Solar PV Output Simulation Under Weather Variability

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Introduction

Solar photovoltaic (PV) systems convert sunlight into electricity, but their output is highly sensitive to weather conditions—especially cloud cover. Even on days with similar clear-sky potential, transient clouds can dramatically reduce energy production and introduce variability that grid operators must manage.

This project addresses a focused question:

How does cloud cover affect solar energy output over the course of a week?

To answer this, we construct a synthetic but physically interpretable model that links:

- clear-sky solar irradiance,
- stochastic cloud cover, and
- PV system power output.

The goal is not to reproduce a specific site, but to demonstrate a coherent modeling chain from weather to energy, suitable for a climate/energy systems portfolio.

Methods

Time-Series Framework

We simulate one week of data at 5-minute resolution. This temporal granularity is fine enough to capture intra-day variability while remaining computationally light.

Each timestamp is associated with:

- hour of day,
- day of year,
- clear-sky irradiance,
- cloud cover,
- cloud-modified irradiance,
- PV power and energy.

This structure mirrors real operational datasets used in solar forecasting and grid integration studies.

Clear-Sky Irradiance Model

We approximate clear-sky global horizontal irradiance (GHI) as a smooth bell-shaped function of solar elevation, represented here as a function of hour of day:

- irradiance is zero at night,
- rises after sunrise,
- peaks around solar noon,
- declines toward sunset.

Although simplified, this captures the dominant diurnal pattern of solar resource and provides a baseline against which cloud effects can be measured.

Cloud Cover and Attenuation

Cloud cover is modeled as a continuous variable between 0 (clear) and 1 (overcast). We construct it as:

- a slowly varying daily pattern (to mimic changing synoptic conditions),
- plus random noise (to represent short-term variability).

Clouds attenuate irradiance using a simple multiplicative model:

$$\mathrm{GHI}_{\mathrm{eff}} = (1 - \alpha \cdot \mathrm{cloud\_cover}) \cdot \mathrm{GHI}_{\mathrm{clear}}$$

where α is an attenuation factor (here, 0.8). This means that heavy cloud cover can reduce irradiance substantially, while partial cloud cover has a more moderate effect.

PV System Model

We consider a fixed-size PV system with:

- nameplate capacity (e.g., 100 kW),
- lumped efficiency parameter,
- effective area inferred from capacity and efficiency.

DC power output is modeled as:

$$P_{\mathrm{PV}}(t) = \eta \cdot A \cdot \frac{\mathrm{GHI}_{\mathrm{eff}}(t)}{1000}$$

where:

- η is the efficiency,
- A is the effective area,
- GHI is in W/m²,
- the factor 1000 converts irradiance to kW/m².

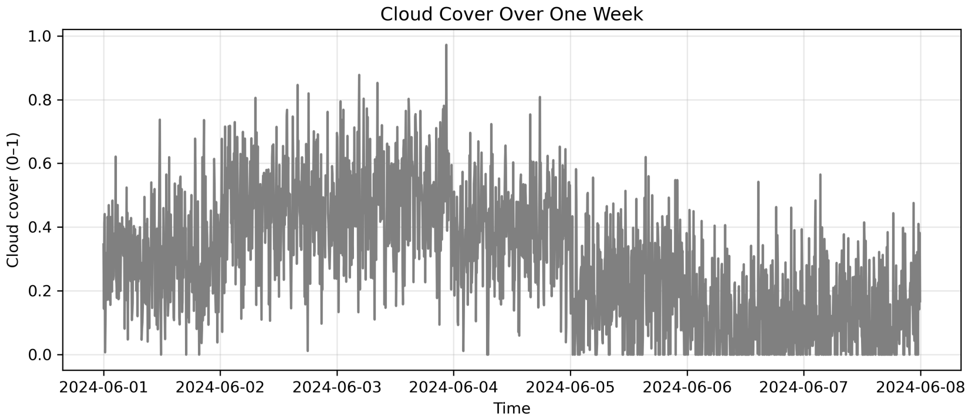
Energy over each 5-minute interval is then:

$$E(t) = P_{\mathrm{PV}}(t) \cdot \Delta t$$

with Δt in hours. Daily energy is obtained by summing over all intervals in a day.

Results

Cloud Cover Over the Week

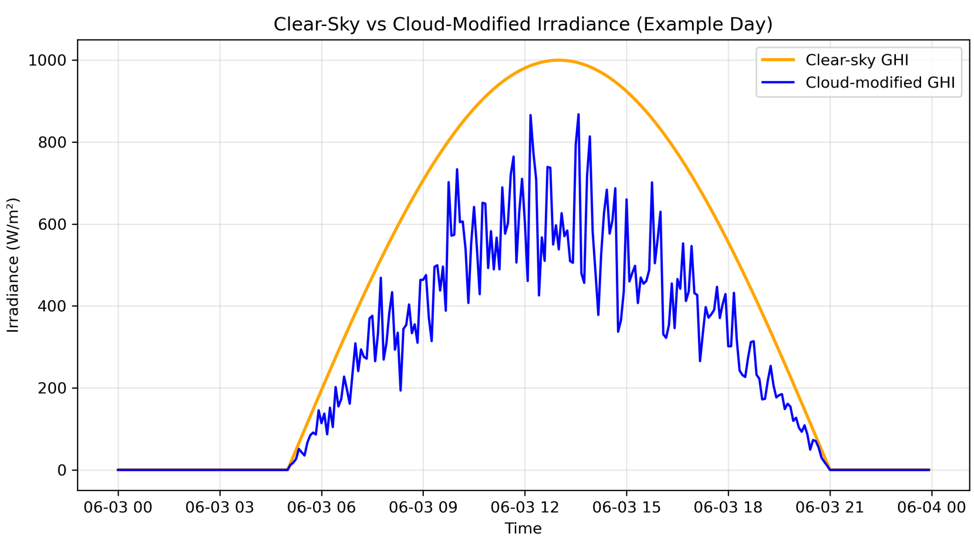


The cloud cover time series shows a mix of:

- relatively clear periods,
- more overcast intervals,
- day-to-day variability.

This structure is intentional: it creates a realistic testbed where some days are "good solar days" and others are degraded by clouds.

Clear-Sky vs Cloud-Modified Irradiance (Example Day)



For a representative day, we compare:

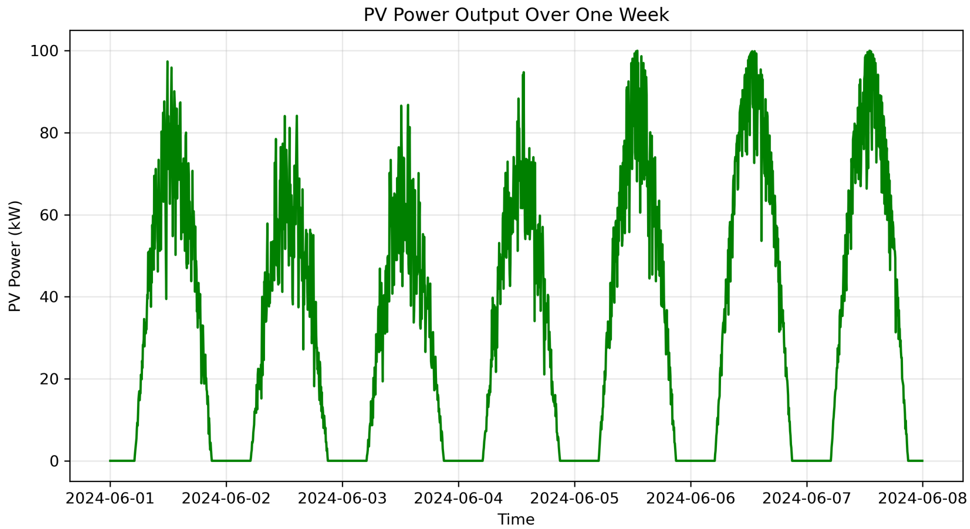
- the **clear-sky GHI** (orange curve),
- the **cloud-modified GHI** (blue curve).

Key observations:

- The clear-sky curve follows a smooth, symmetric shape around midday.
- Cloud-modified GHI deviates downward whenever cloud cover increases.
- Short-term fluctuations in cloud cover translate directly into dips in irradiance.

This figure makes the physical link explicit: clouds act as a time-varying filter on the solar resource.

PV Power Output Over the Week



The PV power time series inherits structure from both:

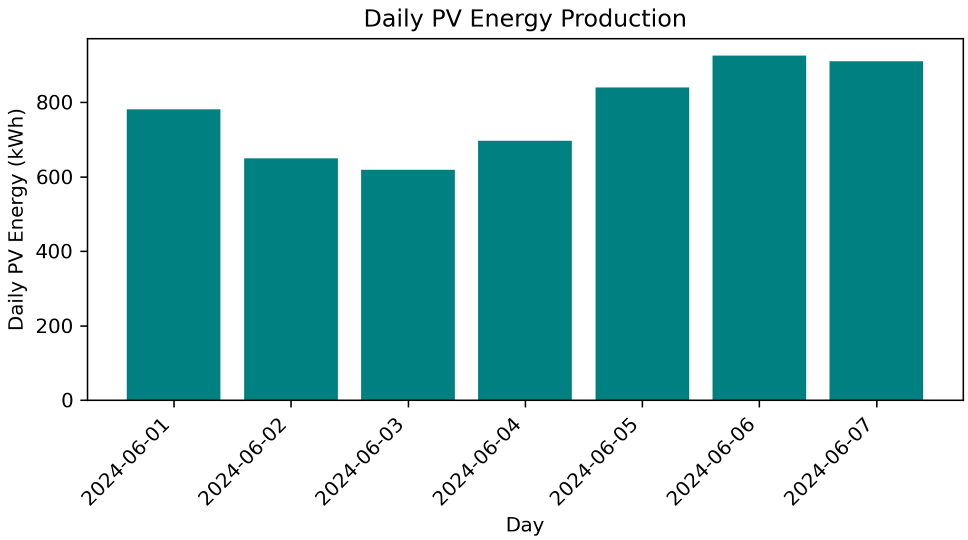
- the diurnal cycle of solar irradiance, and
- the stochastic variability of cloud cover.

We see:

- clear, repeated daily cycles,
- days with strong, smooth peaks (low cloud cover),
- days with flattened or jagged peaks (higher cloud cover).

From a systems perspective, this variability is exactly what grid operators must anticipate when integrating solar into the energy mix.

Daily Energy Production



Aggregating to daily energy smooths out intra-day fluctuations and reveals:

- which days are high-yield vs low-yield,
- how much total energy is lost on cloudy days compared to clearer ones.

Even over a single week, the spread in daily energy illustrates the operational challenge: planning around a resource that is both predictable (diurnal pattern) and uncertain (clouds).

Discussion

This project demonstrates a complete modeling chain from weather to energy:

1. **Clear-sky physics** provides a baseline solar resource.
2. **Cloud cover** introduces realistic, time-varying attenuation.
3. **PV modeling** translates irradiance into power and energy.
4. **Time-series analysis** reveals both short-term variability and daily aggregates.

Key insights:

- Cloud cover does not simply "scale down" solar output uniformly; it introduces structured variability that depends on timing and intensity.
- Daily energy production can vary significantly from one day to the next, even under the same nominal system and location.
- Time resolution matters: high-frequency data captures operational variability, while daily aggregates are more relevant for planning and energy yield assessment.

From a portfolio standpoint, this project shows your ability to:

- design a physically grounded simulation,

- work with time-series data in Python,
- produce clear, publication-style visualizations,
- and tell a coherent scientific story from assumptions to implications.

Conclusion

By simulating solar PV output under variable cloud cover, this project quantifies how weather variability propagates through to energy production. The framework is intentionally simple but extensible: real irradiance data, more detailed PV models, or probabilistic forecasting could be layered on top.

Within your broader climate and energy systems series, this project establishes a solid foundation in solar resource modeling and sets the stage for more advanced work in climate response and grid load forecasting.