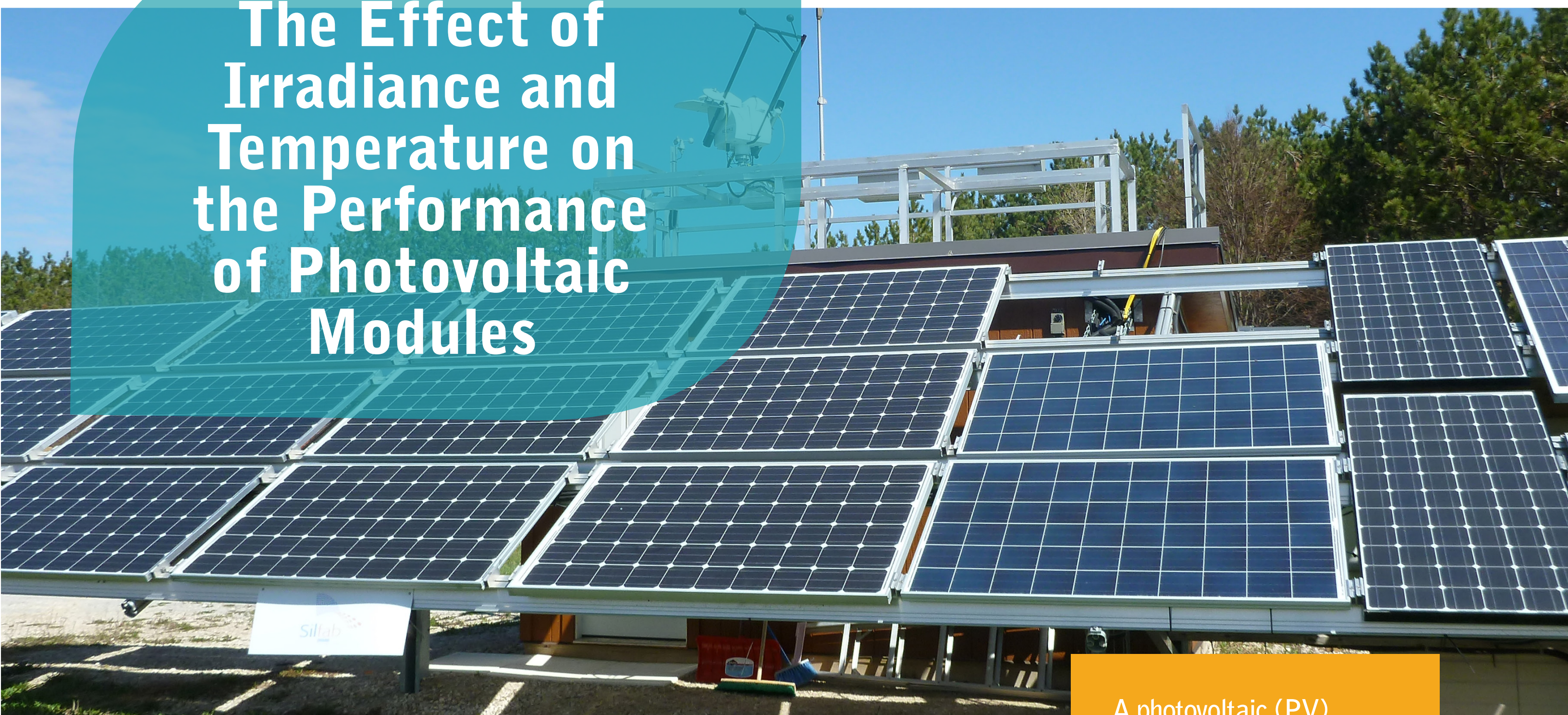
TECHNICAL BRIEF

Sustainable Technologies
EVALUATION PROGRAM

Renewable Energy

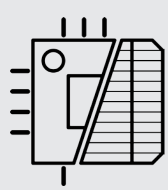
The Effect of Irradiance and Temperature on the Performance of Photovoltaic Modules



Photovoltaic (PV) module performance is typically rated using a single operating point at standard test conditions (STC) as per the IEC 61215 standard, consisting of a 1000 W/m^2 irradiance, 25 $^{\circ}$C module temperature and an AM1.5 spectrum. These ratings help PV system designers to predict annual energy yields. However, actual PV installation performance will vary under a wide range of real-world operating conditions and a robust yield estimate ought to take this into account. This can be modelled or it can be determined experimentally, as proposed in the rating procedures of the newly developed IEC 61853 series of standards.

A previous STEP project collected high-resolution data on PV module power production, back surface temperature and plane-of-array irradiance, for 14 mono-crystalline silicon (mono-c-Si) modules, across 5 different manufacturers, for the 2012 year. This dataset was re-evaluated to compare the variations in efficiency at different module temperatures and irradiance levels for modules from the different manufacturers. Measured efficiency values were normalized to STC conditions to form a fair comparison. The normalized efficiency values varied notably with irradiance and temperature but, across all modules, they agreed with eachother to within the experimental error at any given operating point. Such consistent behaviour suggests that detailed temperature-irradiance characterization may not be required for all mono-c-Si module models.

Currently, the dominant photovoltaic module technology is based on solar cells made from mono- or multi-crystalline silicon. Silicon is a plentiful material. In fact, it is one of the most abundant elements on the planet. Thin film cells, such as a-Si, Cd-Te or CIGS, are the main competitors to crystalline silicon but currently they comprise only a small percentage of the worldwide market share.



A photovoltaic (PV) module's rated efficiency helps a PV system designer compare modules from different manufacturers, as well as estimate how much electrical energy the module will produce. However, accurate energy yield predictions also need to take into account the fact that the as-installed efficiency will depend on the module operating temperatures, irradiance levels, irradiance spectra, wind speeds and incident angles, among other factors. This causes the actual efficiency to be different than the rated efficiency.

EXPERIMENTAL SET-UP

All measurements took place at STEP's PV testing facility located at the Living City Campus (LCC) in Vaughan, Ontario. Fourteen new mono-c-Si modules from five different manufacturers were monitored (mounting is shown on the cover image). The rated power of the modules varied between 245 and 305 W. The modules were installed on a south-facing mounting rack with a 30° tilt, a common orientation used in Southern Ontario. The maximum power-point (MPP) of the modules was tracked using power optimizers from SolarEdge which were connected to a SolarEdge inverter. The DC current and DC voltage of the modules was logged at a one second time scale but aggregated into minute-averaged values for the purpose of analysis. DC current was measured using a current shunt. The mV signal from the shunt and the module voltage was read using Compact Field Point (cFP) modules from National Instruments (NI) and a custom LabView logging program. Irradiance was measured simultaneously by a CMP11 pyranometer from Kipp & Zonen.

Module back surface temperatures were measured using a single surface-mount temperature sensor placed centrally on the back of each module (Figure 1). Temperature sensors were 3-wire class A surface-mount Pt100 RTDs read by an NI cFP module. It is not ideal to determine module temperature from a single back-surface measurement. However, the scope of the original work was such that accurate back-surface temperature measurements were not essential. This matters less for this short study because the bins used in the analysis were relatively course, as will be described below. To further mitigate this source of error, a Fluke TiR infrared camera was used to analyze the spatial variation of the modules' temperature near STC operating conditions (Figures 2). No hot spots due to failed cells were observed.

DATA ANALYSIS

The normalized efficiency was calculated for each module as a function of both the module back-surface temperature and irradiance using nearly a full-year of data from 2012. The normalized efficiency, shown in Equation 1, is the ratio of the actual efficiency being produced at any given operating point (i.e. at different levels of irradiance or module temperature) over the STC efficiency. The variables are described in Table 1.

Normalized efficiency was used as a performance metric because it would allow for a comparison between different module manufacturers. It allows a clearer look at how modules performed at various operating points *with respect to their own performance at STC*. It follows that those modules with a notably higher or lower efficiency should not necessarily have a notably higher or lower *normalized* efficiency. Note that the actual efficiency at any given temperature and irradiance can

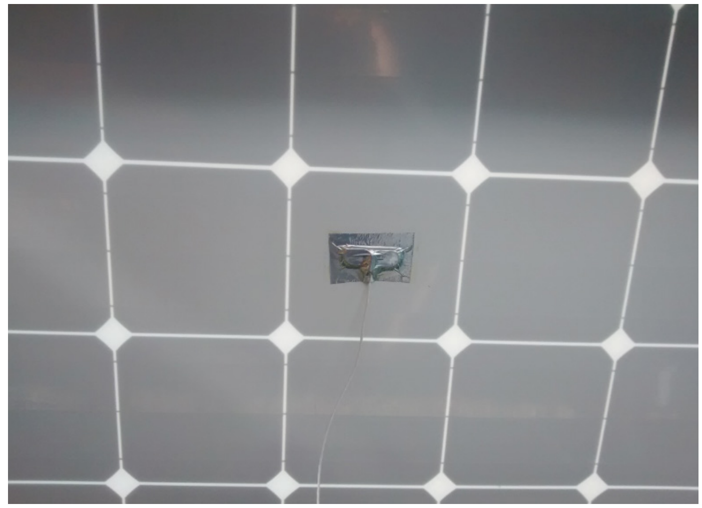


Figure 1. Temperature sensors were mounted on rear of the modules.

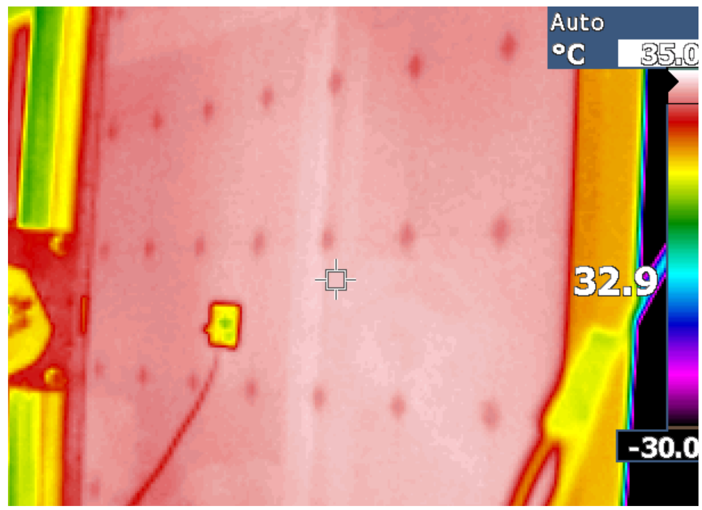


Figure 2. Rear-surface module thermographs demonstrate no failed solar cells.

be determined by multiplying the efficiency at STC with the normalized efficiency corresponding to that operating point.

Within this analysis, η_{NORM} (G,T) was determined experimentally for each module and, since it is a unitless ratio, the modules' performance was directly compared at different levels of irradiance and module temperature. To determine η_{NORM} (G,T), the minute-averaged data for P(G,T), G and T from each module were put into two-dimensional bins of temperature and irradiance. Irradiance bins were 100 W/m^2 in magnitude. The lowest bin was 0 to 100 W/m^2 and the largest, 1200 to 1300 W/m^2. Temperature bins were 10 °C wide in magnitude. The lowest bin was 0 to 10 °C and the largest, 60 to 70 °C. P_{STC} and η_{STC} were determined using the average power of data points between 900 and 1100 W/m^2 and 20 to 30 °C.

Data was only considered if the number of minute-averaged data points in a given two-dimensional bin was greater than

$$\eta_{NORM}(G,T) = \frac{\eta(G,T)}{\eta_{STC}} = \frac{P(G,T)}{P_{STC}} \cdot \frac{1000}{G} \quad (1)$$

60 (i.e. at least one hour of operation total). This number was arbitrarily chosen and it is intended, to some extent, to account for the fact that the analysis relies on having many data points so as to mitigate certain sources of error, discussed in detail in the following section.

Table 1. Description of key variables.

Variable	Description
η_{NORM} (G,T)	The normalized efficiency at any operating point of irradiance (G) and module temperature (T)
η(G,T)	The actual efficiency at any operating point of irradiance (G) and module temperature (T)
η_{STC}	The module efficiency at STC
P(G,T)	The actual power output at any operating point of irradiance of irradiance (G) and module temperature (T)
P_{STC}	The module power at STC

Data Filters

The data was put through a series of several filters prior to the calculation of normalized efficiency so as to remove any potentially erroneous data. These filters are listed below:

- To mitigate error associated with the difference in the incidence angle modifier (IAM) between the pyranometer and the module, all data points with a beam radiation angle of incidence greater than 40° were excluded.
- Data from the winter months were inspected manually to identify all cases of full or partial snow coverage of the modules and/or pyranometer, and any day with evidence of snow coverage was removed from the dataset.
- Any irradiance points below 50 W/m^2 and any points with normalized efficiencies exceeding 130% were excluded. Data points below 50 W/m^2 were excluded because the measurement uncertainty error increases dramatically at low currents. Uncharacteristically high normalized efficiencies were not common but were excluded because these likely resulted from events that partially shaded the pyranometer but not the module (for example, birds).

It should be noted that when data was omitted, it was omitted across all modules so that there was the same number of data points for each module. Not all sources of error could be taken into account. These are listed below:

- Incident angle effects associated with albedo or diffuse radiation were not accounted for.
- No consideration was given for spectral variations.
- The response time of the pyranometer (5s) is longer than the response time of the modules (nearly instantaneous) but this may have been mitigated as a large number of data points were averaged within a given bin.
- Error associated with the MPPT of the SolarEdge power optimizers was possible as well but, by comparing the results of different modules of the same manufacturer, no obvious cases were observed.

FINDINGS

The dependence of the normalized efficiency on module temperature and irradiance was very similar across all modules. Figure 3 plots the normalized efficiency from each of the modules as a function of irradiance when the module temperature was between 20 and 30 °C. Similar plots were created for the different temperature bins and good agreement between the different manufacturers was observed. There is a clear trend of increasing, and then decreasing, normalized efficiency. This has a simple explanation: Initially, efficiency increases with irradiance because the fill factor improves as the module I-V curve is shifted up the vertical axis. However, losses from parasitic resistances increase as well and this eventually causes the normalized efficiency to degrade as the irradiance continues to increase, giving rise to a maximum value somewhere in the vicinity of 750 W/m^2 for this module temperature. Good agreement between different modules was also observed when the normalized efficiency was plotted as a function of module temperature for constant levels of irradiance. Variations between different modules were small, as illustrated in the standard deviations presented in Table 2.

A set of normalized efficiency curves was created by averaging the results of each module. This is shown in Figure 4. The effects of module temperature and irradiance are clear: (i) there is a decrease in normalized efficiency with an increase in module back-surface temperature and (ii) there is typically a maximum value of normalized efficiency achieved when the irradiance is somewhere below 1000 W/m^2. The dataset is also presented in Table 2.

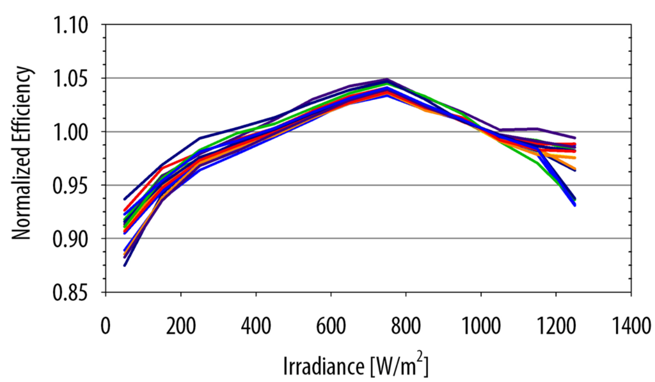


Figure 3. The normalized effiiciency (shown here when the back-surface temperature was between 20 and 30 °C) does not vary greatly across all modules that were monitored in this study.

Table 2. The average normalized efficiency across all 14 mono-c-Si modules is shown. The provided uncertainty is equal to 2 standard deviations within the 14 module dataset.

	Irradiance												
Temp [°C]	50	150	250	350	450	550	650	750	850	950	1050	1150	1250
5	0.90 ±0.04	1.00 ±0.02	1.04 ±0.02	1.08 ±0.02	1.10 ±0.03	-	-	-	-	-	-	-	-
15	0.86 ±0.04	0.94 ±0.02	0.99 ±0.02	1.03 ±0.01	1.05 ±0.01	1.07 ±0.01	1.07 ±0.01	1.11 ±0.02	1.08 ±0.03	1.03 ±0.04	1.00±0.06	-	-
25	0.91 ±0.04	0.95 ±0.02	0.98 ±0.01	0.99 ±0.01	1.00 ±0.01	1.02 ±0.01	1.03 ±0.01	1.04 ±0.01	1.03±0.01	1.01 ±0.00	0.99 ±0.00	0.98 ±0.01	0.97 ±0.04
35	-	0.88 ±0.03	0.92 ±0.01	0.93 ±0.01	0.95 ±0.01	0.95 ±0.01	0.97 ±0.01	1.00 ±0.01	0.99 ±0.01	0.98 ±0.01	0.97 ±0.01	0.96 ±0.01	0.95 ±0.01
45	-	-	0.85 ±0.02	0.86 ±0.01	0.88 ±0.01	0.90 ±0.01	0.91 ±0.01	0.92 ±0.01	0.92 ±0.01	0.92 ±0.01	0.92 ±0.01	0.91 ±0.01	0.91 ±0.01
55	-	-	-	0.81 ±0.01	0.83 ±0.01	0.85 ±0.01	0.86 ±0.01	0.87 ±0.01	0.87 ±0.01	0.87 ±0.01	0.87 ±0.01	0.86 ±0.01	0.86 ±0.01
65	-	-	-	-	-	-	-	-	-	-	0.83 ±0.01	0.83 ±0.01	0.83 ±0.01

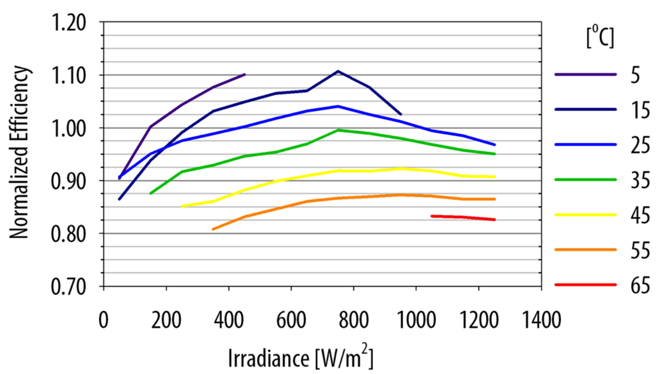


Figure 4. The normalized efficiency changes with module temperature and irradiance.

DISCUSSION AND CONCLUSION

This study examined an existing dataset in an attempt to glean useful insights regarding how the efficiency of commercial mono-crystalline silicon PV modules may vary with module temperature and irradiance, and furthermore, how that might change across different manufacturers. The dataset had a 1s resolution and was aggregated into 1 min averages for the analysis. Monitored parameters included back-surface module temperature, plane-of-array irradiance and module power production for the 2012 year from 14 modules covering 5 different manufacturers. This data was filtered to eliminate erroneous data points and sorted into two-dimensional bins of temperature and irradiance. The normalized efficiency was calculated across each bin and for each module. Binning the data in this way was a course approach - more stringent measurement conditions would yield higher quality data. However, these field results show that the behaviour of PV modules varies considerably under varying temperature and irradiance conditions and also, that mono-c-Si modules from different manufacturers behave very similarly.

Module rating procedures that involve expanded experimental characterization also introduce additional cost. It is worthwhile to identify where that additional cost is truly required, and where simpler measurements, like those at STC, are sufficient. The consistent behaviour observed in this study suggest that, for this sample of mono-c-Si modules, expanded experimental characterization at different module temperatures and irradiance levels may not be necessary because performance could be sufficiently extrapolated from an STC operating point based on a general trend (i.e. that shown in Table 2). Note that the normalized efficiency trends will vary between different PV cell technologies. Future work may include additional PV cell technologies, and it may compare these experimental results with predictions from simulation tools. It may also compare these results with those obtained from the indoor and outdoor methods of IEC 61853-1.

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