The Solar Radiation and Energy Laboratory (ESEL) at Limassol, Cyprus: infrastructure, QA/QC procedures and first year of results

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ABSTRACT

This study presents the infrastructure, measurement procedures and one year of measurements of the newly founded The Solar Radiation and Energy Laboratory (ESEL) at Limassol, Cyprus [34.67˚ N, 33.04˚E, altitude of 31m]. The data include: solar broadband measurements of global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI), with an annual availability exceeding 99%, solar spectral measurements at the UV and visible range, infrared measurements and cloud camera information. The measurements underwent rigorous quality control procedures, including range, closure, and consistency tests, ensuring the reliability of the dataset. Annual sums of GHI shortwave (SW) irradiance reveal a total of 2004 kWh/m² and DNI (SW) of 2307 kWh/m², emphasizing the region's high solar energy potential. Temporal variations indicate peak solar energy availability during summer, with marked diurnal and seasonal patterns influenced by solar geometry and atmospheric conditions.

The station follows the Baseline Surface Radiation Network (BSRN) recommendations for quality control procedures, ensuring robust and reliable data for long-term analysis. Closure tests were performed to verify the consistency among the radiation components by assessing the ratio of diffuse to global horizontal irradiance and the ratio of global horizontal irradiance to the sum of its direct and diffuse irradiance components as they have been measured individually. The latest is expected to remain close to 1, indicating the physical coherence of the measurements. The results confirmed the dataset's accuracy, with some deviations observed under specific atmospheric conditions and due to technical sporadic failures.

These measurements represent the first year of operation, but the station is designed for long-term monitoring to support ongoing research and regional energy planning. Having a monitoring station that measures global, diffuse, and direct solar radiation provides highly valuable data across a range of scientific, engineering, and industrial disciplines such as: Renewable Energy (designing and optimizing solar power systems), Meteorology/Climatology (studying climate patterns, energy balance, and atmospheric dynamics), agriculture (applications related with photosynthesis related data), aerosol and atmospheric physics (Studying the effects of particles, gases on solar radiation) and remote sensing (Calibrating/validating satellite data with ground truth measurements).

Keywords: Solar Radiation Measurements, solar energy, climatic research, Cyprus

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1. INTRODUCTION

High quality solar radiation measurements are essential for various research communities including, climate research, atmospheric investigations, and renewable energy applications [1]. In Cyprus, a Mediterranean region rich in solar resources, high-quality irradiance data are crucial for evaluating solar energy potential and enhancing forecasting models [2],[3],[4],[5]. The Eratosthenes Centre of Excellence (ECoE) under the EXCELSIOR project has founded the Solar Radiation and Energy Laboratory (ESEL) to exploit Cyprus's significant solar potential [6]. ESEL's research includes solar radiation monitoring, radiative transfer modeling, and atmospheric studies. The significance of these measurements/databases encompasses among others energy planning, climate modeling, and solar radiation predictions, rendering dependable data essential for decision-making in scientific and industrial contexts.

The objective of this study is to describe the ESEL infrastructure, the quality assurance and quality control (QA/QC) procedures and some preliminary examples of the first year of operation.

2. Methodological Framework

The solar station in Limassol is situated in an urban environment, surrounded by traditional tiled rooftops and mid-rise buildings. Despite its urban context, the site offers an unobstructed view of the sky, ideal for solar radiation and atmospheric observations. The Limassol station presented in Figure 1 is equipped with radiometric sensors that adhere to Baseline Surface Radiation Network (BSRN) standards [5]. The measurement system comprises an EKO sun-tracker STR 22G, which guarantees precise monitoring of the sun for direct normal irradiance (DNI) measurements. Global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) are measured using EKO MS-80 pyranometers, whilst DNI is assessed with an EKO MS-57 pyrheliometer. Longwave radiation is monitored with an EKO MS-21 pyrgeometer. Furthermore, a Kipp&Zonen SUV-E actinometer measures erythemal UV exposure, while a DMc150 Bentham spectrophotometer delivers high-resolution spectral data within the 280–600 nm range. Cloud cover is consistently observed using an ASI-16 All Sky Imager.

Measurements of GHI, DNI and DHI are taken at a high temporal resolution of 1Hz using a Campbell Scientific CR1000X datalogger/ One-minute averages are computed, along with their associated standard deviation, maximum, and minimum values.

Figure 1. Limassol Solar Radiation Station. The two platforms, one with the spectrophotometer and and All-Sky Camera and the other one with the Sun-tracker, pyranometers, pyrgeometer, pyrheliometer and one erythemal UV actinometer

Quality Control and Data Validation

Ensuring the accuracy of solar irradiance measurements requires a robust quality control framework. The methodology applied in this study follows the Baseline Surface Radiation Network (BSRN) guidelines and integrates advanced data validation procedures and BSRN recommended QC tests. Range tests, closure tests, and consistency checks were performed to eliminate measurement anomalies and maintain dataset reliability[7]. The quality control process incorporated the Libinsitu software [8], a widely used tool for evaluating solar radiation datasets. Figure 2, illustrates a comprehensive assessment of the dataset using multiple quality control indicators. The upper panels show the distribution of GHI, DNI, and DHI throughout the year, highlighting seasonal variations. The range tests validate the measured values against theoretical top-of-atmosphere (TOA) irradiance, ensuring no unrealistic values are present. The closure tests, seen in the lower panels, confirm the consistency between global and component irradiance values, ensuring physical coherence in the dataset.

Furthermore, the leveling-induced error test assesses the impact of sensor misalignment, while the shadow analysis evaluates potential obstructions affecting DNI. These tests ensure that environmental factors such as sensor tilt and shading do not introduce biases into the dataset. The closure residual distribution, depicted in Figure 2, confirms that the majority of GHI-GHI* (GHI* is the summary of direct and diffuse irradiances that have been measured individually) values remain within acceptable limits, reinforcing the dataset's accuracy. The inclusion of these automated tests ensures that the solar irradiance dataset is reliable for further atmospheric and solar energy applications.

For further details on the quality control methodology, refer to the Libinsitu documentation (https://libinsitu.readthedocs.io/en/1.4/qc.html).

3. Findings and Analysis

The analysis of the inaugural year's results indicated substantial solar energy potential in Limassol. The total annual GHI measured was 2004 kWh/m², whereas total annual DNI was 2307 kWh/m². Maximum irradiance levels were recorded in the summer months owing to the elevated sun angle, exhibiting diurnal changes that conformed to a Gaussian distribution.

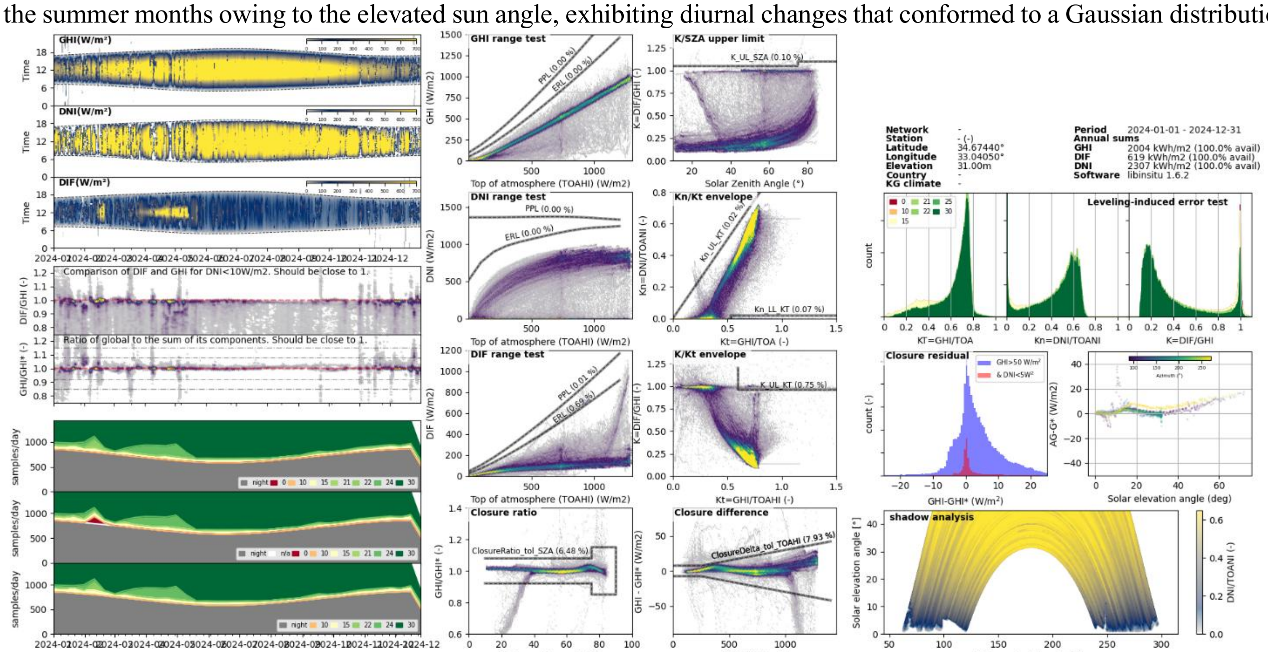

Figure 2. QA&QC analysis of Limassol solar station for the period of one year 2024

Seasonal fluctuations were seen, with diminished values in winter due to reduced daylight duration and heightened air attenuation

Initial findings from ESEL's research suggest that Cyprus exhibits elevated ultraviolet (UV) radiation levels, with UV index values attaining as high as 10 during the summer months[6],[9]. This highlights the necessity for public awareness of suitable preventive measures against overexposure. The data quality assessment verified that the closure tests exhibited consistency, with deviation levels remaining within acceptable BSRN values. Fewer than 1% of the dataset was marked for small discrepancies, that were mostly due to highly variable cloudiness conditions, some obstacles during moring and evening, some issues when raining conditions occur, for instance there was an issue with the display of diffuse irradiance during certain days in spring as the shading ball position change. Based on this measurement erors such as shadowing failures visible in Figure 2 we can identified and post corrected the data.

In Figure 3 Daily values of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) recorded near local solar noon in Cyprus throughout 2024. Each data point corresponds to the closest measurement to 12:00 local time. The seasonal variation is clearly visible, with higher irradiance during summer months and lower values during winter.

The incorporation of an All Sky Imager facilitated real-time observation of cloud effects, hence augmenting the dataset's dependability, Figure 4.

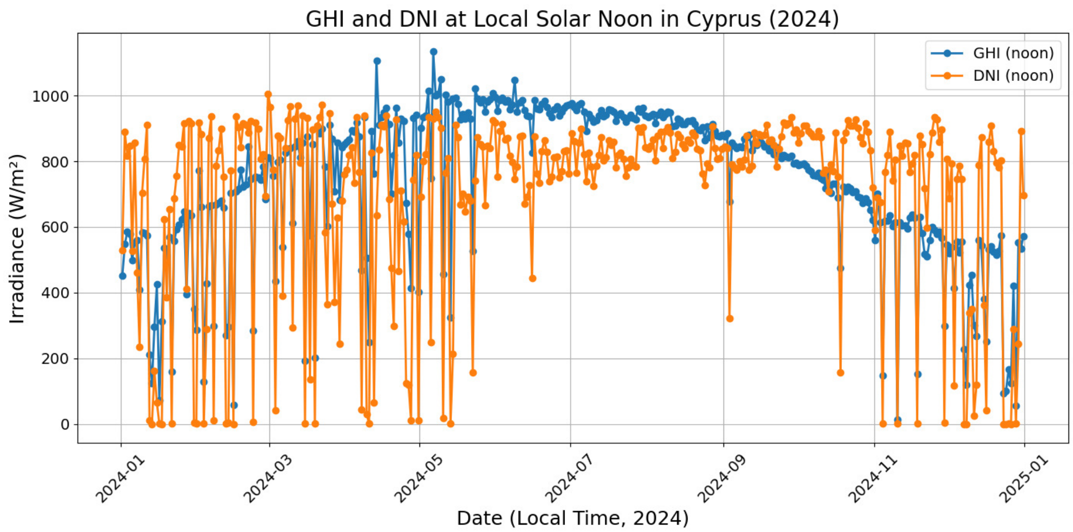

Figure 3. Daily values of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) recorded near local solar noon in Cyprus throughout 2024.

4. Case Study: Cloudy Day Analysis Using All Sky Imaging and Irradiance Measurements

In this section, we present a case study to highlight the importance of integrating all-sky imaging with radiometric observations for understanding the effects of cloud cover on solar irradiance. Specifically, we examine a day with variable cloud conditions using data from the all sky camera and simultaneous measurements of GHI, DNI, and DHI.

Figure 4 displays two hemispheric images of the sky taken by the ASI-16 All Sky Imager at different times on 19 January 2024.. The left image shows a scene with scattered clouds, allowing direct sunlight to intermittently reach the sensor, while the right image presents a denser cloud cover scenario with significant portions of the sky obscured, reducing direct sunlight. The changing sky conditions between these two timestamps exemplify the dynamic atmospheric variability that affects solar radiation.

Corresponding to this sky state, Figure 5 illustrates the temporal evolution of GHI, DNI, and DHI on the same date (19^{th} of January 2024). The irradiance time series reflects the impact of transient clouds, especially on the direct component (DNI), which exhibits strong fluctuations with rapid drops and recoveries. These sharp variations are consistent with episodic solar obstruction due to moving clouds, a typical signature of broken cloud condition.

Global irradiance (GHI) shows a smoother response compared to DNI, as it includes both the direct and diffuse components, which mitigates the variability. The diffuse irradiance (DHI) exhibits periods of increase corresponding to

cloud scattering events, notably peaking when the direct beam is attenuated. This anti-correlation between DNI and DHI is a characteristic indicator of partly cloudy conditions.
The ratio of the sum of direct and diffuse irradiance to global horizontal irradiance ~ 1, indicating the physical coherence of the measurements and the ratio of global horizontal irradiance to the diffuse irradiance ~ 1 to the cloudy cases. (Figure 6).
Such case studies are essential for validating the responsiveness of radiometric instruments to atmospheric variability and for testing the robustness of forecasting models under non-clear-sky conditions. They also demonstrate the complementary role of sky imaging and irradiance data in diagnosing atmospheric influences on solar radiation.

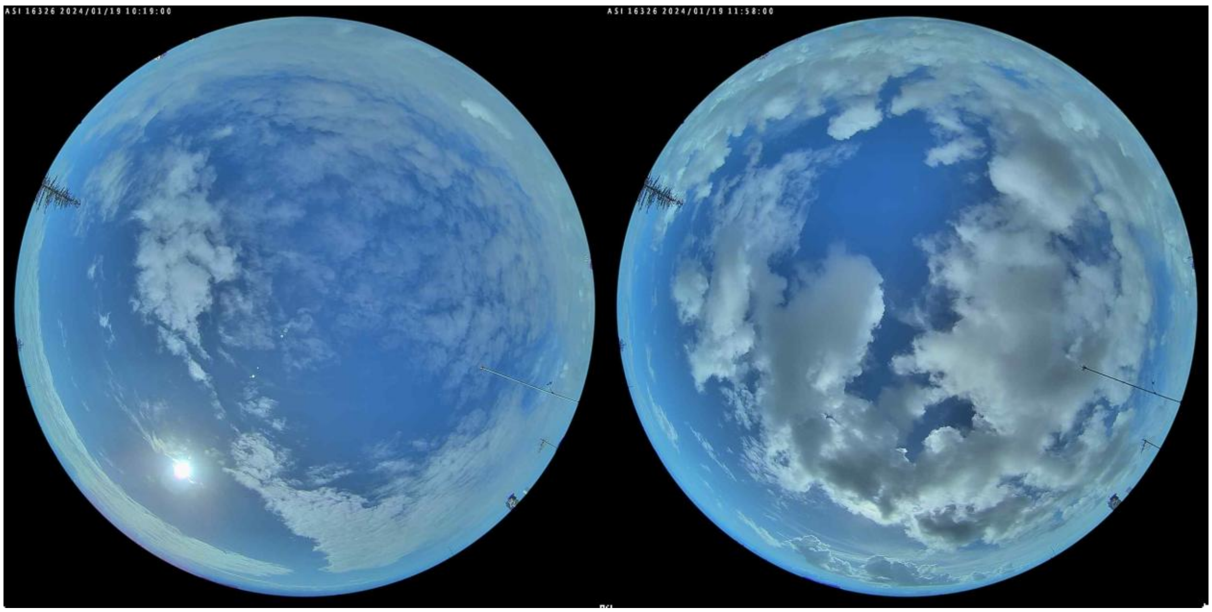

Figure 4 : View of the sky captured by the ASI-16 All Sky Imager

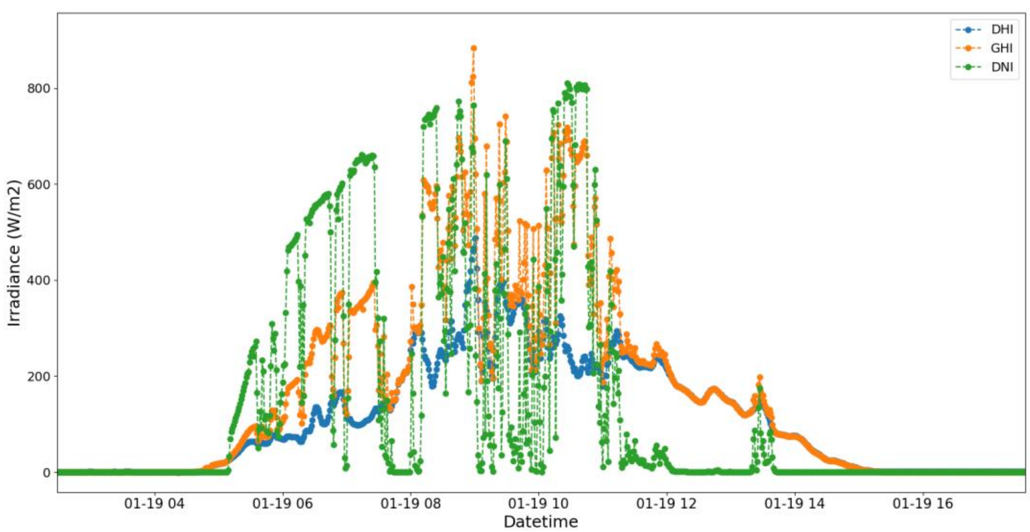

Figure 5: Time series of irradiance components (DHI, GHI, and DNI) on 19 January 2024.

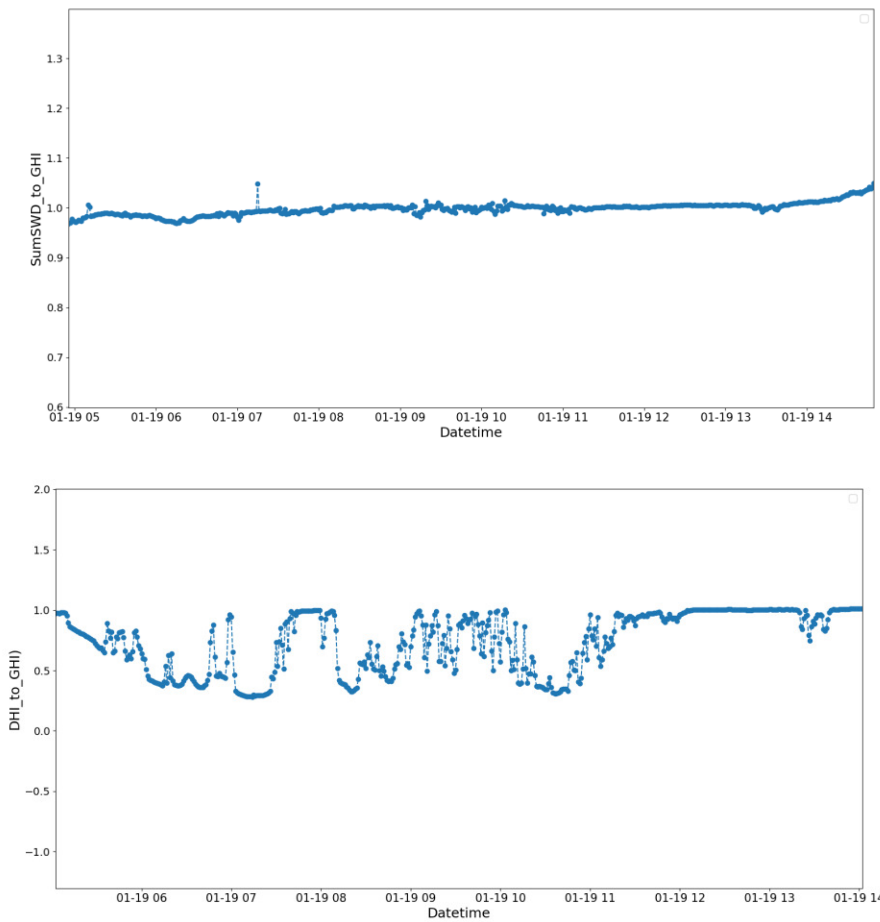

Figure 6 : The ratio of global horizontal irradiance to the sum of direct and diffuse irradiance (DNI + DHI)/ GHI and ratio of the diffuse irradiance to global horizontal irradiance on the 19th of January 2024

4. Conclusion

This study presents the infrastructure, the quality control procedures and first year of results of ground-based solar irradiance measurements collected over one year at the newly established Limassol station in Cyprus, ESEL. The analysis confirmed the reliability of the radiometric system and highlighted the station's ability to capture detailed irradiance variability under diverse atmospheric conditions, including clear and cloudy skies. A case study analysis demonstrated the responsiveness of the instruments and the added value of combining all-sky imaging with irradiance data. The dataset has many potential applications in solar energy forecasts, atmospheric research, and regional energy planning. More specifically, during a recent study the data were used as a benchmark for corroborating numerical weather prediction models and enhancing short-term solar irradiance forecasts [10]. Additionally, it can be used to enhance radiative transfer modeling and aerosol impact evaluations, hence aiding climate research initiatives.The founding of ESEL and its continuous research endeavors seek to establish the laboratory as a benchmark for the Eastern Mediterranean, Middle East, and North African regions, thereby making substantial contributions to the scientific infrastructure that underpins many industries in Cyprus and abroad. Future endeavors will encompass the enhancement of monitoring capacities at four regional stations: Kyperounta, Athalassa, Polis Chrysochou, and Frenaros [6]. These sites will augment the spatial coverage of solar radiation measurements throughout Cyprus, yielding a more extensive dataset for regional study. Initiatives will be undertaken to include cloud cover predictions with numerical weather forecasting models to enhance irradiance forecasting for energy applications. The year of sun irradiance measurements at the Limassol station offers significant insights into the region's solar energy potential. The stringent quality control protocols guarantee that the dataset is dependable and appropriate for prolonged monitoring. The results underscore the necessity of ongoing, high-caliber terrestrial measurements in facilitating climate research, solar energy initiatives, and regional energy strategizing. The station's sustained functioning will facilitate the creation of a solar atlas for Cyprus and enhance future progress in solar radiation modeling.

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