VIPERLAB

FULLY CONNECTED **VI**RTUAL AND **P**HYSICAL P**ER**OVSKITE PHOTOVOLTAICS **LAB**

D 10.3

DATABASE WITH SOLAR RESOURCE DATA FOR DIFFERENT EUROPEAN LOCATIONS

DELIVERABLE REPORT

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FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB VIPERLAB

DELIVERABLE

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Project References

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DISCLAIMER

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EXECUTIVE SUMMARY

VIPERLAB is an infrastructure project that aims to create a European environment, where various physical and virtual infrastructures from 13 VIPERLAB partners can be accessed by different users from Europe and abroad. VIPERLAB identifies perovskite PV as the key emerging technology that will be the lever for a future market penetration of EU-based PV production with lowest costs and lowest carbon footprint.

The overall goal of the work package 10 is to provide guidance for the infrastructure and technology development within VIPERLAB by evaluating and optimizing the environmental, social and economic impact of new perovskite-based technologies. To this end, this work package will:

• Provide the data (material, process flows etc.) necessary for such an evaluation

• Evaluate the environmental (Life Cycle Assessment, LCA), social and economic (Levelized Cost of Electricity, LCOE) impact of new perovskite-based technologies and how this impact is affected by the application, device design, choice of equipment and process.

This report presents the available solar resource data i.e., the irradiated power and its spectral composition ideally split into a diffuse and direct component in different European locations. The data collection was performed through the consortium members and existing literature plus publicly available resources. The main data source was from the Helmholtz-Zentrum Berlin (HZB) which provided spectral data from their measurement site in Berlin (Northern Germany) and Fraunhofer ISE which has spectral data at their testing installation in Freiburg (Southern Germany). Apart from these two sites, spectral data from the National Solar Resource Database made publicly accessible by NREL was also collected for two sites in Southern France and Southern Spain to have a diverse spread of European locations. The details on the type of spectral data, its resolution, equipment's used for the measurement and time interval and length of measurement are provided in brief within the report. The subsequent goal is to transfer the collected and available spectral data onto the VAPO platform to facilitate ease of access to the same for the broader research community interested in energy yield modelling for photovoltaics.

1. INTRODUCTION

As incoming solar radiation enters the Earth's atmosphere, it is altered by various mechanisms until it reaches the surface which has a direct impact on different scientific fields such as meteorology, atmospheric sciences, solar energy, among others [1]. The growing deployment of PV technologies has made the precise performance rating of PV modules a matter of great importance for all relevant stakeholders. The characteristic parameters of PV modules are rated using standard test conditions (STC) given by 1000 W/m^2 of irradiance, 25 °C of module temperature and an airmass AM1.5G spectrum [2]. For reference, the standard AM1.5G spectrum refers to the spectrum at the zenith angle of approximately 48° incident on a plane of 37° tilt with atmospheric conditions defined in ASTM G-173-03 [3].

Although the effects of irradiance and temperature on PV performance have been extensively studied worldwide, the impact of varying solar spectral irradiance has not been explored to the same extent [4], despite several studies which have been conducted worldwide investigating the general influence of the spectrum on the performance ratio of PV modules [5]. However, the results of these studies are not easy to compare, as they focus on different regions and different time scales for the energetic influence (instantaneous, monthly, annual), use different indicators and usually do not consider measurement uncertainty. They agree, however, in one important aspect: the influence of varying spectral irradiance on the performance of PV devices generally depends on its spectral response. A second overall conclusion is that the spectral impact is dependent on location in terms of latitude, longitude, climate, rural or urban environment, albedo etc [6]. Spectral irradiance is typically measured by spectroradiometers, instruments which employ optical diffraction to measure irradiance across a series of narrow wavelength ranges. A given diffractive optic and its detector can sample only a limited wavelength range, so spectroradiometers for PV applications often measure total wavelength ranges of around 300 to 1100 nm or 900 to 1700 nm, covering about 97% of the power in the extraterrestrial (AM0) spectrum [7].

Another important point to consider is that the impact of spectral variation on single junction cells is generally known. PV devices with narrower spectral response (SR) (i.e., a-Si, CdTe) are more sensitive to such variation compared to the PV devices with wider spectral response (i.e., c-Si, CIGS, HIT) [8, 9]. In case of a tandem solar cell the two sub-cells absorb a different part of the solar spectrum. The sub-cell generating the lower current limits the current through the tandem in a serial connected configuration. The voltages add up and the world record efficiency for such devices outperform single junction Si devices and have surpassed 30% efficiency [10]. A tuning of the bandgaps to a maximum power output is usually done under AM1.5G and any deviation of the incoming spectrum leads to a different share of the incoming photons between the two sub-cells and thus to losses [11]. This deliverable report, as well as the created database, also serves as a proof of reaching milestone M31.

2. DATA COLLECTION AND CONSOLIDATION

For the collection of the spectral irradiance data, VIPERLAB consortium members with suitable measuring equipment onsite which could provide such data were contacted – primarily HZB, Fraunhofer, CENER and CEA-INES – and were requested if they were able to share such data for the provision of a database, as spectral irradiance data is scarce owing to the high cost and complexity of the sensors and measurement setup. Among the contacted consortium members only HZB and Fraunhofer collected the required data measured over an entire year or longer – CENER does not measure spectral data over an entire year but rather only at specific times mainly for equipment calibration, whereas CEA-INES only provided irradiation intensity (in kW per square meter) unrelated to the overall spectrum. In the case of HZB, a complete published dataset was provided from their measurement site in Berlin (Northern Germany), further detailed in [12], whereas Fraunhofer also has spectral data measured over the last two years from their testing installation in Freiburg (Southern Germany) which is suitable for analysing photovoltaic performance. However, Fraunhofer could not share this data publicly as it is currently ‘internal as measured’ data and has not yet gone through the required quality assurance checks. Depending on interest from external project partners for access to this data, this can be resolved bilaterally.

Apart from these two sites, spectral data from the National Solar Resource Database (NSRDB [13]) made publicly accessible by NREL was also collected for two sites in Southern France and Southern Spain to have a diverse spread of European locations. The details on the type of spectral data, its resolution, equipment's used for the measurement and time interval and period of measurement are provided in the following sections.

2.1. Spectral data from Helmholtz Zentrum Berlin

The data was acquired using pairs of spectrometers installed outdoors on top of a building in Berlin (52°25′52.5″N 13°31′25.7″E) on a metallic rack with two different tilt angles (Figure 1) [14].

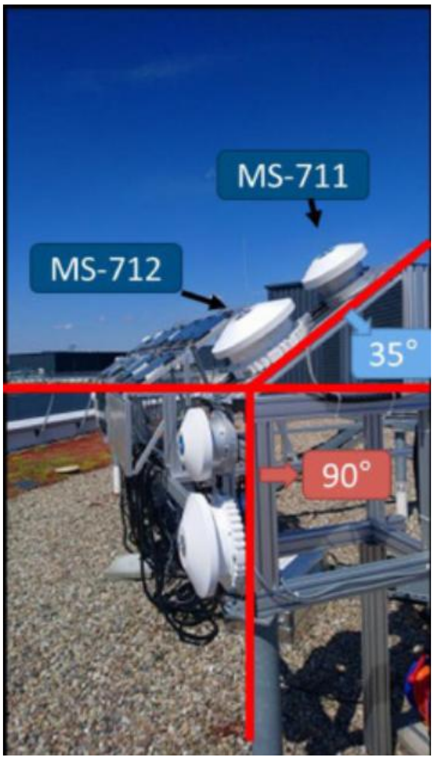

Figure 1 Picture of the installation of two sets of spectrometers MS-711 and MS-712 at two different tilt angles: 35° and 90°.

The datasets are provided as compressed raw data as measured by the MS-711 (300–1100 nm) spectrometers (S1) and by the MS-712 (900–1700 nm) spectrometers (S2). The merged data measured by MS-711 and 712 (S1+S2) is also provided. Figure 2 shows a flow chart of the data measurement and collection. Due to the size of the three-year datasets, the whole datasets were divided in three smaller compressed packages (.zip) per angle and per year, as described in Figure 3.

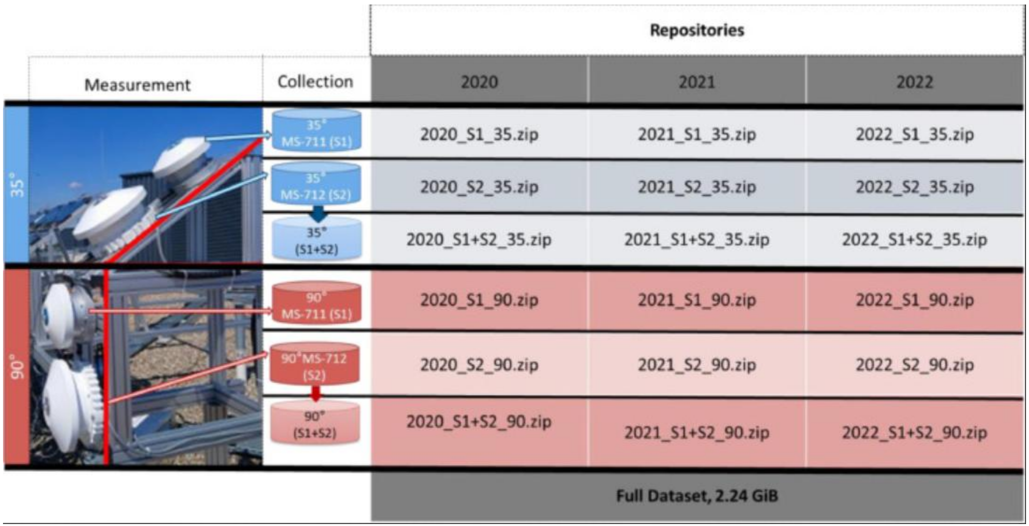

Figure 2 Data acquisition/collection and storage per spectrometer.

Year	Angle	File name	Description
2020	35	2020_S1_35.zip	Data measured by MS-711 (300–1100 nm) during 2020 at 35° divided in three files: Jan to Mar; Apr to Jul; Aug to Dec.
		2020_S2_35.zip	Data measured by MS-712 (900–1700 nm) during 2020 at 35° divided in three files: Jan to Mar; Apr to Jul; and Aug to Dec.
		2020_S1+S2_35.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2020 at 35° divided in three files: Jan to Mar; Apr to Jul; and Aug to Dec.
2020	90	2020_S1_90.zip	Data measured by MS-711 (300–1100 nm) during 2020 at 90° divided in three files: Jan to Mar; Apr to Jul; and Aug to Dec.
		2020_S2_90.zip	Data measured by MS-712 (900–1700 nm) during 2020 at 90° divided in three files: Jan to Mar; Apr to Jul; and Aug to Dec.
		2020_S1+S2_90.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2020 at 90° divided in three files: Jan to Mar; Apr to Jul; and Aug to Dec.
2021	35	2021_S1_35.zip	Data measured by MS-711 (300–1100 nm) during 2021 at 35° divided in three files: Jan to Jun; and Jul to Dec.
		2021_S2_35.zip	Data measured by MS-712 (900–1700 nm) during 2021 at 35° divided in two files: Jan to Jun; and Jul to Dec.
		2021_S1+S2_35.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2021 at 35° divided in two files: Jan to Jun; Jul to Sep; and Oct to Dec.
2021	90	2021_S1_90.zip	Data measured by MS-711 (300–1100 nm) during 2021 at 90° divided in two files: Jan to Jun; and Jul to Dec.
		2021_S2_90.zip	Data measured by MS-712 (900–1700 nm) during 2021 at 90° divided in two files: Jan to Jun; and Jul to Dec.
		2021_S1+S2_90.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2021 at 90° divided in two files: Jan to Jun; and Jul to Dec.
2022	35	2022_S1_35.zip	Data measured by MS-711 (300–1100 nm) during 2022 at 35° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.
		2022_S2_35.zip	Data measured by MS-712 (900–1700 nm) during 2022 at 35° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.
		2022_S1+S2_35.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2022 at 35° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.
2022	90	2022_S1_90.zip	Data measured by MS-711 (300–1100 nm) during 2022 at 90° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.
		2022_S2_90.zip	Data measured by MS-712 (900–1700 nm) during 2022 at 90° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.
		2022_S1+S2_90.zip	Merged data measured by MS-711 and 712 (300–1700 nm) during 2022 at 90° divided in three files: Jan to Apr; May to Oct; and Sep to Dec.

Figure 3 Description of raw data provided

The spectrometers were provided by EKO-instruments [15]. The first spectrometer is the model MS-711, which measures spectral irradiance within a range of 300–1100 nm. The second spectrometer is the model MS-712 with a measurement range of 900–1700 nm. The spectrometers have a wavelength accuracy of ±0.2 nm. Both spectrometers have an optical (wavelength) resolution (FWHM) better than 7 nm and both spectrometers possess a field of view of 180°. The MS-711 has a temperature dependency below ±2% within an operating temperature of −10 to 50 °C, whereas the MS-712 has a temperature dependency of ±5% within a working temperature of −10 °C and 40 °C. The temperature is controlled at 25 °C (±2 °C) within an ambient temperature range from −10 °C to about 40 °C and between 25 °C and 32 °C above an ambient temperature of 40 °C and below 50 °C. Each measurement is controlled automatically, with an exposure time from 10 to 5000 milliseconds and a field of view of 180°. The dome material of the MS-711 is synthetic quartz, whereas BK7 glass is used for the dome of the MS-712 sensor.

Calibration certificates issued by the manufacturer indicate combined uncertainties (including cosine and temperature dependency) for MS-711 of 17.4% (300–350 nm), 5.1% (350–450 nm), 4.2% (450–1050 nm) and 5.3% (1050–1100 nm). For the MS-712, uncertainties of 4.5% (900–950 nm), 4.84% (950–1600 nm) and 23.67% (1600–1700 nm) were indicated.

For the acquisition of this data the integration time was set to 5 min intervals. The data was merged automatically by software provided by EKO-instruments (i.e. WSDac, WSDisp). No preconditioning of any kind was employed. This means that the data was collected completely under outdoor conditions and is presented as measured. The periods in which the light is below the sensitivity range of the spectrometers is also not included.

In total, three years of solar spectra for the optimum installation angle of 35° and the building-integrated-photovoltaics relevant vertical angle of 90° was made available. After integration of each solar spectrum, the data can be used as an input for calculations regarding yearly PV energy yield [16].

2.2. Spectral data from Fraunhofer

The spectral irradiance at Fraunhofer is collected at their measurement site in Freiburg, Southern Germany (48.009N, 7.832E) from 2020 to today (with certain gaps due to maintenance and malfunctions) in 1 minute resolution without a quality assurance check. Thus, in its current state, the Fraunhofer data cannot be publicly shared and is treated as ‘internal as measured’ data. For spectral DNI the wavelength range goes from 305-2000 nm for the Tec5 and for spectral GHI from 350-1750 nm for the EKO MS710 & MS712. Spectral DNI was measured using a high precision (+/- 0.1 deg.) dual-axis solar tracker, whereas for spectral GHI the spectroradiometer is simply placed horizontally and facing upward. As was mentioned previously, depending on interest from project partners for access to this data, this can be resolved by performing the requisite quality assurance check and necessary processing of data in the form of a bilateral project.

2.3. Spectral data from the NSRDB

To have more sources, existing publicly available spectral data was also sought. Apart from the two sites in Berlin and Freiburg, spectral on demand data from the National Solar Resource Database (NSRDB) made publicly accessible by NREL was also collected for two sites in Southern France and Southern Spain to have a spread of European locations. The spectral on-demand data service provides solar irradiances on inclined PV panels for 2002 narrow-wavelength bands from 0.28 to 4.0 µm. Based on users' selection of location, period of time, and PV system (fixed or one-axis PV system), a dedicated high-performance server located at NREL computes the spectral data in real time using the Fast All-sky Radiation Model for Solar applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT) [17] and broadband and ancillary data served by the NSRDB. Shows the interface of the NSRDB webpage for reference.

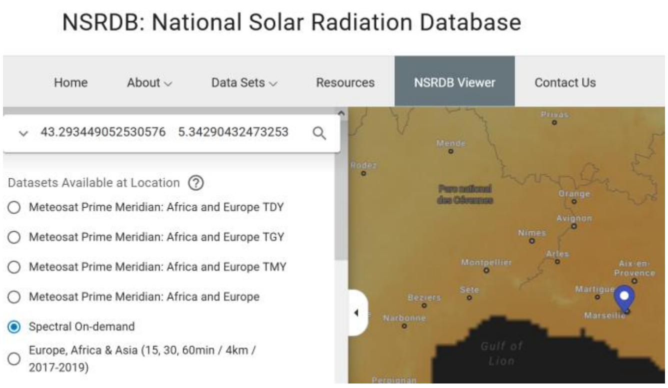

Figure 4 Screenshot of NSRDB webpage with the available datasets at global locations [13]

FARMS-NIT is an innovative radiative transfer model developed at NREL to efficiently and simultaneously calculate the spatial distribution of solar energy (radiances) in narrow-wavelength bands which are integrated over inclined PV panels to infer the plane-of-array (POA) irradiances. For clear-sky conditions, the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) is employed to rapidly provide the optical properties of a given clear-sky atmosphere. The clear-sky radiances in the narrow-wavelength bands are computed by considering three paths of photon transmission and solving the radiative transfer equation with the single-scattering approximation. For cloudy-sky conditions, FARMS-NIT uses cloud reflectance of irradiance and bidirectional transmittance distribution function (BTDF) from a precomputed lookup table by the LibRadtran model with a 32-stream Discrete Ordinates Radiative Transfer (DISORT).

The data for Southern France (38.25N, -1.1E) and Southern Spain (38.25N, -1.1E) was downloaded for the year 2019 for both single axis tracking and fixed tilt (33 and 31 degrees for France and Spain respectively) systems with a time interval of 60 minutes which was the only available time interval and the latest available year of data.

2.4. Data Consolidation

The spectral data from HZB is stored on the HZB data repository [18] and can be freely downloaded from their webpage without any access details. As described in Figure 3, raw data is provided for the years 2020, 2021 and 2022 for both fixed tilt and vertical installations through two spectrometers. The data for each spectrometer and their merge are provided in compressed ZIP archives containing the CSV files related to a complete year of data for 2020, 2021 and 2022, respectively with the complete dataset being over 2 GB in size. The subsequent goal would be to upload part of this data (for example for one year) on to the VAPO platform. Similarly, the data for Southern France and Southern Spain accessed from the NSRDB will also be uploaded onto the VAPO platform. Currently, the data is available as excel files in CSV format with Fraunhofer and will be shared with the consortium.

3. SUMMARY AND NEXT STEPS

The deliverable report D 10.3 within the VIPERLAB project addresses the task related to the development of a database with solar resource data for different European locations required for performing an energy yield assessment based on the different available energy yield models of the participating institutions. The data collection was performed through the consortium members and existing literature plus publicly available resources. The main data source was from the HZB, which provided spectral data from their measurement site in Berlin (Northern Germany) and Fraunhofer ISE which has spectral data at their testing installation in Freiburg (Southern Germany). Apart from these two sites, spectral data from the National Solar Resource Database made publicly accessible by NREL was also collected for two sites in Southern France and Southern Spain to have a diverse spread of European locations.

The details on the type of spectral data, its resolution, equipment's used for the measurement and time interval and length of measurement are provided within this report. Since the size of the datasets are quite large (over 2 GB in some cases) and the raw data is in the form of excel files (CSV format), the subsequent goal is to transfer the collected and available spectral data onto the VAPO platform to facilitate ease of access to the same and reducing the scarcity of such data for the broader research community interested in energy yield modelling for photovoltaics.

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