European Journal of Applied Sciences – Vol. 10, No. 2
Publication Date: April 25, 2022
DOI:10.14738/aivp.102.12098.
Reda, I., Andreas, A., & Gotseff, P. (2022). A Procedure to Correct the Historical Atmospheric Longwave Irradiance Data When the World Reference Is Established with Respect to the International System of Units. European Journal of Applied Sciences, 10(2). 274-281.

A Procedure to Correct the Historical Atmospheric Longwave Irradiance Data When the World Reference Is Established with Respect to the International System of Units

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ABSTRACT

Historical atmospheric longwave irradiance data sets with traceability to the International System of Units (SI) are essential for renewable energy and atmospheric science research and applications. To date, all pyrgeometers used to measure the irradiance are traceable to the interim World Infrared Standard Group (WISG), not to SI units. In 2013, the Absolute Cavity Pyrgeometer (ACP) (Reda et al. 2012) was developed at the National Renewable Energy Laboratory (NREL) to measure the atmospheric longwave irradiance. The ACP has been compared against the InfraRed Integrating Sphere (IRIS), developed by the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) (Gröbner 2012). The ACP and the IRIS are absolute instruments traceable to SI units through the International Temperature Scale of 1990. Results of six comparisons between the ACP and the IRIS at different locations have shown that the irradiance measured by WISG pyrgeometers underestimates clear-sky atmospheric longwave irradiance by 2 W/m^2 to 6 W/m^2 (Gröbner et al. 2014); therefore, once the world reference is established with traceability to SI units, the WISG would be corrected, then used to calibrate field pyrgeometers with traceability to SI units. The following described method is used to correct the historical atmospheric longwave irradiance data sets in anticipation of the WISG scale change.

SIGNIFICANCE STATEMENT

The purpose of using the described method in the submitted manuscript is to correct the historical atmospheric longwave irradiance data sets in anticipation of changing the world reference with traceability to the International System of Units (SI). Pyrgeometers are radiometers that measure the atmospheric longwave irradiance are deployed worldwide for renewable energy and atmospheric science research and applications. All deployed pyrgeometers have been calibrated using the present world reference that underestimates the measured atmospheric longwave irradiance; therefore, once the world reference is re-established with traceability to SI, the historical data sets would be corrected with lower uncertainty; this would undoubtedly improve the validation of satellite surface products and climate model outputs used for renewable energy and atmospheric science applications.

PROCEDURE

a. Measurement Equations

1) National Renewable Energy Laboratory Equation

From Reda et al. (2002):

$$W_{atm} = K_1 V + K_2 W_r + K_3 (W_d - W_r) \qquad (1)$$

where:

- W_{atm} is the atmospheric longwave radiation in W/m^2.
- K_2 and K_3 are the calibration coefficients of the pyrgeometer, calibrated at the PMOD.
- K_1 is the reciprocal of the pyrgeometer's responsivity, calculated from the outdoor calibration described below.
- V is the pyrgeometer thermopile output, in microvolts.
- W_r is the pyrgeometer receiver radiation = $\sigma * T_r^4$, and $T_r = T_c + K_4 * V$, where:
  - σ is Stefan-Boltzman constant = $5.6704 * 10^{-8}$ W/m^2/K^4
  - T_c is the pyrgeometer case temperature, in Kelvin.
  - S is the Seebeck coefficient = 39 V/K.
  - n is the number of thermopile junctions = 56 junctions.
  - E is the thermopile efficiency factor = 0.65.
  - K_4 is the thermopile efficiency factor equal to $1/(S * n * E) = 0.0007044$ K.uV^{-1}.
- W_d is the pyrgeometer dome radiation = $\sigma * T_d^4$, where T_d is the dome temperature in Kelvin.

Equation (1) is rewritten in the following form:

$$W_{out} = W_{atm} - W_{net} = W_{atm} - K_1 V \qquad (2)$$

where:

- W_{net} is the net irradiance measured by the pyrgeometer thermopile:

$$W_{net} = -K_1 V \quad (3)$$

- W_{out} is the outgoing irradiance from the pyrgeometer:

$$W_{out} = K_2\, W_r + K_3 (\, W_d - W_r) \qquad (4)$$

2) Physikalisch-Meteorologisches Observatorium Davos Equation

From Philipona, Fröhlich, and Ch. Betz (1995):

$$W_{atm} = \frac{V}{C}(1 + K_1 \sigma T_b^3) + K_2 W_b + K_3 (W_d - W_b) \quad (5)$$

where C is the pyrgeometer responsivity, and T_b is the case temperature.

Similar to Eq. (2) and Eq. (3):

$$W_{net} = \frac{V}{C}(1 + K_1 \sigma T_b^3) \qquad (6)$$

$$W_{out} = K_2 W_b + K_3 (W_d - W_b) \qquad (7)$$

b. Step-by-Step Procedure for Each Site

1. Download the data for at least 2 years. Data include pyrgeometer serial number and calibration coefficients traceable to the WISG, V, T_{case}, and T_{dome}.
2. Calculate W_{net} using Eq. (3) or Eq. (6).
3. Calculate the minimum and maximum values of W_{net} = Min and Max.
4. Choose a site where W_{net} is the smallest minimum value.

5. Define the new scale from 0 W/m^2 to X W/m^2, where X is the consensus value approved by the World Meteorological Organization Commission for Instruments and Methods of Observation. Note that 0 W/m^2 represents cloudy-sky conditions, and X W/m^2 represents clear-sky conditions and the lowest W_{net} at the NREL site.
6. Calculate the slope:

$$S = \frac{Max - Min}{0 - X} \quad (8)$$

7. Calculate the W_{net} correction:

$$Z = \frac{W_{net}}{S} \quad (9)$$

8. Calculate the corrected W_{net}:

$$W_{net,corr} = W_{net} - Z \quad (10)$$

9. Calculate the corrected W_{atm}:

$$W_{atm,corr} = W_{net,corr} + W_{out} \quad (11)$$

10. Calculate the uncertainty of the irradiance measured by each pyrgeometer with respect to the SI units, U_{95}:

$$U_{95} = \sqrt{U_{ref}^2 + U_{test}^2} \quad (12)$$

where:

$$U_{ref} = \sqrt{U_{ACP\&IRIS}^2 + U_{WISG}^2} \quad (13)$$

The estimated values of $U_{ACP\&IRIS}$ = ± 2 W/m^2 and U_{WISG} = ± 1 W/m^2; and U_{test} is the calibration uncertainty of the pyrgeometer under test.

RESULTS

Historical data were downloaded from NREL's Solar Radiation Research Laboratory Baseline Measurement System and three U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program sites: sgpbrsC1, spgsirsE13, and sgpserisS01. In this method, X = 5 W/m^2 is used as an example to show the following results, the consensus value of X would be used once it is approved.

Table 1 includes sites and the pyrgeometers calibration coefficients: U_{test}, slope, minimum W_{net}, and U_{95}. NREL's slope is applied to the three DOE ARM sites because NREL is one of the international sites that has the lowest value of W_{net}.

Table 1. Sites parameters and uncertainty

Site	Serial #	k1	k2	k3	k4 = kr	U_{test}	slope	Wnet	U_{95}
NREL	PIR31193F3	0.26317	1.0006	-4	7.04E-04	2.7	42.3	-206.3	3.5
NREL	CG410548	0.0737	1.0013	0	7.04E-04	2.9	33.5	-167.5	3.7
sgpbrsC1	PIR30695F3	0.24487	0.9968	-3.6	7.04E-04	3.1	42.3	-141.2	3.8
spgsirsE13	PIR38870F3	0.26379	0.9942	-4.6	7.04E-04	3.0	42.3	-147.4	3.7
sgpserisS01	PIR30689F3	0.25271	0.9963	-3.6	7.04E-04	3.1	42.3	-84.7	3.8

Figure 1 shows NREL's precision infrared radiometer (PIR) corrected W_{net}. Figure 2 shows the precipitable water content at NREL. Using descriptive statistics for the data set results in mean = 10.56 W/m², standard error = 0.09 W/m², median = 9.4 W/m², and mode = 6.7 W/m². This implies that most of the time, the precipitable water content is larger than 10 mm; therefore, the scale correction is required for all pyrgeometers deployed at NREL and the DOE ARM Southern Great Plains (SGP) sites (Gröbner et al. 2014).

Figures 3 and 4 show the correction of PIR W_{atm} and the corrected W_{net} versus W_{net} correction for all sky conditions. Figure 5 shows the CG4 corrected W_{net} versus the W_{net} correction. Figures 6 through 11 show the three SGP sites results using PIRs, the corrected W_{net}, and the corrected W_{net} versus W_{net} correction for all sky conditions.

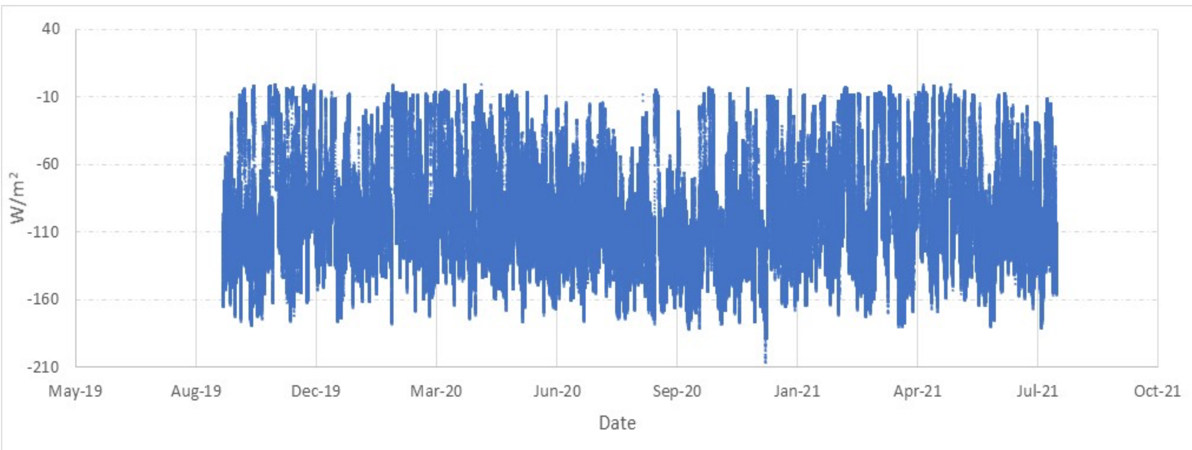

Fig. 1. Corrected W_{net} PIR at NREL from September 14, 2019, to August 8, 2021

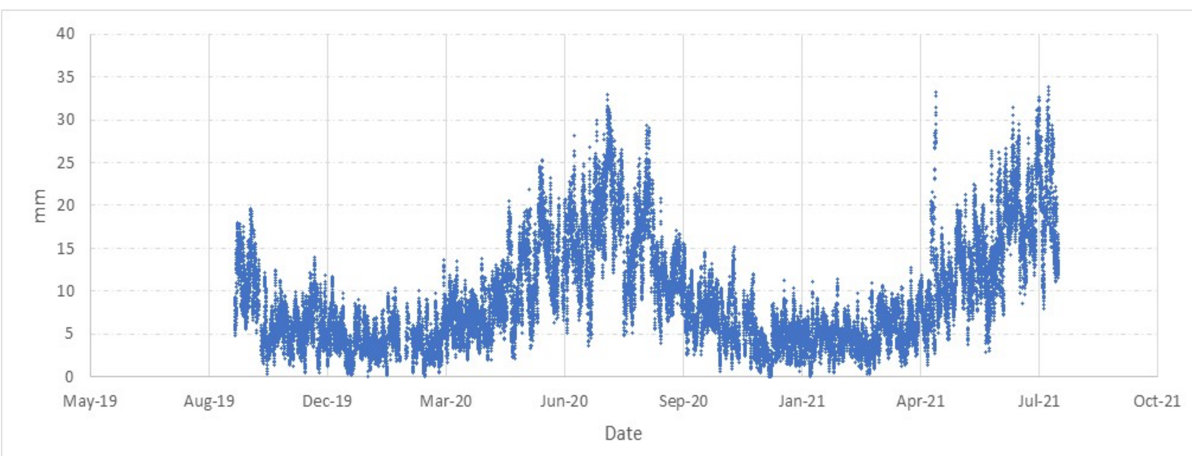

Fig. 2. Precipitable water [mm] at NREL from September 14, 2019, to August 8, 2021.

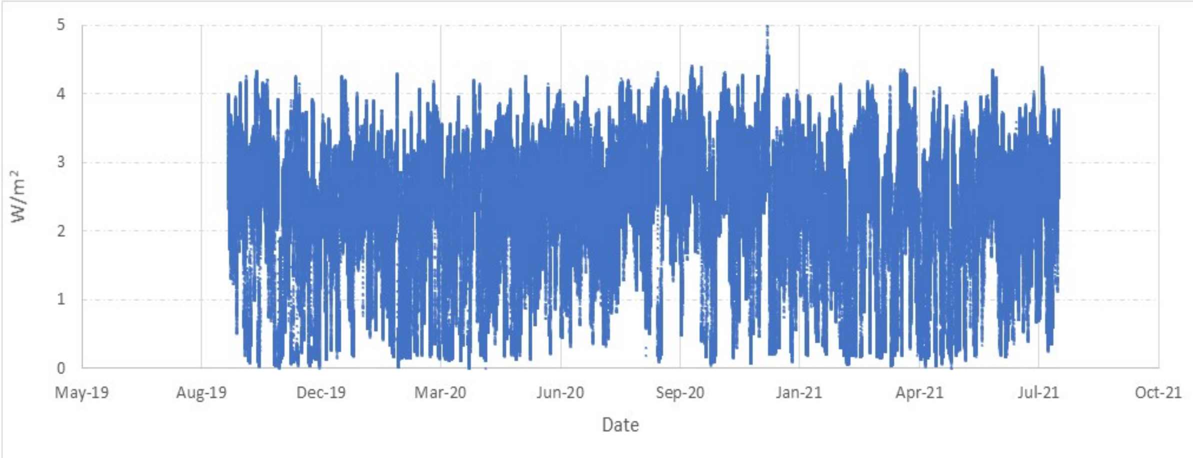

Fig. 3. Corrected W_{atm} PIR at NREL from September 14, 2019, to August 8, 2021

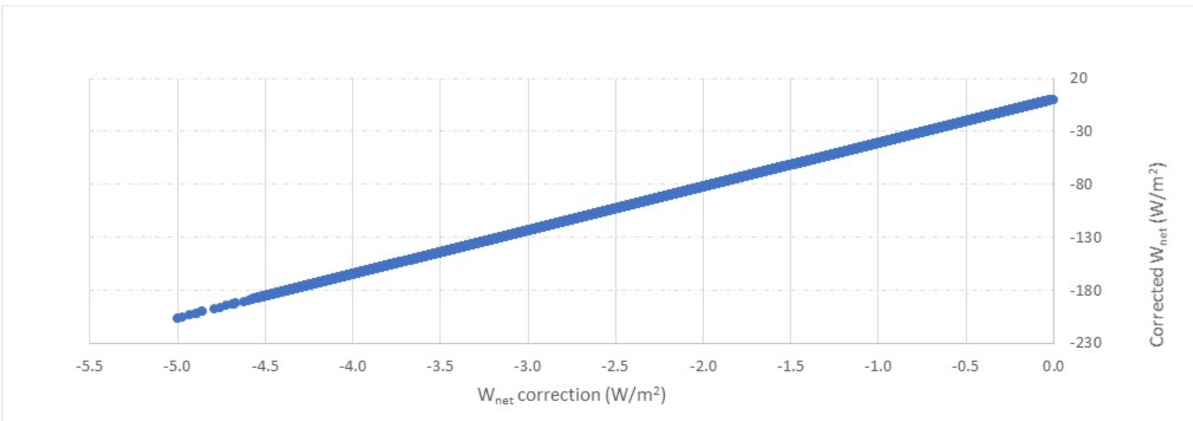

Fig. 4. PIR at NREL corrected W_{net} versus the W_{net} correction

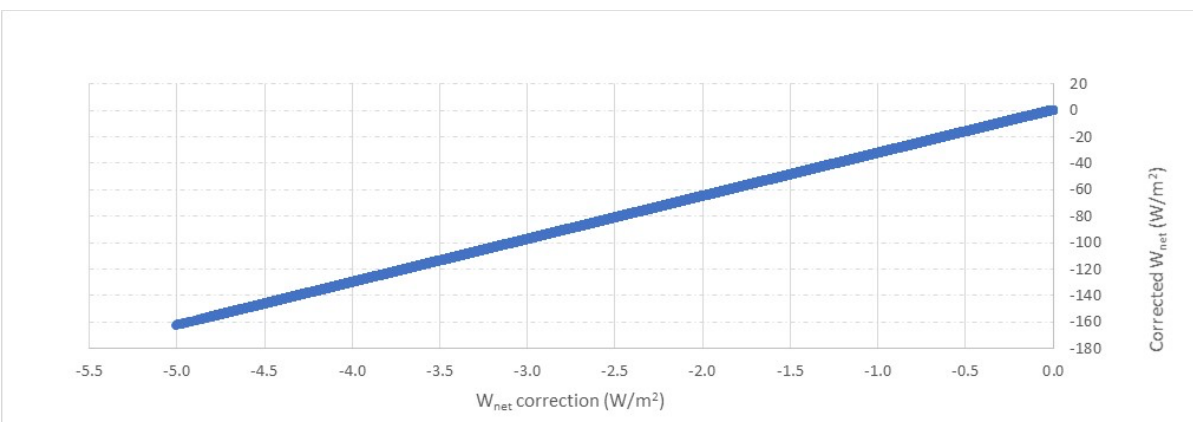

Fig. 5. CG4 at NREL corrected W_{net} versus the W_{net} correction

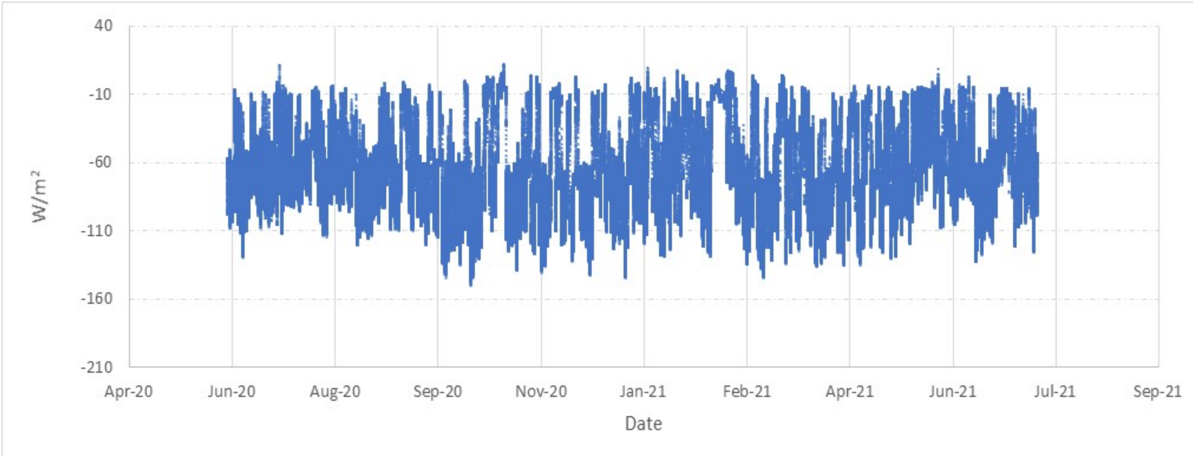

Fig. 6. Corrected W_{net} PIR at the SGP station sgpsirsS01 from June 16, 2020, to July 14, 2021

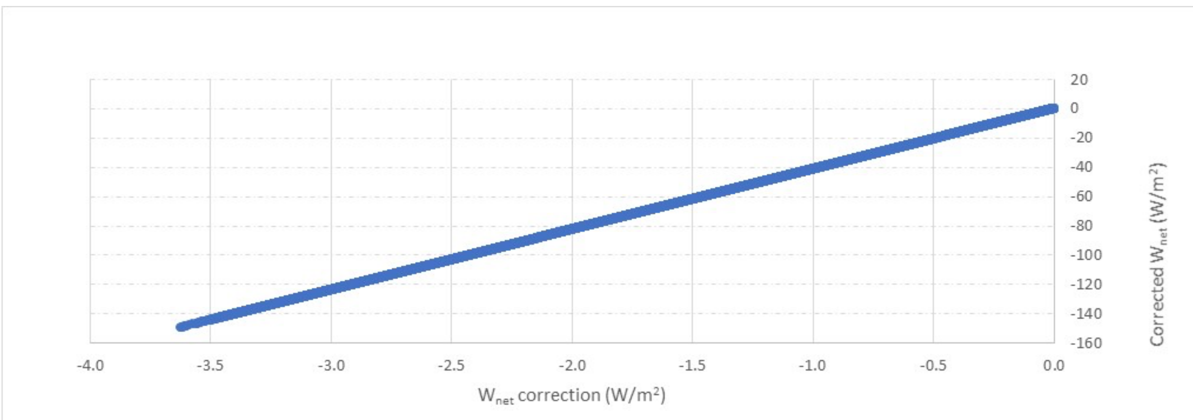

Fig. 7. Corrected Wnet versus the W_{net} correction PIR at the the SGP station sgpsirsS01

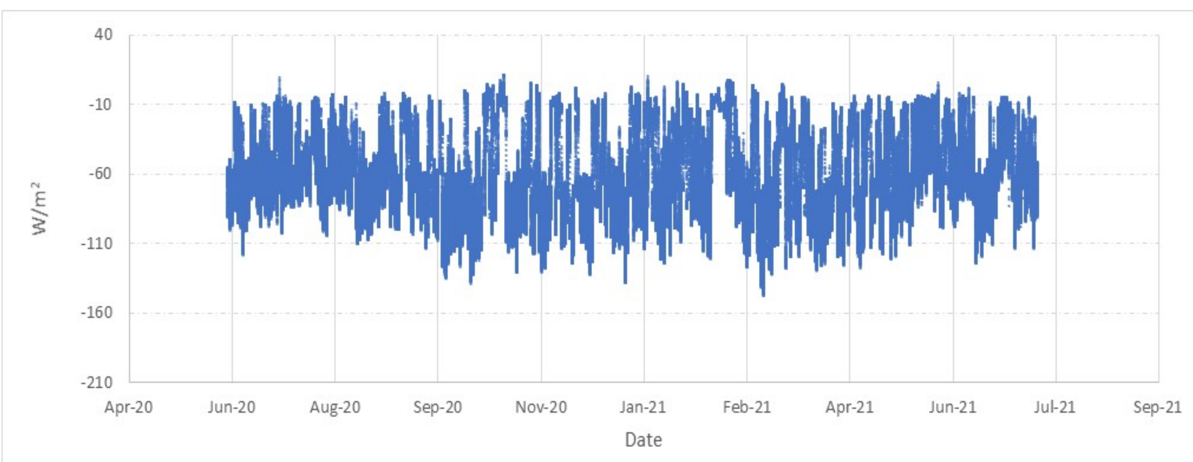

Fig. 8. Coorrected W_{net} PIR at the SGP station sgpsirsE13 from June 16, 2020, to July 14, 2021

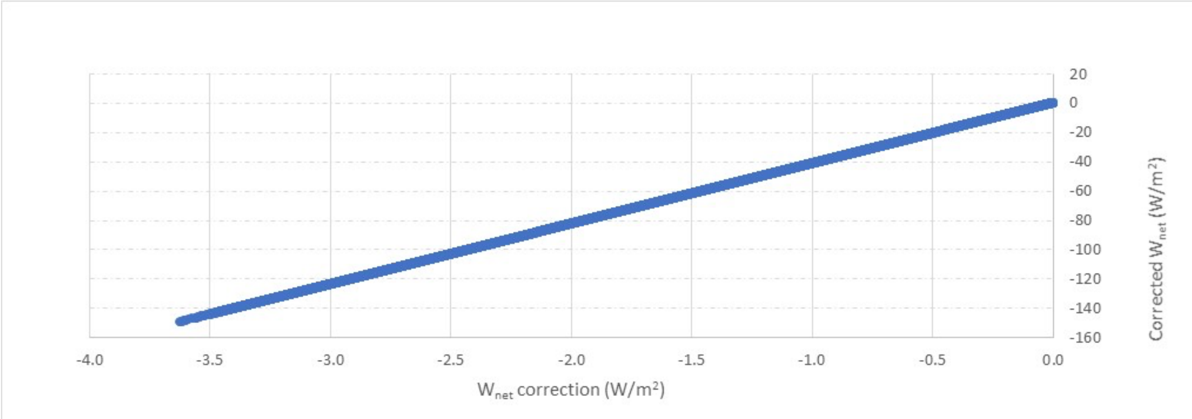

Fig. 9. Corrected W_{net} versus the W_{net} correction PIR at the SGP station sgpsirsE13

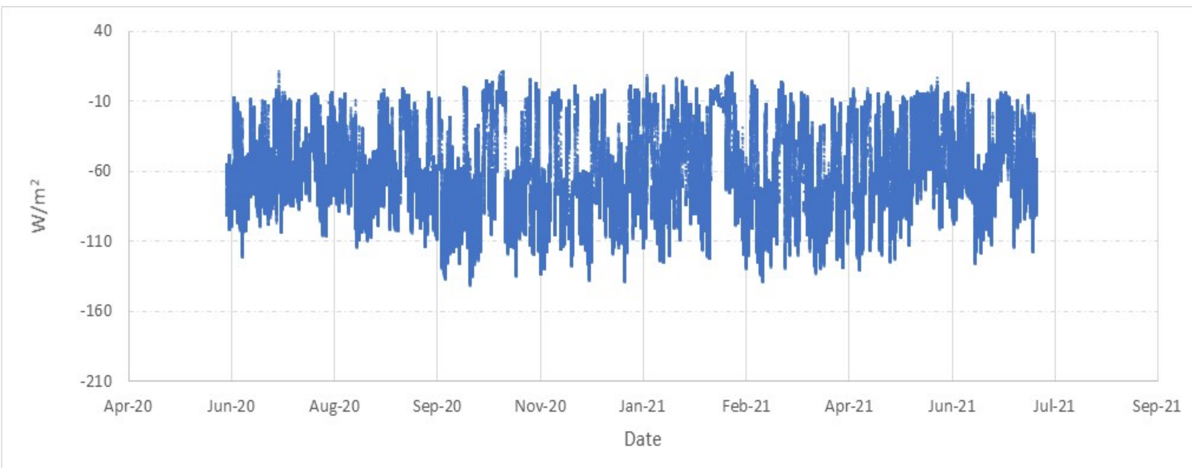

Fig. 10. Corrected W_{net} PIR at the SGP station sgpbrsC1 from June 16, 2020, to July 14, 2021

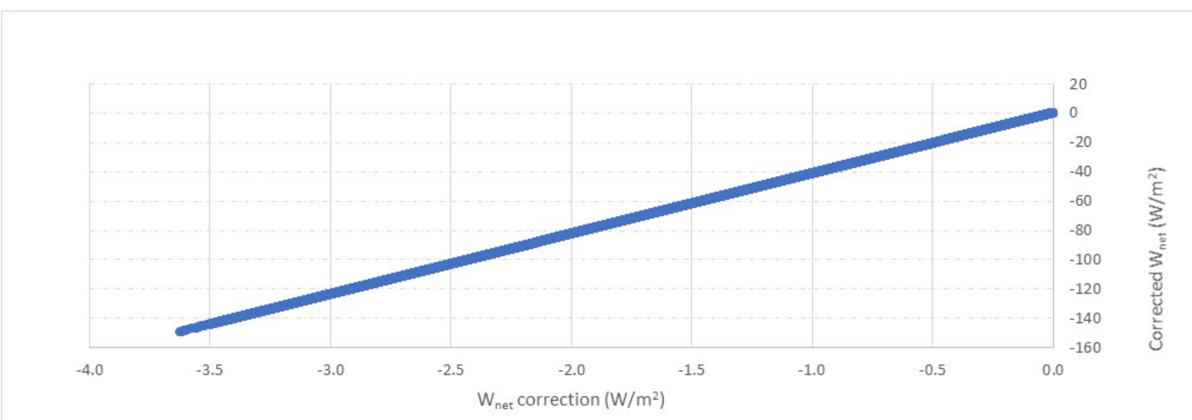

Fig. 11. Corrected W_{net} versus the W_{net} correction PIR at the SGP station sgpbrsC1

CONCLUSIONS

Based on the results, this procedure might be used to correct historical data measured by all pyrgeometers deployed in U.S. sites using the default slope, e.g., 42.3 for PIRs and 33.5 for CG4s. Once the international reference is established with traceability to the SI units, a larger data set for 5 years might be used to recalculate the default slope to account for all sky conditions at

NREL and other international sites that have minimum W_{net}. To use this method, the pyrgeometer serial number and the calibration coefficients traceable to WISG, V, T_{case}, and T_{dome} must be available to properly correct the data. For the Baseline Surface Radiation Network data set, it is recommended that in the future the data must include the pyrgeometer serial number and the calibration coefficients traceable to the WISG, V, T_{case}, and T_{dome} to correct future data if the international reference changes when other reference instruments with lower uncertainty are developed.

ACKNOWLEDGMENTS

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the Atmospheric Radiation Measurement program (Interagency Work Order 353925-A-Q1. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Additionally, we thank National Renewable Energy Laboratory (NREL) staff members Martina Stoddard and Mark Kutchenreiter, who helped to ensure the quality of the outdoor data at NREL; and Julian Gröbner, from the Physikalisch-Meteorologisches Observatorium Davos, for continuously sharing ideas about such a challenging subject.

Data Availability Statement

- Baseline Measurement System is fully accessible at: https://SRRL BMS Daily Data (nrel.gov)

- Three U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program sites sgpbrsC1, spgsirsE13, and sgpserisS01 data are accessible at: https://www.arm.gov/data/

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