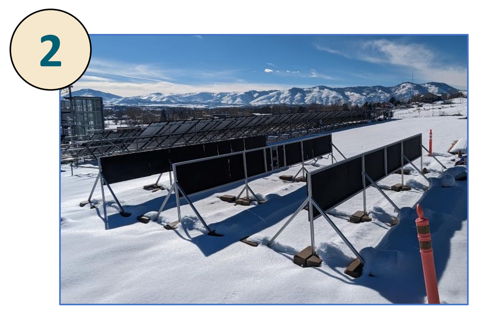
Golden, Colorado, 40°N 105°W

1 E-W Vertical Bifacial Testbed

- Designed & assembled a 3-row vertical testbed composed of 80/20 frame, plywood, and 6 IMT silicon reference cells
- Reflective material simulates 'snow'
  - Average measured albedo = 0.62



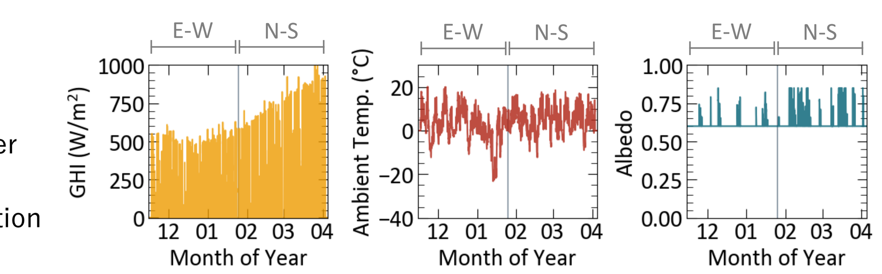
2 N-S Vertical Bifacial Testbed



- Vertical testbed is rotatable and additionally tested in N-S orientation

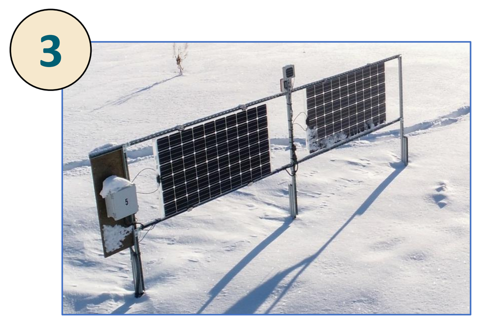
Meteorological Data

- NREL Measurement and Instrumentation Data Center
- 15-minute resolution
- 70 days of data per orientation



Fairbanks, Alaska, 65°N 148°W

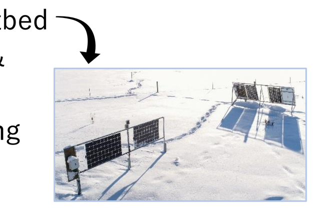
3 E-W Vertical Bifacial Testbed



- Maintained by Alaska Center for Energy & Power, described in Ref. [8]
- 2 E-W vertical modules
- 2 silicon reference cells measuring east & west irradiance

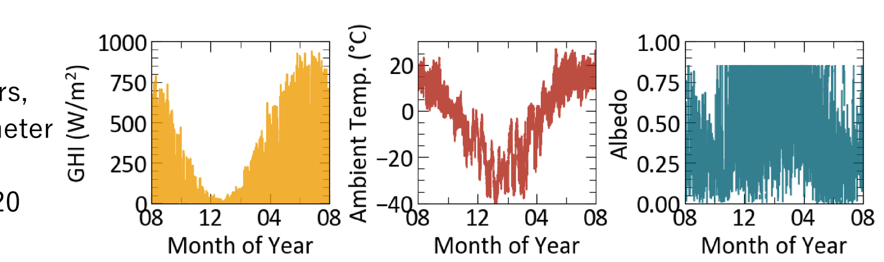
4 South-Tilted (60°) Bifacial Testbed

- Co-located with E-W vertical testbed
- 4 south-tilted modules (bifacial & monofacial)
- 2 silicon reference cells measuring front & rear irradiance



Meteorological Data

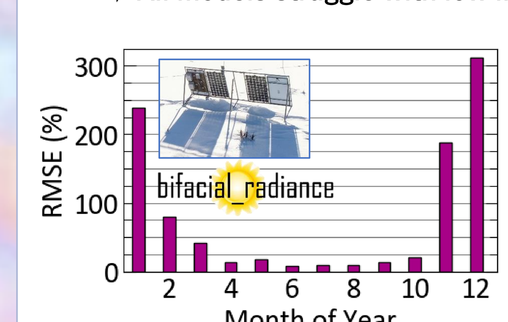
- On-site heated pyranometers, pyrheliometer, and albedometer
- 15-minute resolution
- 1 full year of data, 2019-2020



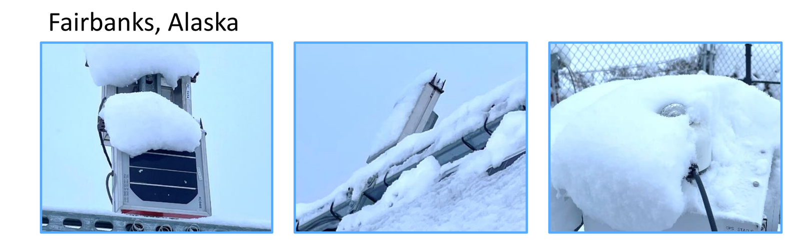
Outlook for PV Models in the North

Model choice depends on the application

- All models over-estimate N-S vertical irradiance in Colorado
- 2D view factor models under-estimate E-W vertical irradiance in both Colorado and Alaska
  - **All models struggle with low irradiance conditions, clouds, snow → prevalent at high latitudes**



Fairbanks, Alaska



Snow covering the world with sparkles, including useful sensors

- Must allow **larger margins of uncertainty** for designing systems & financial planning
- **Revisit model assumptions** and consider adaptations for high latitudes

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Acknowledgements

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 34910. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

PVSC, June 9-15, 2024
Seattle, Washington, USA