EuroSun 2026

RECONSTRUCTING GLOBAL HORIZONTAL SOLAR SPECTRA FROM DIRECT SPECTRAL MEASUREMENTS THROUGH ATMOSPHERIC PARAMETER RETRIEVAL

Summary

This study presents a methodology to estimate the global horizontal solar spectrum (280–4000 nm) using atmospheric parameters retrieved from spectral direct normal irradiance (DNI) measurements through a genetic algorithm (GA) coupled with a radiative transfer model (RTM). The retrieved atmospheric parameters are used as inputs to the SMARTS RTM to reconstruct the global spectral irradiance. The reconstructed spectra are validated against spectroradiometric measurements (294–1100 nm). Results show very good agreement within the measured spectral range and high consistency in integrated broadband irradiance when compared with pyranometer measurements. The RTM–GA framework therefore accurately captures atmospheric conditions and enables reliable estimation of global spectral irradiance. The proposed methodology enables the generation of full shortwave solar spectra beyond the instrumental limits of conventional spectroradiometers while simultaneously providing a diagnostic reference for instrument performance assessment under real operating conditions.

Keywords: GHI spectra, DNI spectra, SMARTS, photovoltaic

Field of application for the findings: precise performance modeling and spectral optimization in advanced photovoltaic and agrivoltaic systems

Addressed audience: photovoltaic research community

1. Introduction

Accurate spectral characterization of solar radiation is increasingly required across modern solar-energy technologies. Beyond traditional broadband irradiance measurements, spectrally resolved data are required for advanced photovoltaic (PV) performance modelling, particularly for bifacial systems where spectral global horizontal irradiance (GHI) influences ground-reflected irradiance and plane-of-array conditions (Lewis et al., 2025). Detailed GHI spectra are also relevant for other solar-energy applications such as agrivoltaic systems and solar thermal technologies, where wavelength-dependent effects influence energy conversion processes. Previous studies have demonstrated that neglecting spectral variability can lead to significant inaccuracies in PV energy-yield modelling (Bevanda et al., 2025).

Despite this growing relevance, long-term spectral observations remain scarce and geographically uneven because high-quality spectroradiometers are costly and operationally demanding. Even at well-instrumented locations, measurements are frequently limited to a single observation geometry, meaning that many monitoring stations provide either spectral DNI or spectral GHI, but not both. This limitation restricts the availability of spectral GHI datasets.

This work addresses the limited availability of spectral GHI observations by exploiting spectral DNI measurements to reconstruct the corresponding global horizontal solar spectrum without additional instrumentation. The approach builds upon the methodology introduced by López et al. (2026), where a GA coupled with a RTM retrieves key atmospheric parameters from measured spectral DNI. In the present study, these retrieved atmospheric parameters are used as inputs to the SMARTS RTM (Gueymard, 2019) to simulate the global horizontal spectrum over the full shortwave range (280–4000 nm) under cloudless conditions. Beyond enabling the estimation of spectral GHI at sites where only spectral DNI is available, the proposed framework also provides a physically consistent reference for assessing the quality and internal consistency of measured spectral GHI at stations where both spectral components are monitored.

2. Experimental setup and methodology

Measurements were conducted at the Solar Testing Laboratory of the Universidad de Huelva, located at the La Rábida Campus in southwestern Spain (37.2° N, 6.92° W). Spectral DNI and spectral GHI, G_λ, have been routinely monitored at this site since February 2021, using EKO MS-700N (350–1050 nm) and EKO MS-711 (294–1100 nm) spectroradiometers, respectively. In parallel, broadband GHI, G, was continuously monitored by means of a secondary-standard EKO MS-802 pyranometer with spectral sensitivity between 285 and 3000 nm. Pyranometer data were used as broadband reference for validating the reconstructed GHI spectra. All measurements were acquired with a temporal resolution of one minute.

Two representative cloudless days with contrasting aerosol conditions were selected for detailed analysis: 24 March 2021, characterized by very low aerosol optical depth and pristine atmospheric conditions, and 4 April 2021, influenced by Saharan dust intrusion resulting in elevated aerosol loading. In addition, five supplementary days covering a wider range of aerosol conditions were included for extended validation, spanning low-aerosol situations, the onset and peak of a dust episode, and an extreme aerosol event. This dataset ensures a robust evaluation of the methodology under diverse atmospheric regimes.

The atmospheric state is characterised using three key parameters: aerosol optical depth, Ångström exponent, and precipitable water. These parameters are retrieved from spectral DNI measurements using the RTM–GA approach described by López et al. (2026). In the present study, the retrieved values are used as inputs to the SMARTS RTM, while the remaining atmospheric variables are fixed to representative site conditions. SMARTS simulations provide high-resolution spectral GHI across the shortwave domain extending up to 4000 nm.

To enable direct comparison with MS-711 measurements, the simulated spectra are adapted to the instrument spectral response through a dedicated smoothing procedure. A wavelength-dependent Gaussian convolution projects the high-resolution SMARTS output onto the MS-711 wavelength grid. In the absence of detailed manufacturer slit-function data, a Gaussian instrumental response with a full width at half maximum (FWHM) of 7 nm is assumed.

The resulting spectra are compared with measured irradiance in the 294–1100 nm range and integrated to obtain broadband irradiance values. Spectral consistency is evaluated using a relative L^2 norm of the spectral residuals, while broadband agreement is assessed using the root mean square error (RMSE).

3. Results and conclusions

Figure 1 compares measured spectral GHI from the EKO MS-711 with the spectra reconstructed using the RTM–GA methodology for two representative instants on 24 March 2021. The agreement is excellent across the measured spectral range. Relative spectral errors remain close to 2 % during the central hours of the day and increase moderately to approximately 3 % at higher solar zenith angles in the late afternoon. This behaviour is consistent with the increased sensitivity of radiative transfer calculations to aerosol effects and air-mass variations at low solar elevations.

Above 1000 nm, the measured spectra exhibit oscillatory behaviour that is not physically consistent with radiative transfer expectations. These fluctuations are attributed to instrumental noise and reduced signal-to-noise ratio of the MS-711 in the near-infrared region. In contrast, the RTM-based reconstruction provides a physically smooth spectral profile, allowing automatic identification of such measurement artefacts. This highlights the potential of the methodology as a diagnostic tool for spectroradiometer quality control.

Figure 2 shows the daily evolution of broadband GHI. The RMSE between broadband irradiance obtained from integrated MS-711 spectra and RTM-GA reconstructed spectra is ≈ 2 %. In addition, the reconstructed broadband irradiance closely matches pyranometer measurements from the MS-802, confirming the radiometric consistency of the reconstructed spectra across the extended spectral domain.

Overall, the results demonstrate that the RTM–GA framework accurately reconstructs GHI spectra under cloudless conditions. The method enables full shortwave spectral estimation (280–4000 nm) beyond the instrumental range of conventional spectroradiometers while also providing a practical tool for automated spectral quality assessment and instrument performance benchmarking. These capabilities are particularly relevant for advanced PV performance modelling and other spectral-sensitive solar-energy applications.

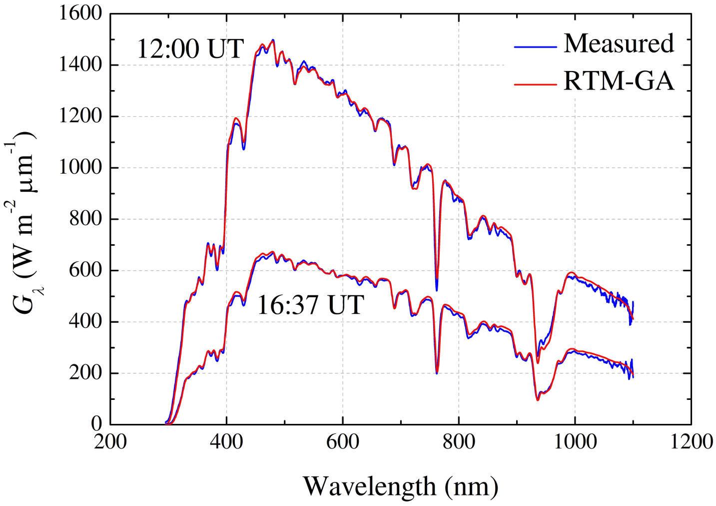

Fig. 1: Comparison between measured and reconstructed GHI spectra obtained using the RTM–GA methodology. Two representative instants on 24 March 2021 are shown.

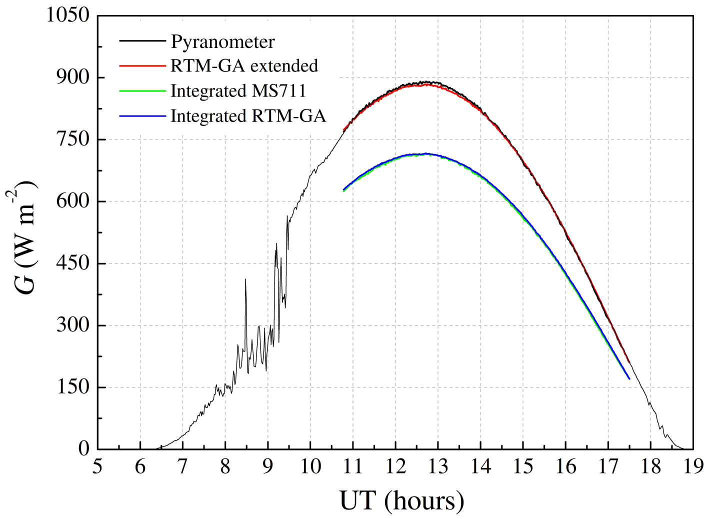

Fig. 2: Daily evolution of broadband GHI from pyranometer measurements (MS-802) and from integrated RTM–GA reconstructed spectra over the extended range (285–3000 nm), together with broadband irradiance obtained from integrated measured MS-711 spectra and integrated RTM–GA spectra within the measured range (294–1100 nm). Results correspond to 24 March 2021.

References

I. Bevanda, P. Marić, A. Kristic, and T. Betti. Assessing the impact of solar spectral variability on the performance of photovoltaic technologies across European climates. *Energies*, 18:3868, 2025.

Christian A. Gueymard. The SMARTS spectral irradiance model after 25 years: New developments and validation of reference spectra. *Solar Energy*, 187:233–253, 2019. doi: 10.1016/j.solener.2019.05.048.

M.R. Lewis, V. Jancowski, C.E. Valdivia, and K. Hinzer. Spectral irradiance correction of photovoltaic energy yield predictions in six high-latitude locations with measured spectra. *Solar Energy*, 300:113816, 2025.

G. López, B. Ivorra, P. Ferrada, and C.A. Gueymard. An efficient genetic algorithm method to extend and upscale direct solar irradiance spectra measured with spectroradiometers. *Solar Energy*, 305:114242, 2026. doi: 10.1016/j.solener.2025.114242.