## Sustainable Technologies
EVALUATION PROGRAM

# Field Comparison of a Photovoltaic Reference Sensor and a Pyranometer

Irradiance is a measure of the *power* contained within sunlight. It has units of watts per square metre (W/m$^2$). A similar parameter, irradiation, is a measure of the *energy* contained within sunlight for a given time period. Irradiation has units of kWh/m$^2$ and is determined by adding together irradiance measurements. Accurate measurements of these parameters are important in many photovoltaic (PV) applications. For example, the annual energy yield of a PV system is often estimated prior to installation and should the *actual* energy yield fall short of expectations, irradiance measurements can help to understand why. Both PV reference cells and pyranometers are commonly used instruments to measure solar irradiance, but they operate based on different principles and may be unequally affected by real-world conditions. This would include factors like irradiance spectra, incidence angle, ambient temperature, the rate of irradiance change, the rate of temperature change, or other parameters. This study compared the measurements of a PV reference cell and a pyranometer installed at the Living City Campus (LCC) PV Testing Facility in Vaughan, ON, over a one year period. Measurements were compared on an hourly, daily, monthly and annual basis. The total annual difference in the irradiation measurements of the sensors was 5%. This was largely due to a linear calibration offset, but other issues, like incidence angle, zero-offset, and snow-shedding, caused larger differences at smaller timescales.

*Sometimes light behaves as if it is composed of massless particles, called photons. Other times light behaves as if it is a self-propagating electromagnetic wave. Prior to the discovery of this "wave-particle duality," physicists had thought that particle-like and wave-like properties were mutually exclusive. The fact that light has these different properties means that there are different approaches to measuring light intensity.*
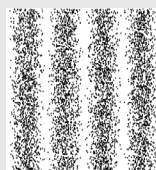
Two common devices for measuring solar light intensity, termed "irradiance," are photovoltaic reference cells and pyranometers. A reference cell is a photoelectric device. Incident photons create free electrons which then generate a measurable electric current. In contrast, a pyranometer is a thermoelectric device. Energy absorbed from the incident solar radiation induces a temperature gradient across an absorber which then creates a measurable voltage.

## EXPERIMENTAL SET-UP

STEP's PV testing field is equipped with an advanced solar radiometric weather station. It measures ambient environmental conditions, including relative humidity, air temperature, air pressure, air density and wind speed/direction, as well as other quantities relevant to solar energy generation.

A Kipp & Zonen Solsys II sun tracker is used for any measurements that require solar tracking, including direct normal irradiance, total normal irradiance, and direct normal spectral irradiance. Several Kipp & Zonen pyranometers are deployed throughout the facility, including measurements of global horizontal irradiance and plane-of-array (POA) irradiance. POA measurements are in reference to a PV array located adjacent to the weather station. It is south-facing with a tilt of 30°. There is both a CMP11 pyranometer and a PV reference cell from IMT (Si-13TC) mounted co-planar to the array (see cover image). The CMP11 is mounted in a CFV3 housing, which provides both heat and ventilation and is claimed to improve the reliability and accuracy of the measurements.

The facility-wide data acquisition infrastructure, including National Instruments hardware and LabVIEW control, logs the data from the sensors at a 1 s interval and stores it in a local SQL database. Separate tables within the database aggregate the data into 1-minute averaged values for analysis.

Using data from 2014, this short study examined the differences in the readings between the POA IMT Si-13TC and Kipp & Zonen CMP11 (hereafter referred to simply as *IMT* and *CMP11*) at minute, hourly, daily, monthly and yearly timescales. The goal of the study was to evaluate the irradiance data from each sensor and to identify contributing factors behind any variations between the readings. Understanding these differences is important because PV system performance analysis often depends on accurate irradiance data and different sensor types may be used.

### Calibration and Uncertainty

Studies have shown that pyranometers and PV reference devices typically have associated uncertainties of ±2.4% and ±5.0% respectively (Dunn, Gostein and Emery 2012). For a pyranometer, the bulk of this uncertainty is due to the device's responsivity, which is accounted for by the calibration uncertainty listed in the device's manual. Additional contributors to measurement uncertainty include spectral mismatch (for PV sensors) and angular response.

The IMT PV reference cell was factory calibrated in April 2013 and has a traceable calibration certificate. Manufacturer specifications indicate that it should agree to within 5% of a pyranometer reading within an ambient temperature range of -20 to 70 °C and normally incident irradiance. The device's nonlinearity is listed as ± 0.3 % for readings between 50 to 1300 W/m$^2$.

The CMP11 installation manual discusses the various sources of uncertainty. Ultimately, it states that, with a confidence of 95%, the pyranometer reading should indicate the absolute truth within an error of 3% for hourly radiation and 2% for daily radiation. The CMP11 pyranometer was factory calibrated, with a traceable calibration certificate, in July 2011. The manufacturer recommends recalibration every two years but the device was not recalibrated after it was installed on-site. It follows that, during this study, the CMP11 had been due for recalibration for between 0.5 and 1.5 years. In the context of this study, the device had not been recalibrated prior to the monitoring period because this is a retrospective case study, looking back at a pre-existing dataset. The year 2014 was chosen because the dataset was mostly complete and closely monitored throughout the year.

### FINDINGS

**The annual difference in the POA irradiation measured between the IMT and CMP11 irradiance sensors for the 2014 year was 5% but monthly and hourly comparisons between the sensors show much more variation.** During the monitoring period, the average daily POA irradiance as determined by the pyranometer was 3.95 kWh/m$^2$ per day and that from the reference device was 3.77 kWh/m$^2$ per day. Figure 1 shows the hour-averaged irradiance data from the IMT with respect to the CMP11. Note that the slope of the fit line is 0.95. Figure 2 shows monthly variations. The summer months show a roughly constant percentage difference and the winter months show differences that are at the extremes, both high and low.
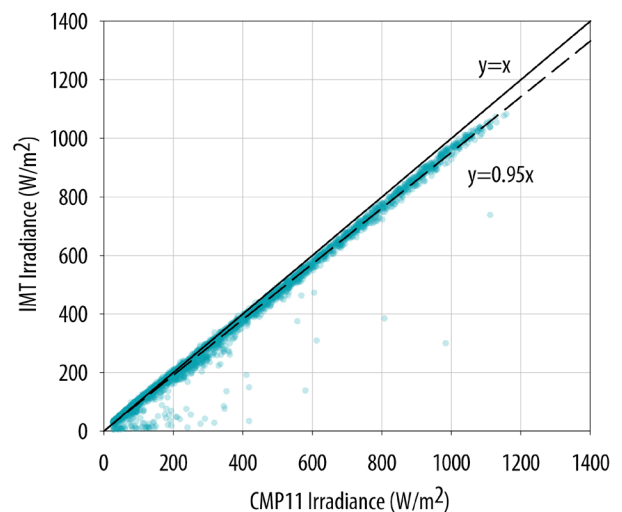


Figure 1. The average hourly IMT irradiance readings are approximately 5% lower than the readings from the CMP11 when averaged across different irradiance levels. Perfect agreement between the two sensors is illustrated by the solid line (y=x).
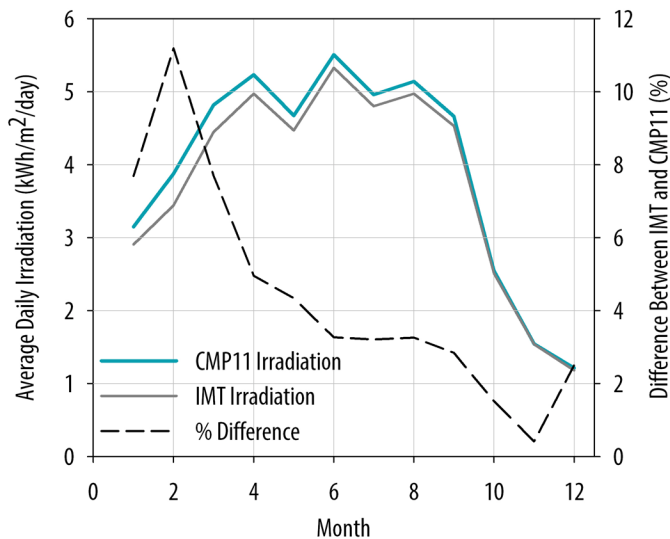
Figure 2. The average annual difference between the sensors is 5% but the monthly differences can have a much greater variation due to the factors discussed below.

**There are at least four factors causing disagreements between the sensors: a linear calibration offset, a zero-offset, incidence angle effects, and snow-shedding characteristics.** These effects are made clearer in Figure 3, which plots hourly data. When the irradiance is above 600 W/m², the percentage difference is nearly constant and the sensors could be made to agree if their linear calibration factors were simply adjusted by a small amount that is within the claimed uncertainties of the sensors. The zero-offset error is evident from the increasingly negative trend as the irradiance approaches zero. With no irradiance, the pyranometer reads slightly below zero and the IMT reads slightly above. The difference is approximately 4 W/m² in magnitude. This constant offset is negligible at high irradiances but is increasingly important towards zero. The other factors are discussed as separate findings.
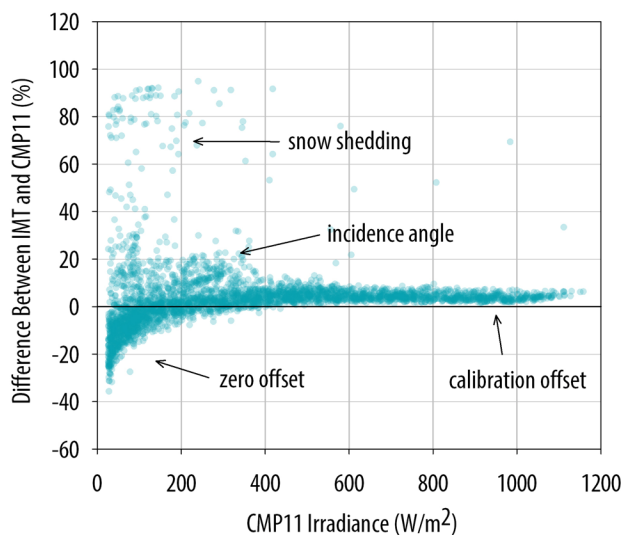


Figure 3. Different factors are made clearer when the percentage difference in the sensor readings is plotted as a function of irradiance. Snow-shedding and zero-offset errors are evident in the low-irradiance region. Incidence angle effects are evident at low-to-medium irradiance and a linear calibration offset is clear at high irradiance.

**The flat geometry of the IMT is affected by the sunlight's angle of incidence much more than the hemispherical geometry of the CMP11.** The amount of light reflected at a glass-air interface is dependent on the angle of incidence of the light, such that a greater angle of incidence causes a greater amount of reflection. Reflected light from the sensor front glass will artificially lower the readings. The hemispherical geometry of the CMP11 (see right, on the cover image) means that direct sunlight (called beam radiation) always strikes the sensor front glass at a perpendicular angle. However, the flat geometry of the IMT means that light will strike it at oblique angles depending on where the sun is in the sky, with the greatest angles occurring during dawn and dusk, when the irradiance is low. Incidence angles effects are also more important for the beam component of sunlight because it has a single direction, as opposed to the diffuse component which is radiated in all directions from the hemisphere of the sky. Figure 4 helps to illustrate how the incidence angle effects create some of the low-irradiance scatter seen in Figure 3. The percentage differences at a *minute* timescale for specific days, both clear and overcast, at different times of the year, are overlayed on the data from Figure 3. As the irradiances decreases on a clear day, the angle of incidence generally increases, and more light is reflected from the IMT front glass. This causes it to read artificially lower, creating a larger percentage difference.
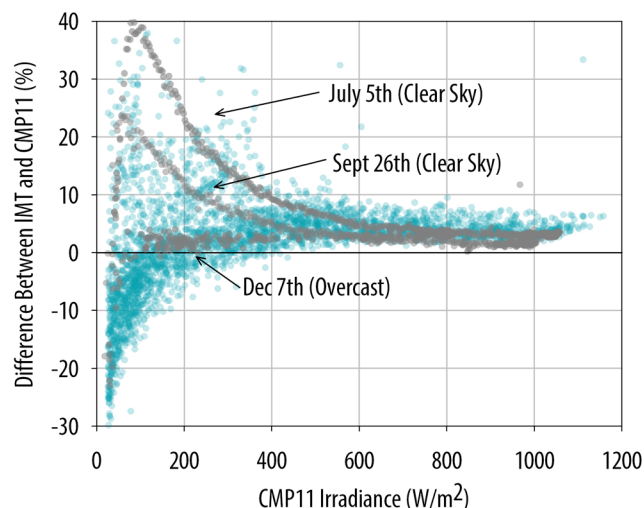


Figure 4. When *minute* data from days with clear and diffuse skies is overlayed on the *hourly* data from Figure 2, the incident angle effects at low irradiance levels is clear.

**Incident angles effects are estimated to affect daily irradiation totals by as much as 1.6% for the latitude (44°) and orientation of this PV installation.** Two days with a clear sky were selected: one near the summer solstice (July 5th) and one near the autumn equinox (Sept 26th). The IMT data was adjusted using a linear calibration factor such that it agreed with the CMP11 near normal incidence. Figure 5 plots the irradiance data from each sensor for the afternoon of July 5th. The shaded area is proportional to the total irradiation for the afternoon. Once the incidence angle passes beyond 60°, the CMP11 and
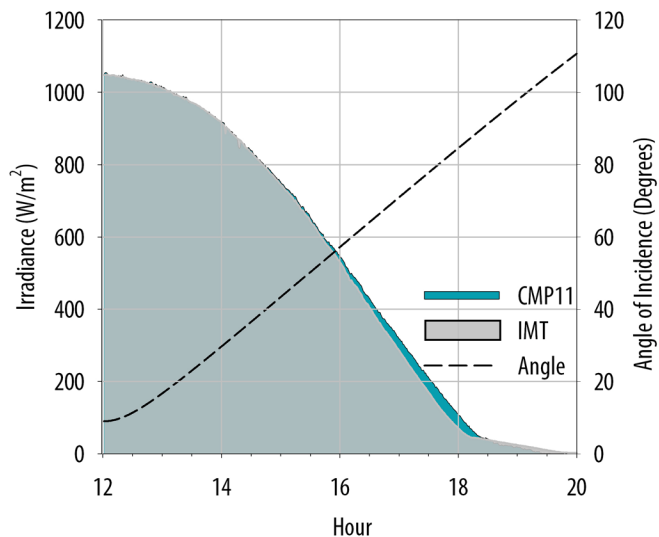
Figure 5. For the afternoon of July 5th, the IMT and CMP11 were adjusted using a linear calibration factor such that they agree in the vicinity of solar noon when the sun is nearly perpendicular to the sensors (perpendicular, or normal, orientation is given by a 0° angle of incidence in the plot). Incident angle effects cause the readings to diverge beyond 60°, creating a difference in irradiation of 1.6% for the whole day.

IMT readings begin to diverge because a greater proportion of irradiance is reflected from the front glass of the IMT. The darker blue area is proportional to the magnitude of the reflected irradiation and it is 1.6% of the total irradiation for the afternoon. The same analysis done for Sept 26th yielded a difference of 1.1%. Note that these effects would vary with the latitude and orientation of the PV array, as well as with the time of year. It would also mostly affect days with clearer skies.

**The CMP11 sheds snow better than the IMT, accounting for a 0.8% difference annually and 2.4% in total for those months with snowfall.** In Figure 2, the very large discrepancies at low irradiance levels are due to the fact that the IMT stays covered by snow longer than the CMP11. STEP staff often removed snow from the sensors and it follows that the consequences of the effect may be underestimated in this study. Using hour-averaged irradiance data, the data points affected by snow-coverage were identified manually and their cumulative effect was calculated.

## DISCUSSION & CONCLUSION

The different factors discussed in this technical brief provide insight into the monthly variations seen in Figure 2.

- Zero-offset errors create a constant difference between the two sensors, resulting in a greater percentage difference when the irradiance is low (with the IMT reading higher).

- Incident angle affects cause the IMT to read lower on days when the sky is relatively clear.

- Snow-shedding behaviour causes the IMT to read lower whenever there is a snowfall.

- A linear calibration offset creates a relative difference that causes the IMT to read lower at all points in time.

Figure 2 can then be explained as follows. The summer months have high average daily irradiation and clearer skies in proportion to the rest of the year. The percentage difference in these months was dominated by the linear calibration offset and incidence angle effects. The autumn months have little snow and typically overcast weather causing a lower average daily irradiation. Incidence angle effects are therefore smaller and, when not accounted for, zero-offset errors started to balance out the linear calibration offset - creating a low percentage difference overall. Differences in the snow-shedding behaviour of the two sensors creates larger differences in the winter months when there is snowfall.

The results of this case study are specific to this site. However, general awareness of these factors can bolster the quality of PV system performance analyses. Zero-offset errors can be directly corrected and linear calibration offsets can be mitigated through comparisons with a calibrated reference device post-installation. Incident angle effects and snow-shedding are trickier to mitigate but knowledge of their impacts adds important context to any PV system performance analysis.

References

International Energy Association (IEA). Improved measurements of solar irradiance by means of detailed pyranometer characterization. April 1996.

L. Dunn, M. Gostein, and K. Emery, "Comparison of Pyranometers vs. Reference Cells for Evaluation of PV Array Performance," Proceedings of the 38th IEEE Photovoltaic Specialists Conference (PVSC), Austin, TX, June 2012.

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