Assessing the variations in long-term photovoltaic yield prediction due to solar irradiance and module temperature

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Abstract

To mitigate the financial investment risks for PV systems stakeholders, it is a prerequisite to reliably predict the long-term energy yield (LTYP). However, this is not usually the case due to several different influencing effects such as: solar resource, system design, the quality of the components as well as degradation. All these effects increase the uncertainties in LTYP. To improve the prediction accuracy, each of these effects should be separately explored. The main aim of this study is to assess the effects solar irradiance used a representative for LTYP. In the manuscript we show that using multi-years repetition approach that include year-to-year climate variability and solar irradiance brightening/dimming effects reduced the variations to ±2.1%. The effect of temperature correction in LTYP model led to variations between ±4.5% in comparison with a non-temperature corrected model but where highly dependent on a given location. Overall, it is shown that for more reliable predictions using the proposed approach, at least 5 years of historical data is needed.

Keywords: Energy yield, solar-irradiance, prediction, PV systems, variations

1. Introduction

A Long-Term Yield Prediction (LTYP) is the estimation of the accumulated total energy production of a defined photovoltaic (PV) system in a given location for a specified period (Reise et al. 2018). For the financial evaluation and planning of PV projects the reliable LTYP is a prerequisite. In principle, different factors affect the accuracy of LTYP by increasing the uncertainty of predicted yield as highlighted in the IEA-PVPS-T13 report (Reise et al. 2018). It is crucial to assess each uncertainty source separately. For example, in (Kaaya and Weiss 2020) the uncertainty due to degradation rate were assessed and shown that using a non-linear yield model with a time dependent degradation rate lowers the LTYP uncertainty. In this study, we add a contribution by assessing the uncertainty due to representative solar irradiance used in LTYP. The typical meteorological year (TMY) data (Cebecaue and Suri 2015) extracted from many years of timeseries data is commonly used as representative input irradiance for LTYP. However, some studies (Ki 2020; Nelken and Żmudzka 2017; Kulesza 2017), have shown that the TMY can lead to under/over-estimation of more than 9% in comparison to Multi-Years timeseries data. The variations are dependent on the location and on the methods for evaluating the TMY. Moreover, the TMY eliminates the year-to-year climate variability. In this study we propose an approach to create representative solar irradiance for LTYP by using irradiance recurrence approach, where historical data is repeated and concatenated into a Multi-Years timeseries that include year-to-year climate variability. Throughout the study, the approach is referred to as "**Multi-Years Repetition (MYR)**". The motivation of the study is partly fostered by the developing interest to use historical data to predict the remaining useful lifetime and hence the yield of PV systems (Kaaya et al. 2020). Prediction of the energy yield of a PV system is highly influenced by solar irradiance. Although several methods are proposed for irradiance forecast, they are mainly based on short term predictions of several hours, days, weeks, or months ahead. When lifetime energy yield predictions are required, simplifications methods such as the TMY are commonly applied for solar irradiance. However, these methods also require the availability of several timeseries data of almost 10 years which are usually not available specially for ground measurements. Therefore, in this paper we assess if using the proposed MYR approach can provide a solution to lifetime yield prediction using limited timeseries solar irradiance data available. The main objective is to check the consistence of the approach and to evaluate the number of repetitions required to provide more accurate representation of long-term irradiance. This is done by assessing different scenarios and benchmarking them with 30 years irradiance data. Moreover, to check the validity of the proposed approach, six different locations with different climate classifications are used. Given that module temperature is another common factor that affects the yield predictions, in the study, the impact of temperature correction on LTYP model is also assessed.

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2. Methodology

2.1 Mathematical model

In (Kaaya and Ascencio-Vásquez 2021) the different models for photovoltaic power prediction are discussed. The simplest and straight forward to apply are the heuristic models that depend mainly on solar irradiance (G) and in some cases on module temperature. In the same study a non-linear degradation term (second term in eq.1 and eq.2) was integrated to model the lifetime performance. The equations are re-written as:

$$P = \left[x \cdot G + y \cdot G^2 + z \cdot G \cdot ln^2\left(\frac{G}{G_{STC}}\right)\right] \cdot \left[1 - exp\left(-\left(\frac{1}{k \cdot t}\right)^{\mu}\right)\right] \qquad \text{(eq. 1)}$$

$$P_{T\_corr} = \left[\left(x \cdot G + y \cdot G^2 + z \cdot G \cdot ln^2\left(\frac{G}{G_{STC}}\right)\right) \cdot (1 - \gamma.(T_{mod} - 25))\right] \cdot \left[1 - exp\left(-\left(\frac{1}{k \cdot t}\right)^{\mu}\right)\right] \qquad \text{(eq. 2)}$$

where P and P_{T_corr} are the power without and with temperature correction term respectively, G is the irradiance, T_{mod} is the module temperature a, b, c, and μ are the model fitting parameters. γ is the temperature coefficient of power in (%/°C) and G_{STC} = 1000 w/m^2. k is the degradation rate.

In this exercise a 6050 W PV system is simulated with a 1.3 %/year degradation rate based on a Cadmium telluride (CdTe) PV system in our previous study (Kaaya et al. 2020). The model parameters x = 6.37, y = -0.00040, z = 0.0015 and μ = 0.35 are also based on fitting the above proposed equations to historical data of the same system. To calculate the module temperature, the King model (King et al. 2004) was used as:

$$T_{mod} = T_{amb} + G \cdot \exp\,(a + b.WS) \qquad \text{(eq. 3)}$$

Where T_{amb} is the ambient temperature, WS is the wind speed, a and b are model coefficients.

2.2 Data used

In this study, 30 years (1990-2020) historical weather data (global horizontal irradiance, ambient temperature and wind speed) are extracted from ERA 5 reanalysis (C3S 2017) in six location as shown in Fig.1. The Typical Meteorological Year (*TMY*) of the correspond locations was also extract from PVGIS (JRC 2021). **Tab. 1** shows the different scenarios analyzed in this study, MYR #1, MYR #2, MYR #3 are the MYR scenarios where the historical data is repeated 10, 6 and 2 times respectively and concatenated to get representative of 30 years irradiance data.

Fig. 1: Map showing the locations of the data used in the study. From Nigeria (9.74°, 9.25°), Thailand (14.07°, 100.62°), Turkmenistan (39.78°, 60.21), Slovenia (46.05°, 14.50°), Germany (52.44°, 13.38°) and Russia (55.68°, 37.71°)

Tab. 1: Irradiance scenarios used for long-term yield prediction. MYR #1, MYR #2, MYR #3 represents the different Multi-Years Repetition scenarios (years repeated to make a 30 timeseries)

Scenario	Corresponding years used	Total number of years
MYT	1990 – 2020	30
TMY	2004 – 2014	10
MYR #1	1990-1993	3
MYR #2	1990-1995	5
MYR #3	1990-2005	15

3. Results

The long-term representative solar irradiance is constructed from the three MYR scenarios for all the six locations. Fig.2. for example, shows the long-term constructed timeseries using MYR #1 where 3 years historical data have been repeated 10 times and concatenated for a location in Slovenia. It should be noted that during the concatenation, a shift in time can be observed and therefore should be removed using the appropriate data processing techniques.

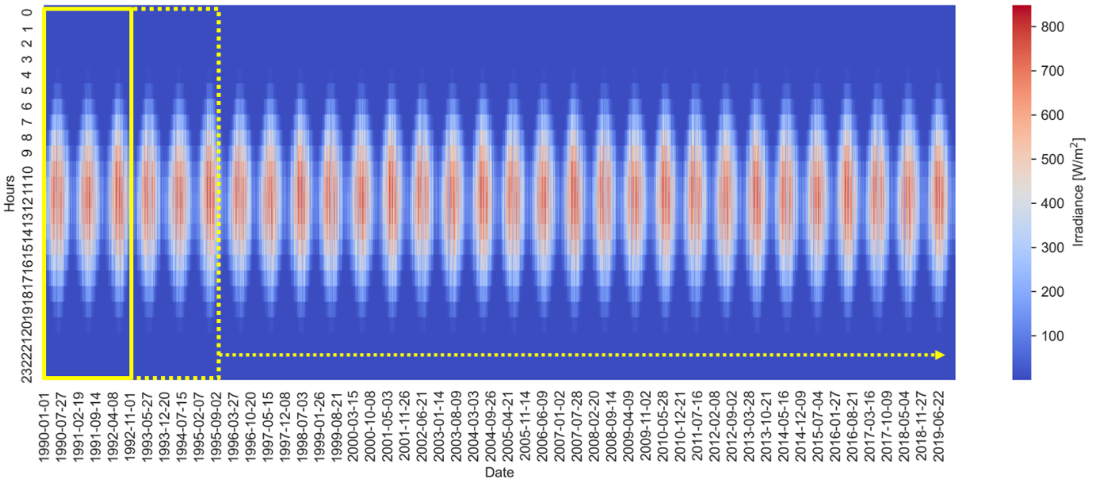

Fig. 2: Solar irradiance using MYR #1, where 3 years data are repeated and concatenated to create a 30 years MYT for a location from Slovenia (46.05°, 14.50°). Bold yellow box shows the original data and dashed yellow box show the repetition.

The MYT, the constructed 30 years irradiance using the three MYR scenarios and the TMY are applied in eq.1 to simulate the 30 years power and hence the energy yield. In Fig.3 (A) the simulated annual yield of the different scenarios is presented for a location in Thailand. It is clearly visible that the year-to-year variabilities in yield are eliminated when using the TMY in comparison with other scenarios. The aim was to assess whether these yearly variabilities if considered counterbalance and hence lower the lifetime yield variations. In Fig.3 (B), the corresponding lifetime yield as well as the relative difference in relation to 30 years MYT are presented. In this example it is shown that using MYR approach can improve the LTYP by reducing the relative difference values in comparison to the TMY.

Fig.4 shows the distribution maps of the relative difference values for scenarios MYR #1, MYR #2, MYR #3 and the TMY plotted with increasing years. The values of MYR #1, MYR #2 and TMY become more positive towards increasing years. This was attributed to the solar dimming effect visible in the 30 years MYT (see Fig.5). The lifetime yield evaluated using MYR #3 shows less variations in comparison to MYT since the dimming effect is reduced by this scenario. It was also observed in some location that the relative difference values become more negative towards increasing years which was attributed to solar brightening effect in these locations. Generally, the effect of solar dimming and brightening was more visible with MYR #1 and MYR #2 because in these scenarios few years of historical data are repeated several times and hence these effects are not captured.

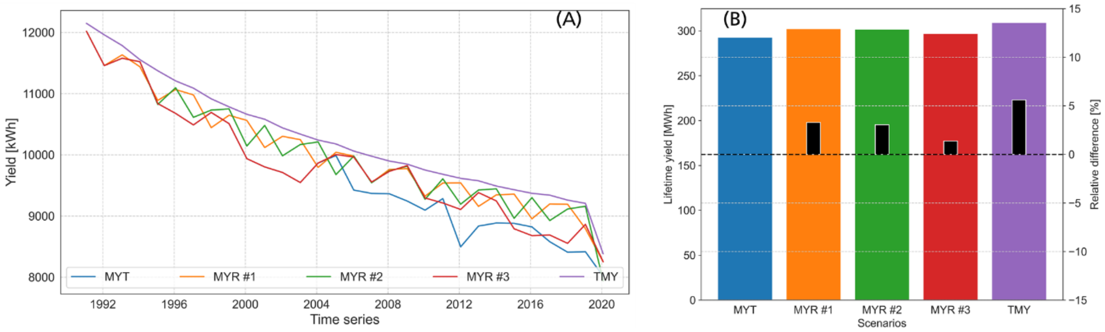

Fig. 3: (A) Yearly yield for different scenarios. (B) lifetime yield (30 years) in MWh for the different scenarios and relative difference (in black). The relative difference is evaluated in relation to the 30 years irradiance data (MYT: 1990-2020)

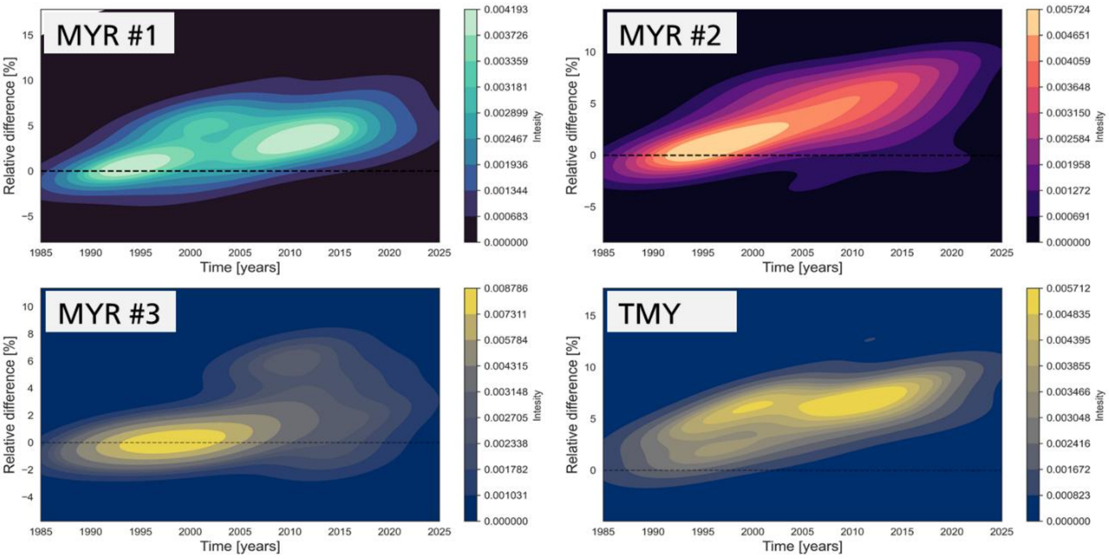

Fig. 4: Distribution maps of relative difference with increasing years for MYR #1, MYR #2, MYR #3 and TMY.

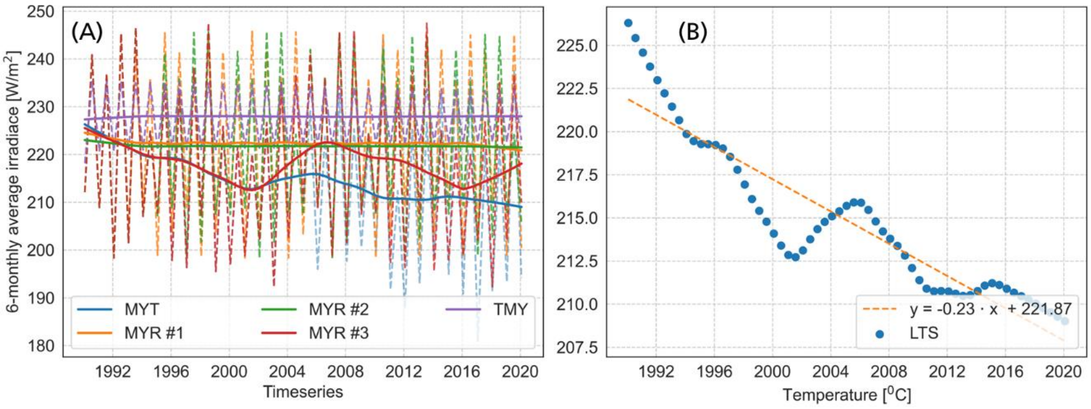

Fig. 5: (A) Extracted trends in long-term irradiance data using the different scenarios. (B) Extracted trend and linear fit in MYT irradiance data showing the solar dimming effect.

Therefore, in locations where solar brightening or dimming is anticipated, a correction to include these effects must be added especially when MYR #1 and MYR #2 scenarios are applied. For example, in this exercise, a linear correction of the irradiance was included as: $(G_{corr} = \delta \cdot t + G)$, where δ is a coefficient that describe the slope due to solar brightening/dimming trend and t is the time in hourly resolution. The coefficient δ is location dependent since brightening/dimming trends varies from location to location. This correction was applied to the proposed MYR approach for all locations. Fig.5(A) and (B) show the relative difference of the simulated lifetime yield using the different scenarios in all the six locations without (A) and with (B) solar irradiance brightening/dimming correction respectively. The relative difference is calculated in relation to MYT. It is visible that when the correction is considered, the error margin of the 50th percentile reduces (i.e from ±3% to ±2.1%). Generally, it can also be deduced that the MYR #3 scenario shows consistently more accurate results in all the six locations according to the relative difference values with and without irradiance correction. However, since for a 30-years lifetime evaluation, scenario MYR #3 means waiting half the PV system lifetime, using MYR #1 and MYR #2 with irradiance correction could be a good option for cases where limited historical data is available. Indeed, it can be concluded from the studied locations that to have good predictions at least 5 years of historical data is needed.

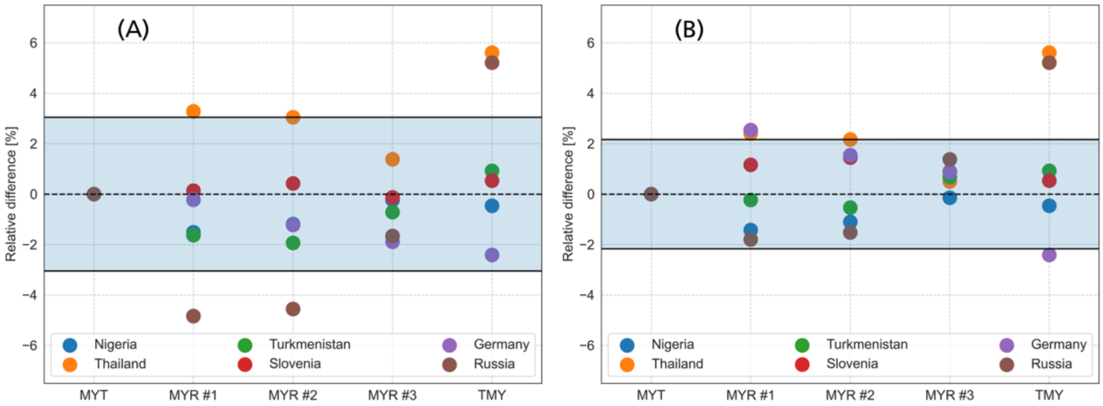

Fig. 6: (A) Relative difference of lifetime yield prediction without solar irradiance correction. (B) Relative difference of lifetime yield prediction with solar irradiance correction. The blue patch shows the 50th percentile of the relative difference values of Thailand (location with highest relative difference)

To assess the effect of temperature correction in LTYP, we applied the models without (eq.1) and with (eq.2) temperature correction term in all the six locations using MYT data. The module temperature was estimated from ambient conditions using the King's model (eq.3). Usually, depending on a given location different model coefficients (a/b) are required to provide good estimations. Therefore, for each location, different values of coefficient were simulated. Using the 50th percentile of the location with maximum errors, the variations in LTYP due to temperature correction are within ±4.5 % margin. In some locations and with good temperature model coefficients, the effect of temperature correction is negligible as shown in Fig.7.

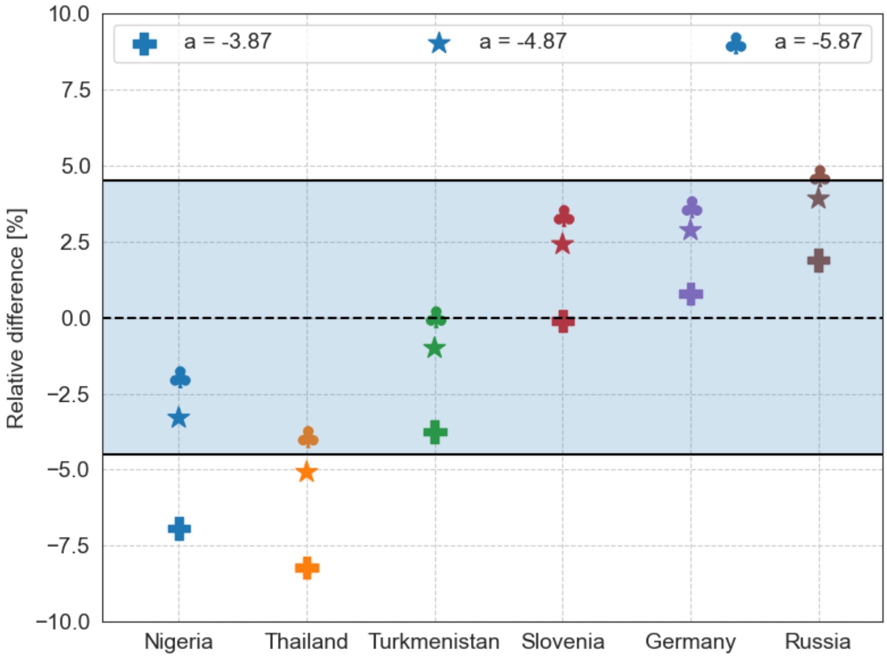

Fig. 7: Relative difference of lifetime yield prediction with and without temperature correction term. The blue patch shows the 50th percentile of the relative difference values of Thailand (location with highest relative difference)

4. Conclusion

We used different solar irradiance scenarios and data from six different locations to analyze their impact on long-term yield prediction. It is found that using historical data repetition method so-called "**Multi-Years Repetition (MYR)**" with year-to-year climate variability could provide better predictions as compared to the TMY which excludes these variabilities. However, to apply this method on few years of timeseries historical data one need to consider the effects of solar brightening or dimming by applying a correction to the generated long-term timeseries. It has been shown that, when the brightening and dimming effects are considered the variations of lifetime yield predictions are reduced from ±3.0 % to ±2.1 %. Generally, it has been shown that for the proposed MYR approach, at least 5 years of historical data is needed to have more reliable predictions. Also, in the study, it has been shown that the inclusion of temperature dependency in long-term yield predictions is highly dependent on a given location, in some locations it's significant and in other locations is negligible. Overall, the variations in lifetime yield prediction due to temperature correction is evaluated between ±4.5%. We believe these findings will help to improve the reliability of long-term yield prediction especially when limited historical data is available. The irradiance MYR approach can be a useful tool in remaining useful energy yield prediction using ground and system-based irradiance measurements for PV operators.

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6. References

C3S. 2017. "Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate . Copernicus Climate Change Service Climate Data Store (CDS), [Internet] Available from: Https://Cds.Climate.Copernicus.Eu/Cdsapp#!/Home, Accessed: 16-November - 2020]."

JRC. 2021. "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." 2021. https://re.jrc.ec.europa.eu/pvg_tools/en/#TMY.

Cebecauer, T, and M Suri. 2015. Typical Meteorological Year Data: SolarGIS Approach. *Energy Procedia* 69 (May): 1958–69. https://doi.org/10.1016/j.egypro.2015.03.195.

Kaaya, Ismail, and Julián Ascencio-Vásquez. 2021. Photovoltaic Power Forecasting Methods. IntechOpen. https://doi.org/10.5772/intechopen.97049.

Kaaya, Ismail, Sascha Lindig, Karl-Anders Weiss, Alessandro Virtuani, Mariano Sidrach de Cardona Ortin, and David Moser. 2020. Photovoltaic Lifetime Forecast Model Based on Degradation Patterns. *Progress in Photovoltaics: Research and Applications* 28 (10): 979–92. https://doi.org/10.1002/pip.3280.

Kaaya, Ismail, and Karl Anders Weiss. 2020. Assessing the Effects of Photovoltaic Modules Long-Term Performance Degradation on Lifetime Energy Yield Predictions. 37th EU PVSEC Proceedings, ISBN: 3-936338-73-6 .

Ki, Laetitia Uwineza, Kim Hyun-Goo, Kim Jin-Young , Kim Boyoung , Kim Chang. 2020. Multi-Year and Typical Year Data for Solar Energy System in South Korea, December, 135–49. https://doi.org/10.7836/kses.2020.40.6.135.

King, D. L., W. E. Boyson, J. A. Kratochvil, David L. King, William E. Boyson, and Jay A. Kratochvil. 2004. Photovoltaic Array Performance Model. https://core.ac.uk/display/100301445.

Kulesza, Kinga. 2017. Comparison of Typical Meteorological Year and Multi-Year Time Series of Solar Conditions for Belsk, Central Poland. *Renewable Energy* 113 (C): 1135–40.

Nelken, Kinga, and Elwira Żmudzka. 2017. "TMY versus Multi-Year Time Series of Meteorological Conditions for the Characterization of Central Poland's Suitability for Photovoltaics. *Meteorologische Zeitschrift*, February, 21–31. https://doi.org/10.1127/metz/2016/0755.

Reise, Christian, Björn Müller, David Moser, Giorgio Belluardo, and Philip Ingenhoven. 2018. *Task 13:* Uncertainties in PV System Yield Predictions and Assessments.