Partly Cloudy Sunshine Can Exceed Clear-Sky

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Motivation

The shadows of clouds passing overhead often rapidly reduce the amount of incoming solar energy that reaches the surface. In certain cases, partial cloudiness can redirect incoming solar energy towards the ground, increasing the total energy that reaches Earth's surface above clear-sky values for those locations. The "extra" solar energy that reaches the surface generates additional photovoltaic (PV) output and can complicate solar energy forecasts. We examine the frequency and magnitude of solar enhancement events using a multi-year data set for a site in eastern North Carolina.

Data and Methods

We utilize synchronous visual all-sky camera and 1-min surface solar irradiance measurements from NCSU's Eastern Carolina Atmospheric Observing Site in Plymouth, NC. Case studies of solar irradiance in the context of all-sky camera images are used to show solar enhancement phenomena. We analyze surface solar irradiance measurements from 792 days spanning from Jan. 1, 2024, to Jun. 24, 2026. Early morning, late afternoon, and night (solar angle <10°) measurements are not included in analysis. The Ineichen-Perez clear-sky model is used to estimate solar energy received in cloudless conditions and is tuned to our location using a linear-fit to historical clear-sky periods. Solar enhancement events are identified where observed clear-sky relative measurements ≥1.12.

Solar Irradiance

Radiation from the sun has two components

- **Direct shortwave radiation** passes directly through the atmosphere without interference
- **Diffuse shortwave radiation** reaches the ground by interactions with cloud or aerosol particles that redirect radiation back towards the ground

When solar radiation interacts with cloud edges, some radiation is redirected back to the surface and increases the diffuse radiation reaching the surface.

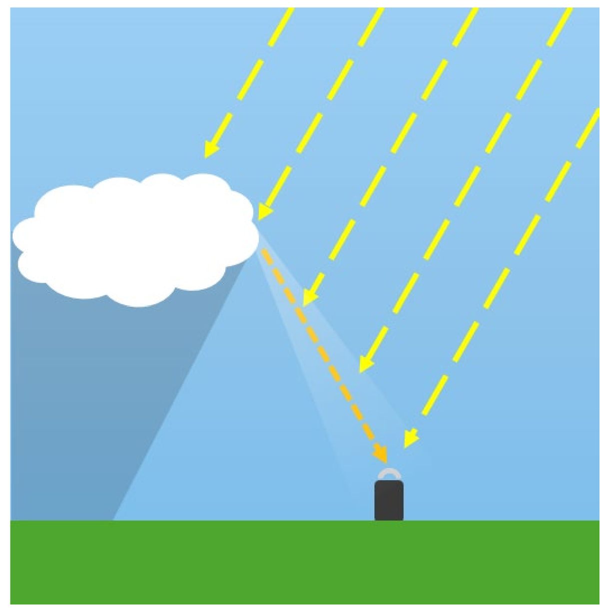


Diagram of Solar Enhancement, Direct Path (Yellow Dashed Line) and Diffuse Path (Orange Dashed Line)

Clear-Sky Index

The clear-sky index is the ratio of observed solar irradiance to the theoretical irradiance when no clouds are present. Values typically range from 0 to 1

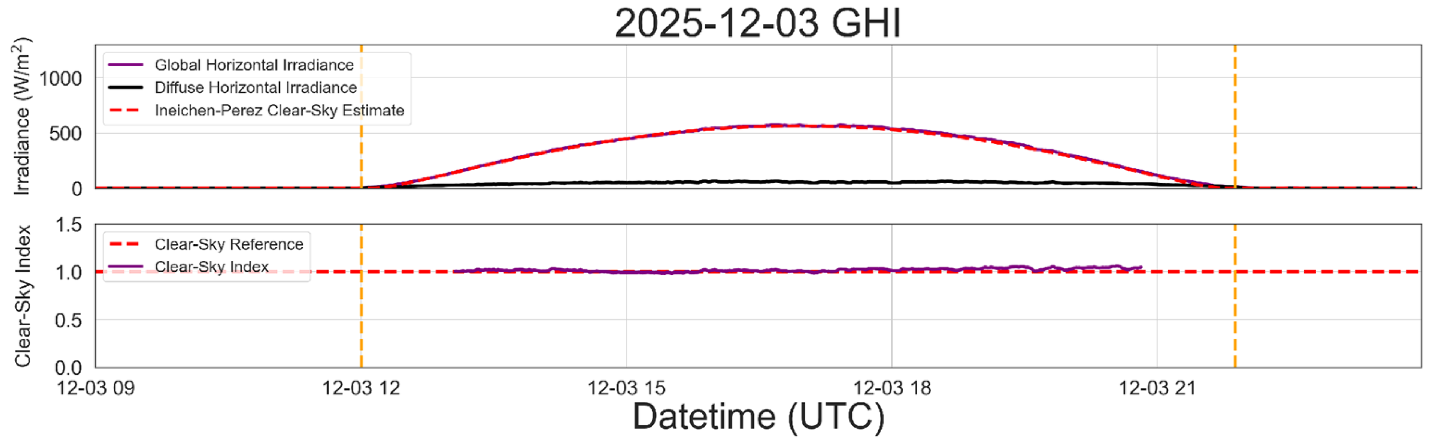
- Index of 0 implies no sunlight reaches the surface
- Index of 1 implies sunlight reaches the surface unobstructed

The clear-sky index accounts for the solar energy variability due to the changes in solar angle and facilitates comparisons of the daily and seasonal relative amounts of sunlight that reaches the surface.

Clear-Sky Day

On clear-sky days, the amount of solar energy that reaches the surface varies as the solar angle (sun's elevation angle) rises above the horizon, peaks near noon and then decreases towards sunset.

Example of clear-sky above Plymouth, NC.

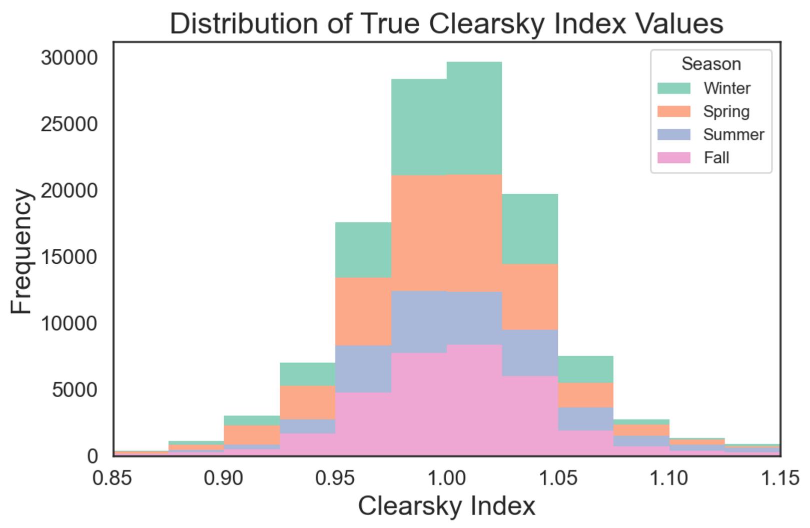


Solar irradiance measurements on a clear-sky day in Plymouth, NC.

Clear-Sky Model Performance

The performance of the clear-sky model varies depending on the clarity of the atmosphere (type and number of aerosols) and may slightly under or overestimate true clear-sky radiation measurements. In practice, we identify clear-sky index ranges from ~0.88-1.12 as no clouds overhead.

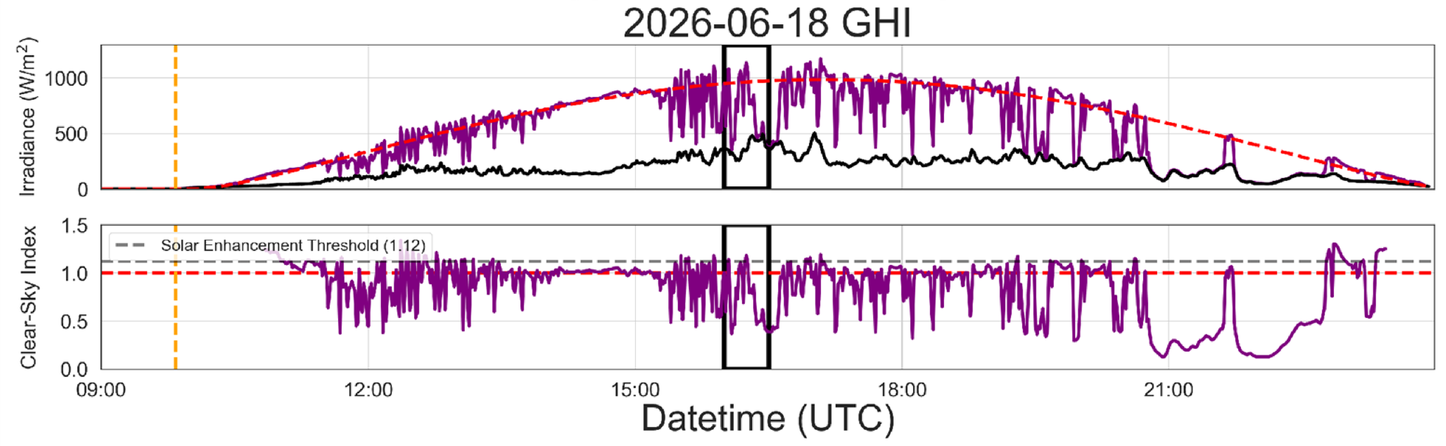
- Cloudless skies at Plymouth, NC are most common in Fall and Winter and less common in Spring and Summer



Distribution of Clear-Sky Index Measurements for Clear-Sky Periods

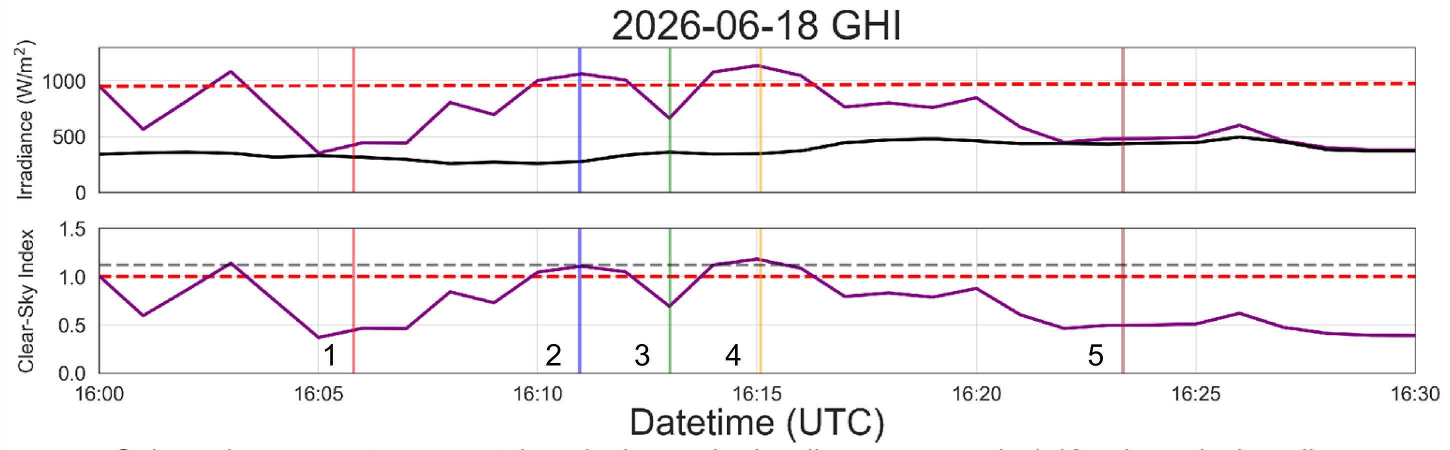
Cloudy Day Irradiance

On cloud days, when sunlight passes through scattered and broken clouds, there are rapid fluctuations in solar energy between very low minimums (shadows) and exceeding clear-sky maximums (enhancements). Energy reflected from cloud edges can cause spikes in energy above clear-sky values.



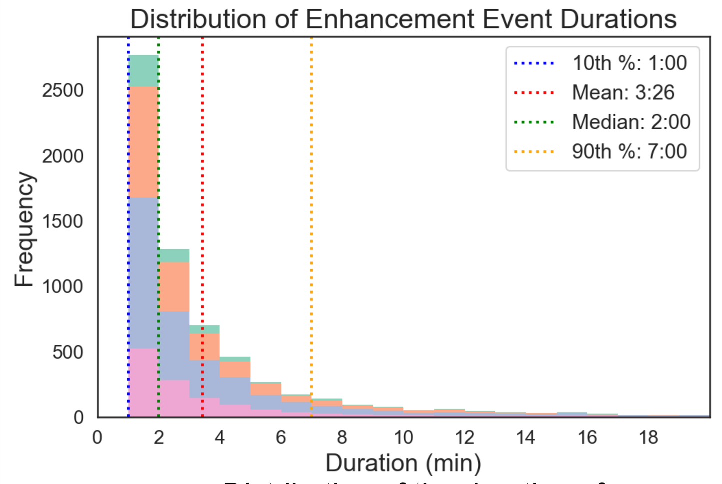
Solar irradiance measurements on a day with variable cloudiness. Clear sky index values of 1.0 (red dashed line) and 1.12 clear-sky index threshold (black dashed line). Box corresponds to 30 min period shown below.

Solar Enhancement Event

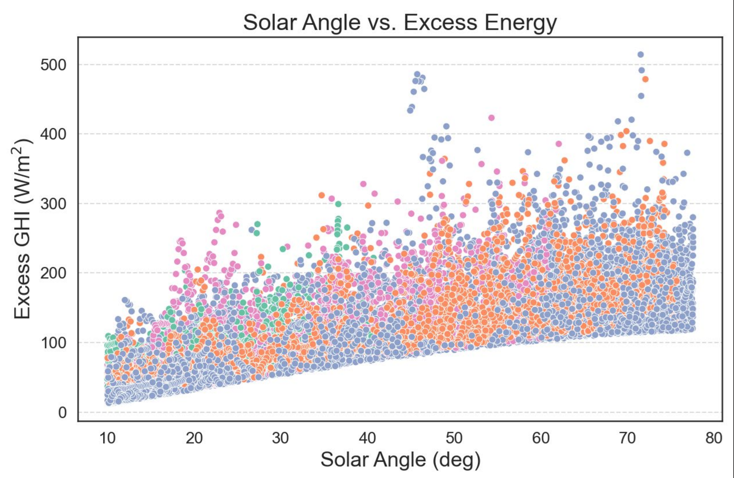


Solar enhancement occurs at time 4 when solar irradiances exceeds 1.12x clear-sky baseline.

Enhancement Event Statistics

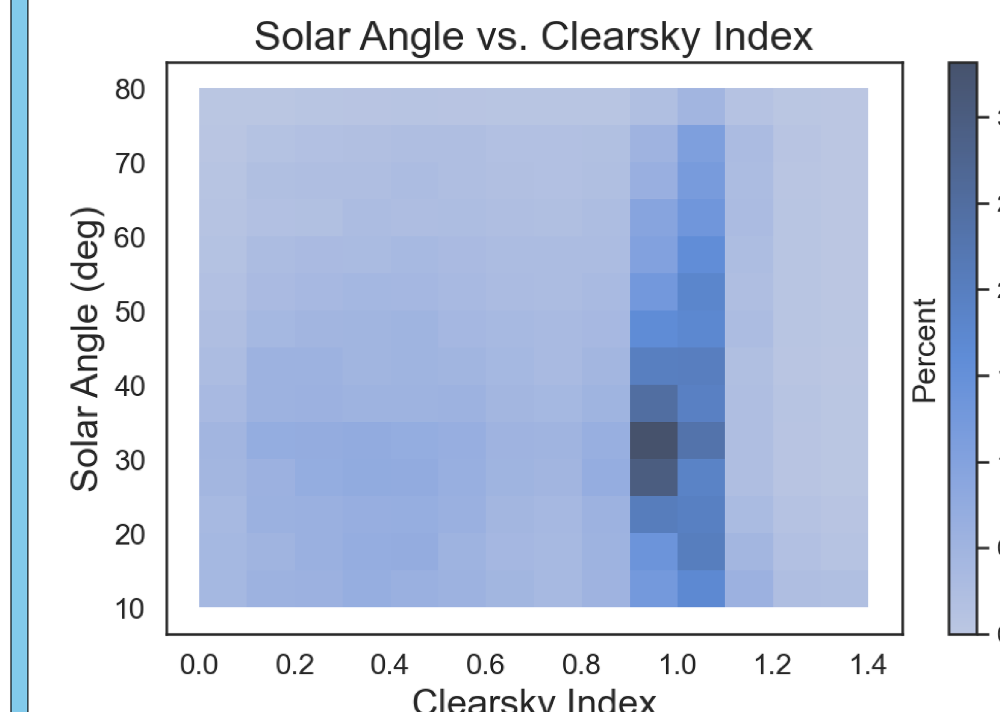


Distribution of the duration of 6,402 enhancement events.



Above clear-sky excess solar irradiance for 21,946 minutes of enhancement events.

Season	# Events	Average Duration	Average Surplus Irradiance (W/m²)
DJF	540	3:37	87
MAM	1873	2:58	119
JJA	2700	3:34	125
SON	1289	3:40	103

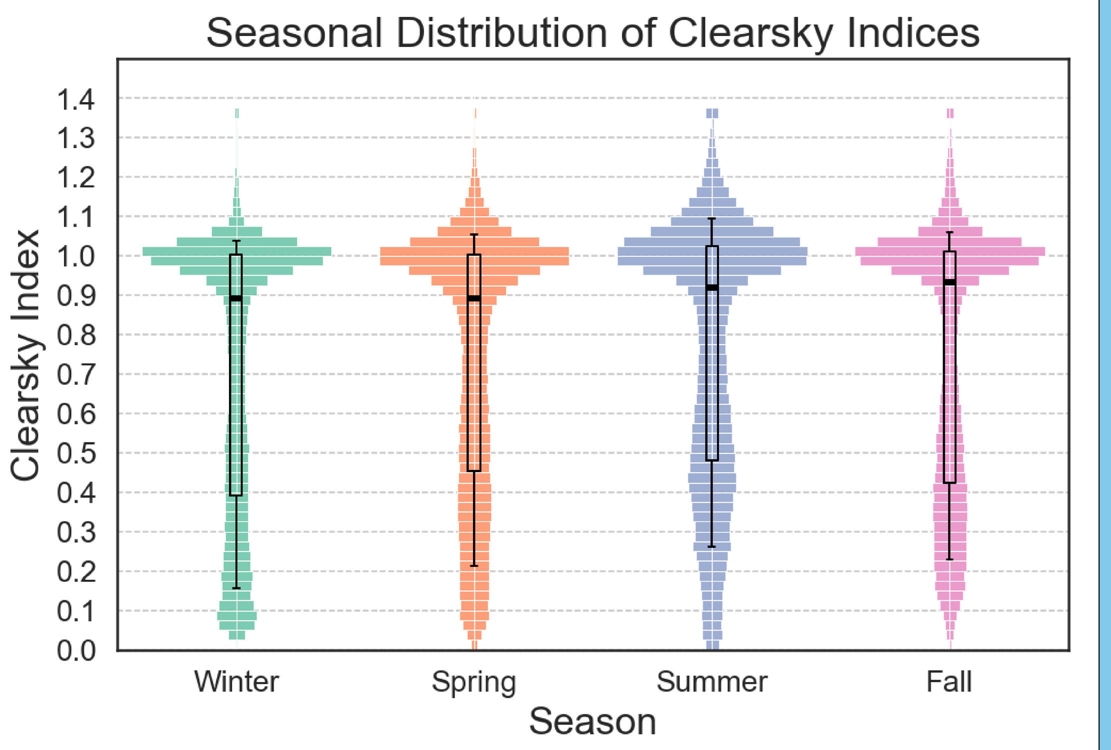


Clear-Sky Index Variation with Solar Angle

- Clear sky index is capped at 1.35 in this plot
- Highest frequency corresponds to clear-sky index between 0.9 and 1.1 and sun angles between 40 and 25 degrees
- Near sunrise and sunset when sun angles are lower (angles < 20 deg) there is a smaller irradiance baseline in W/m² so small deviations in irradiance can have inflated clear sky indexes

Seasonal Clear-Sky Index Distribution

- Partial cloudiness conditions conducive to enhancement events are seasonally dependent
- Summer months have the most frequent and Winter months have the least frequent enhancement events (≥1.12)
- Spring and Winter months have the most frequent and Fall and Summer months the least frequent cloud-induced solar energy reductions (< 0.9)



Summary of Key Findings

- We found 6402 solar enhancement events over 792 days from 2024 to 2026
- On days with at least one event, on average 36 minutes had solar enhancements
- Enhancement events are most common in Summer and least common in Winter
- Enhancements typically generate 105 W/m² surplus irradiance per minute, with more produced in Summer and less in Winter
- Enhancements generate more energy when sun is higher in the sky
- Enhancements are episodic, typically spanning less than 2 minutes, and lasting longer in Fall and shorter in Spring
- When using a standard home rooftop solar installation, a day's worth of enhancement events in summer yield a median total of 5400 W/m² (~0.5 kWh) corresponding to 25 minutes of power for a typical house.

Take-Away

Counterintuitively, direct measurements of solar energy in some partially cloudy conditions can exceed values with no cloud overhead. Cloud fraction estimates based on radiometers need to take this into account. Additional equipment, such as all-sky cameras, should be used in conjunction with surface solar measurements to understand how sky conditions impact solar energy generation.

Acknowledgements

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