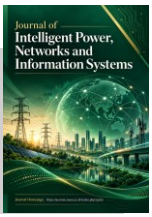
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Daily Energy Generation Characteristics of Solar Photovoltaic Systems: A Scenario-Based Intraday Simulation

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Abstract*— Daily photovoltaic (PV) energy yield is governed not only by the accumulated solar resource but also by its distribution within daylight hours. This study introduces four fully synthetic, reproducible daily sky scenarios to isolate the effects of temporal shape on PV power, energy yield, and short-term ramps. A normalized daylight envelope is multiplied by transparent cloud-transmittance functions at 15-min resolution and converted to output using a 1-kWp reference PV array with a constant 0.78 system performance factor. For clear-sky, partly cloudy, overcast, and intermittent-cloud conditions, calculated daily energy yields are clear sky 5.19 kWh, partly cloudy 4.21 kWh, overcast 2.38 kWh, intermittent clouds 3.81 kWh. The scenario ranking demonstrates that mean attenuation primarily controls daily energy, whereas rapidly changing attenuation governs operational ramps. Temporal aggregation substantially suppresses estimated short-term ramps, emphasizing the dependence of variability conclusions on sampling resolution. All outputs are illustrative simulations without field measurements, calibrated meteorological data, or claims about a specific city. The proposed metrics offer a transparent benchmark for teaching, scenario comparison and the design of future field-based investigations.

Keywords—photovoltaics, daily energy yield, intraday variability, synthetic irradiance, ramp rate, cloud scenarios.

I. INTRODUCTION

Solar photovoltaic systems are increasingly integrated into energy infrastructure, yet a daily energy total alone conceals when and how electricity is produced. For self-consumption, short-term control, storage planning and distribution-system operation, the daily power trajectory is as important as its area under the curve. In particular, cloud motion can create abrupt changes that are averaged away in hourly totals [1]-[3].

Existing studies quantify solar resource variability using clear-sky indices, ramp rates and statistical descriptors [2], [4]. Power conversion during moving-cloud transitions has been investigated using detailed array models [5], [6]. High-resolution studies show that variability metrics depend strongly on the sampling interval and cloud structure [7]. Subsequent work further explores cloud-driven power fluctuation models, sky classification and physically interpretable variability measures [8]-[12].

These contributions provide rigorous evidence from actual sites. A complementary need is a fully disclosed pedagogical benchmark in which the daytime irradiance envelope and cloud disturbances can be modified independently, without conflating results with observations. Such a simulation does not establish real-world predictive accuracy; instead, it clarifies what each selected metric can- and cannot-identify.

The research question is: how do alternative synthetic intraday irradiance distributions alter PV daily energy and power-ramp characteristics under an identical conversion model? The contribution is a controlled four-scenario comparison combining integrated yield, normalized energy reduction, maximum instantaneous output and ramp intensity, with an explicit test of temporal averaging. This differs from annual solar-resource assessments and from module temperature or tilt optimization studies.

II. MATERIALS AND METHODS

A. Reproducible synthetic daylight model

Time t is measured in local solar hours from 06:00 to 18:45, with a 15-min step (Δt=0.25 h). The potential irradiance $G_0(t)$ (W/m²) is defined by: $G_0(t)=1000[\max(0,\sin(\pi(t-6)/12))]^{1.35}$. This smooth, symmetric daylight envelope is a deliberately idealized boundary condition, not a computed clear-sky model or an observed site irradiance series. The effective incident irradiance is $G_s(t)=G_0(t)k_s(t)$, where ks is a dimensionless transmittance scenario.

Four scenarios are constructed deterministically: clear sky ks=0.96; partly cloudy ks=clip[0.88−0.35 exp(−((t−10.1)/0.55)²)−0.42 exp(−((t−13.8)/0.65)²)+0.07 sin(3.6t),0.1,1.04]; overcast ks=clip[0.44+0.05 sin(1.8t),0.25,0.6]; and intermittent clouds ks=clip[0.72+0.20 sin(3.2t)+0.14 sin(8.2t)−0.18 exp(−((t−12.5)/0.32)²),0.10,1.05]. The clip operator restricts

each scenario to its specified bounds. Trigonometric arguments use radians.

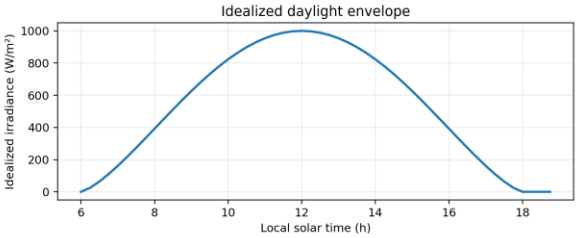


Fig. 1. Idealized daylight envelope used in all scenarios.

B. PV conversion and assessment metrics

The simulated reference plant is 1 kWp with fixed conversion factor PR=0.78. This factor combines unmodeled system losses as a constant; cell temperature, spectral variations, inverter clipping, shadows and grid curtailment are excluded. The instantaneous AC-equivalent output is $P(t)=1\ \text{kWp} \times [Gs(t)/1000\ \text{W m}^{-2}] \times 0.78$. Thus the model intentionally preserves proportionality between irradiance and output.

Daily energy is evaluated using trapezoidal numerical integration: $E=\Sigma\ 0.5[P(ti)+P(ti+1)]\Delta t$. The normalized daily loss relative to the clear-sky reference is $L=100(1-Es/Eclear)$. Signed ramp rate is $ri=[P(ti+1)-P(ti)]/\Delta t$; the largest absolute ramp, peak power, and aggregate absolute power change $A=\Sigma|P(ti+1)-P(ti)|$ are reported. The ramp indicators are not a measure of measured grid instability.

TABLE I. REFERENCE SIMULATION ASSUMPTIONS.

Parameter	Baseline specification
System capacity	1 kWp
Conversion factor (PR)	0.78, constant
Resolution	15 min
Daylight window	06:00–18:45
Maximum envelope	1000 W/m²
Sky scenarios	4 synthetic functions
Thermal model	Not included

C. Temporal-aggregation test and limitations

The intermittent-cloud profile is averaged into successive non-overlapping 15-, 30-, 60- and 120-min blocks. Ramps are recomputed from these aggregated averages, with block length used in the rate denominator. Sampling interval is therefore a model-design variable rather than a measured sensor characteristic. Because no calibration data are employed, conventional field-validation measures such as RMSE against observations are not reported.

III. RESULTS AND DISCUSSION

A. Shape of intraday PV output

Figure 2 separates a smooth baseline from broad cloud disturbances, persistent attenuation and intermittent fluctuations. Clear-sky power follows a unimodal envelope; partly cloudy conditions generate two distinct depressions around late morning and early afternoon; overcast conditions suppress the entire trajectory; intermittent clouds create multiple peaks and troughs. These profiles should be read as controlled boundary conditions, not as a classification of real days or evidence of their relative frequency.

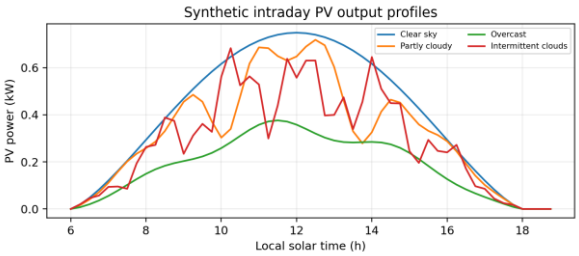


Fig. 2. PV power trajectories for four synthetic sky conditions.

In grid-connected installations, a rapid drop in generation can require balancing or local control even if its energy penalty is modest. Research involving actual PV data has documented cloud-induced ramps and sensitivity to spatial smoothing [1], [6]. The present model does not reproduce spatial averaging but provides an isolated illustration of temporal structure.

B. Daily energy and comparative losses

TABLE II. SIMULATED DAILY ENERGY AND PEAK OUTPUT.

Scenario	Energy (kWh)	Peak (kW)	Loss vs clear (%)
Clear sky	5.187	0.749	0.0
Partly cloudy	4.212	0.718	18.8
Overcast	2.379	0.376	54.1
Intermittent clouds	3.809	0.683	26.6

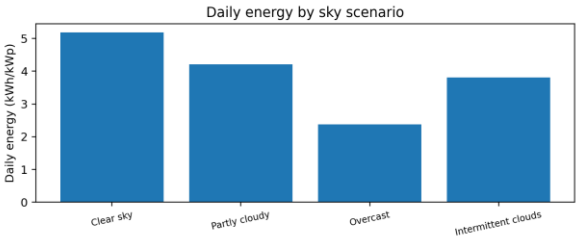


Fig. 3. Integrated daily energy by assumed sky scenario.

The daily energy comparison is governed by the duration-weighted irradiance attenuation. Although instantaneous cloud fluctuations strongly change the profile, they need not create the largest reduction in integrated energy. In contrast, a persistent overcast factor suppresses nearly every interval and therefore produces the smallest daily yield. This is why an analysis limited to maximum power fails to represent daytime energy availability.

The total daily yield should be interpreted per 1-kWp reference system under the chosen PR and smooth daylight envelope. These are not estimates for a typical Indonesian day. Changing the daylight length, envelope exponent, transmittance coefficients or PR would change the numerical outcomes. A scientific contribution of the benchmark is therefore its reproducibility and explicit dependence on assumptions, not its predictive accuracy.

C. Ramps and temporal variability

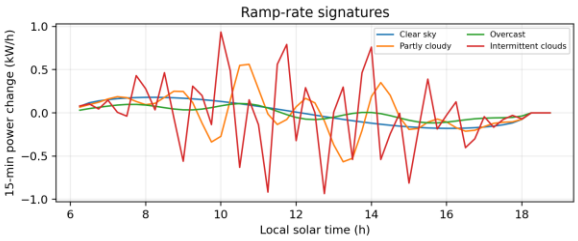


Fig. 4. Modeled 15-min changes in PV power expressed as rates.

The intermittent-cloud scenario produces the most frequent sign reversals, while the smooth clear-sky trajectory produces a gradual morning ascent and afternoon descent. High daily energy and large ramps can coexist because cumulative yield measures area, whereas ramps measure adjacent-interval differences. This distinction is central when considering energy scheduling versus flexible response requirements. Earlier investigations similarly emphasize differences between daily irradiation descriptors and fluctuation-specific metrics [2], [4], [7].

TABLE III. SIMULATED VARIABILITY INDICATORS AT 15-MIN RESOLUTION.

Scenario	Peak abs ramp (kW/h)	Sum |ΔP| (kW)
Clear sky	0.180	1.498
Partly cloudy	0.566	2.285
Overcast	0.116	0.757
Intermittent clouds	0.935	3.685

D. Effect of temporal averaging

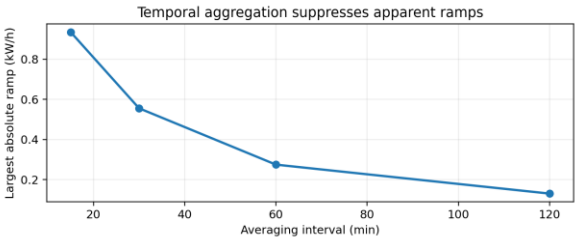


Fig. 5. Highest apparent ramp under increasing averaging interval.

Figure 5 demonstrates how time averaging can hide high-frequency fluctuations even though the broad energy trajectory remains visible. This is a property of the sampled synthetic signal, not a universal monotonic law for all data. In real observations, cloud type, spatial scale and sensor aggregation can materially alter ramp statistics; subhourly research has identified substantial differences between fine- and coarse-resolution metrics [7]. Therefore, a paper reporting PV variability should disclose the time interval along with any ramp-rate threshold.

E. Scope, uncertainty and implications

The principal limitations are the simplified fixed conversion factor, arbitrary though fully specified sky transmittance functions, absence of temperature coupling, lack of measured irradiance and electrical output, and the absence of forecast verification. Deterministic scenario values have no sampling errors or confidence intervals; it would be inappropriate to assign inferential significance to their differences. The daily envelope is fixed at an idealized 12-hour daylight period, so the model does not characterize seasonal daylight variation or site meteorology.

Nevertheless, the framework can be used as an openly specified test case for understanding intraday metrics, exploring data resolution, and designing future validation. A next-stage empirical study should obtain synchronized plane-of-array irradiance and PV power at 1–5-min resolution, retain observed cloud transitions, include measured module temperature, and compare calculated ramps and energy totals against the actual measurements. Such validation would test external realism without misrepresenting the present synthetic experiment.

IV. CONCLUSION

This study evaluated the daily energy generation characteristics of solar photovoltaic systems under four synthetic sky conditions: clear sky, partly cloudy, overcast, and intermittent clouds. The simulation results revealed distinct differences in energy production and temporal power variability across the evaluated scenarios. Clear-sky conditions provided the highest daily energy generation of 5.187 kWh, whereas overcast conditions produced the lowest at 2.379 kWh. Meanwhile, intermittent cloud conditions exhibited more pronounced short-term power fluctuations, demonstrating that lower energy production does not necessarily indicate greater power stability. The analysis also highlighted the influence of temporal resolution on power variability assessment, as longer averaging intervals can obscure rapid fluctuations. These findings indicate that daily energy yield and short-term power dynamics should be considered complementary indicators when evaluating photovoltaic generation characteristics.

The main contribution of this study is a reproducible simulation-based assessment that distinguishes cumulative energy production from intraday power variability under different atmospheric scenarios. This approach provides a systematic basis for understanding how cloud conditions influence photovoltaic generation beyond conventional energy-based evaluation. However, the findings are limited to synthetic irradiance profiles and simplified electrical conversion assumptions without experimental validation. Future research should incorporate high-resolution field measurements and temperature-dependent photovoltaic models to assess the applicability of the proposed approach under actual operating conditions. Such improvements could strengthen photovoltaic performance evaluation and support more effective energy management under variable solar irradiance conditions.

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