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ENHANCING SHORT-TERM SOLAR IRRADIANCE FORECASTING USING GROUND-BASED PYRANOMETERS AND HEMISPHERICAL SKY IMAGERS

Summary

Tropical photovoltaic (PV) systems are severely impacted by small, fast-moving convective clouds that induce abrupt solar irradiance ramps, threatening grid stability and reducing the efficiency and lifetime of coupled battery and hydrogen storage systems. Existing forecasting solutions based on numerical weather prediction and satellite data lack the spatial and temporal resolution required to anticipate these rapid fluctuations. Ground-based pyranometers provide accurate measurements but cannot predict incoming cloud-induced irradiance drops. This study demonstrates the critical role of hemispherical sky imagers for very short-term solar forecasting in tropical environments. Using multiple synchronized cameras, stereoscopic reconstruction enables the retrieval of cloud height, motion, and shadow projection over PV plants. Cloud motion vector techniques can then be applied to forecast irradiance variability minutes ahead. Coupling sky imagers with pyranometer measurements further enables the estimation of cloud radiative impact. This approach provides a robust framework for anticipating irradiance ramps and represents a key step toward improving PV forecasting and enabling reliable integration of solar energy with advanced storage systems in tropical regions.

Keywords: solar forecasting, in-situ measurements, sky imagers

Field of application for the findings: short term solar forecasting

Addressed audience: PV asset manager

1. Introduction

The rapid expansion of solar energy deployment is transforming power systems worldwide, with particularly strong growth in tropical regions where the solar resource is abundant. However, tropical climates are characterized by highly dynamic atmospheric conditions, dominated by small, fast-moving convective clouds that induce strong and rapid fluctuations in surface solar irradiance. These high-frequency variations pose significant challenges for the integration of photovoltaic (PV) energy into electrical grids, especially as energy systems increasingly rely on tight coupling between PV generation and energy storage technologies such as batteries and green hydrogen production. In this context, accurate very short-term forecasts, from a minute to tens of minutes ahead, are essential to optimize energy management, ensure grid stability, and maximize the efficiency of storage systems.

While numerical weather prediction models and satellite observations provide valuable information at larger spatial and temporal scales, they often lack the resolution required to capture rapid local irradiance variability. Ground-based measurements therefore play a critical role in addressing this gap. Pyranometers provide precise, high-frequency observations of global horizontal irradiance, forming the backbone of local monitoring systems. In addition, hemispherical sky imagers offer complementary information by continuously observing cloud cover, motion, and morphology. The combination of these instruments enables the detection and tracking of small-scale cloud structures responsible for short-term irradiance variability (Schmidt et al., 2016).

This study demonstrates the importance of integrating local measurements, such as pyranometers, in solar forecasting solutions and highlights that only multiple hemispherical sky cameras can handle drop in surface irradiance. Such approaches are key to facilitating the continued growth of solar energy and its effective coupling with emerging storage solutions.

2. Context

Solar forecasting solutions are based on a combination of Numerical Weather Prediction (NWP) forecasts, satellite images and less frequently in-situ measurements. NWP spatial resolution is about a tenth of kilometer and temporal resolution is 1 hour for commonly available global coverage models. Update frequency of NWP is 6 hours. Recent meteorological satellites spatial resolution is up to 500 m and each image is made available each 15 minutes. These data sources are necessary to realize a mid-term solar forecast but are unable to provide sufficient high-resolution information to capture fast moving small to medium clouds.

Unfortunately, in tropical region small and fast-moving clouds are dominant and lead, to rapid surface solar irradiance fluctuations, and to locally enhanced solar irradiance (scattering and diffusion due to clouds; Mol, 2023). Rapid fluctuations in solar irradiance induced by small convective clouds (ramps-up or ramps-down) result in significant short-term variability of photovoltaic power output. These fluctuations pose major challenges for grid stability and are particularly critical for photovoltaic systems coupled with battery storage or hydrogen production, as they induce frequent charge–discharge cycles, accelerate system degradation, reduce conversion efficiency, and complicate optimal energy management (Enasel and Dumitrascu 2025). Accurate very short-term solar irradiance forecasting is therefore essential to ensure reliable and efficient operation of such hybrid renewable energy systems.

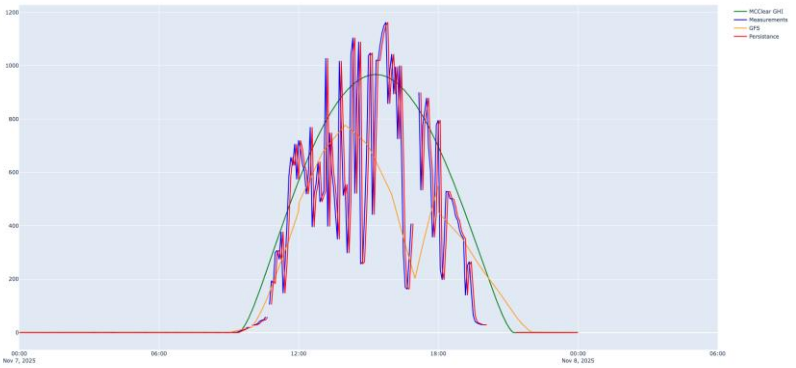

Fig. 1: Solar irradiance on the 7th of November 2025 in French Guyana: clear sky irradiance obtained from CAMS McClear model (Lefèvre et al., 2013) in green, local measurements in blue, 5 min persistence in red, and GFS forecast timeseries in orange.

Figure 1 illustrates a typical day under tropical small-cumulus conditions observed at a photovoltaic power plant in French Guiana during the austral winter. Local measurements clearly highlight the rapid fluctuations of surface solar irradiance, which can occasionally exceed clear-sky values due to cloud-edge enhancement effects. By construction, the persistence model reproduces short-term variability relatively well; however, it systematically exhibits a time lag equal to the measurement sampling interval (5 minutes in Fig. 1). In contrast, due to their coarse spatial and temporal resolution, Global Forecast System (GFS) forecasts are unable to capture high-frequency irradiance variability.

To evaluate the performance of each method, three standard statistical metrics are used, defined as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(\widetilde{I_t} - I_t)} \quad \text{(eq. 1)}$$

$$MAE = \frac{1}{N}\sum_{t=1}^{N}\left|\widetilde{I_t} - I_t\right| \quad \text{(eq. 2)}$$

$$MBE = \frac{1}{N}\sum_{t=1}^{N}\left|\widetilde{I_t} - I_t\right| \quad \text{(eq. 3)}$$

where I_t is the measured solar irradiance at time *t* and $\widetilde{I_t}$ is the forecasted irradiance. However, Vallance et al. (2017) highlighted the limitations of these conventional metrics for evaluating ramp detection performance and introduced complementary indicators such as the Temporal Distortion Index (TDI), the Temporal Distortion Mix (TDM), and the ramp rate.

Tab. 1: Metrics for both persistence and GFS forecasts for the month of November 2025

Methods	MBE ($W.m^{-2}$)	MAE ($W.m^{-2}$)	RMSE ($W.m^{-2}$)	TDI (%)	TDM (%)	Ramp-rate ($W.m^{-2}.h^{-1}$)
Persistence	2.12 (0.47%)	85.56 (18.89%)	151.39 (33.43%)	0.06	98.39	62.91
GFS	25.10 5.54%)	187.28 (41.35%)	257.12 (56.77%)	0.39	0.21	194.51

None of these approaches provides reliable short-term forecasts in terms of ramp detection, as they are unable to anticipate rapid irradiance drops. Numerical weather prediction models are too coarse to resolve small-scale cloud dynamics, while local pyranometer measurements only provide point-based information at the current time. In this context, sky imagers offer significant added value by capturing instantaneous hemispherical images of the sky, providing information on cloud presence and spatial distribution in the vicinity of the site (see Fig. 3). This hemispheric view represents a first step toward cloud localization; however, multiple synchronized sky cameras are required to enable stereoscopic reconstruction, allowing the determination of cloud height and motion. With this critical information, short-term irradiance variability can be more accurately anticipated.

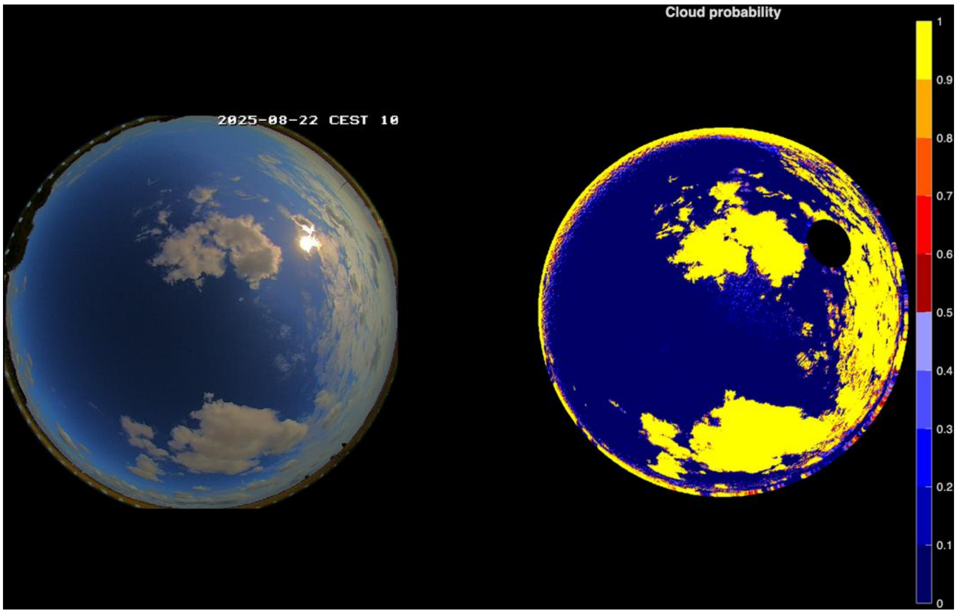

Fig. 3: example of a sky camera image and the associated cloud probability

3. Future work

Using stereoscopic vision, cloud base height can be retrieved, enabling the projection of cloud shadows onto the ground. By analyzing successive images, the temporal displacement of clouds can also be estimated. Applying an approach like Cloud Motion Vector (CMV) method described by Carrière et al. (2021) for satellite observations, the future position of cloud shadows can be forecasted. Further work is required to quantify the impact of these shadows on surface solar irradiance by estimating cloud optical properties. This can be achieved using simplified physical approaches, such as direct beam extinction models, or more advanced methods based on machine learning techniques. Coupling sky imager observations with coincident pyranometer measurements offers a promising framework to relate cloud characteristics to their radiative impact and improve short-term irradiance forecasting accuracy.

4. References

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