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INFLUENCE OF LOW-LIGHT MODULE PERFORMANCE ON THE ENERGY PRODUCTION OF CANADIAN GRID-CONNECTED PV SYSTEMS

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Abstract

Traditionally, the energy production of a grid-connected photovoltaic (PV) system is predicted as a product of the STC (standard test conditions; 1000 W/m^2, 25°C and Air Mass 1.5 Global) power rating of the modules and TMY (typical meteorological years) sunhours of the site. This simple energy prediction does not account for the negative influence of module operating temperatures, module low-light efficiency, loss of photons at higher incident angles and influence of spectral changes. As a result, end users have experienced much lower energy production than predicted.

After accounting for the influences of other factors, this work identifies, based on the performance analysis of three grid-connected Canadian systems, that the efficiency of many commercial crystalline-silicon PV modules at low-light conditions (below 200 W/m^2) is significantly lower than the high-light (above 200 W/m^2) efficiency.

This paper concludes that the overall energy production of a Canadian PV system can not be accurately predicted without accounting for the efficiency of the PV modules at low-light conditions.

Two typical building-supported (roof and façade) and one open rack mounted systems located in three Canadian sites are considered for this study. These sites are: Varennes, Iqaluit and Edmonton. This study also briefly discusses some of the needed improvements in the power model of WATSUN-PV simulation program to account for the performance of the PV modules under low-light conditions.

1. INTRODUCTION

The energy production of PV modules is traditionally predicted by assuming that it is directly proportional to the STC power rating. In this energy rating method, the following oversimplified assumptions have been made:

(i) the module always operate at a temperature of 25°C — in reality, the module operates over a temperature range of -10 to +80°C and its power output decreases as its temperature increases [1];

(ii) the efficiency or fill factor (FF) of a PV module is independent of irradiance level — in reality, the efficiency of many commercial modules is lower, because of imperfections in the PV cells, at low irradiance levels (below 200 W/m2) as compared to a high irradiance levels (above 200 W/m2) [1, 2];

(iii) the sun always shines perpendicular to the module surface — in reality, the angle of irradiance on a module changes with the time of a day/season [3, 4]; and

(iv) the sunlight's spectral distribution does not change from AM 1.5 Global — in reality, the spectrum changes with time of a day and the climatic conditions [5, 6].

The use of these assumptions has lead end users to experience much lower system energy output than the output predicted from the STC power rating.

The first part of this paper (Section 3.1) presents the results on the extent of low-light availability in Canada. The second part (Section 3.2) presents a detailed analysis on the influence of irradiance level on the efficiencies of three grid-connected PV arrays in Canada. The sites and systems are: Varennes - open rack mounted; Iqaluit - façade mounted; and Edmonton - roof mounted.

WATSUN-PV is a solar simulation program that predicts the energy production of a PV system by accounting for the influence of module temperature only. The third part (Section 3.3) of this study briefly discusses the needed improvements in WATSUN-PV to account for the influence of irradiance level.

2. SYSTEM DESCRIPTION AND DATA COLLECTION

The arrays of all the three systems (Varennes, Edmonton and Iqaluit) consist of 1 to 3 sub-arrays with the rated total output of 2.3 to 15 kW_p. Each array consists of monocrystalline and/or polycrystalline modules from AstroPower Canada (APC 5103), Solarex (MSX 60), Solec (S-53) and Siemens (PC4-JF and M-55). An analysis of the measured performance data is presented for only one sub-array of each system. The data obtained for tilted insolation of above 30 W/m^2 are considered for this analysis. Obtaining an efficiency lower than 5% under high-light conditions (above 200 W/m^2) is unrealistic for the modules utilized in this work and hence the data points with less than 5% efficiency under high-light conditions are not considered for this analysis. Table 1 describes each system.

Parameter	Varennes	Edmonton	Iqaluit
Latitude	45.2^o N	53.3^o N	63.75^o N
Longitude	73.2^o W	113.5^o W	68.5^o W
Installation	Rack	Roof	Façade
Tilt angle	45^o (south facing)	27^o (south facing)	90^o (south facing)
Inverter used (with MPPT)	4 kW Omnion Power Eng.	3 kW Statpower PROsine GT	3 kW Statpower PROsine GT
Insolation sensor	Eppley PSP	Kipp and Zonen CM5	LiCor LI 200SA
Data saving period	Every hour	Every 15 min.	Every hour
Data analysis period	Apr/1996 to Feb/1998	Sep/1995 to Feb/1998	Mar/1996 to Aug/1997

Table 1: Details of three Canadian grid-connected PV Systems

3. RESULTS AND DISCUSSION

3.1 Extent of low light energy

The portion of global insolation in low-light conditions (below 200 W/m^2) for the three sites is shown in Figure 1A for the horizontal plane and Figure 1B for the tilted plane. This portion varies between 8% and 69% in the horizontal plane and, between 7% and 19% in the tilted plane. These results clearly indicate that a significant portion of the seasonal or annual insolation (horizontal or tilted), for all the three sites, arises under low-light conditions. This demonstrates that the efficiency of modules under low-light conditions is a very important consideration for PV application in Canada.

It is interesting to note that the tilt angle of 27° for the Edmonton-roof system was selected to optimise the system's summer power production as a demand-side management system [7]. For this system, the low-light tilted insolation accounts for only 7% in the summer; therefore, the requirement for low-light module performance for this system is less stringent.

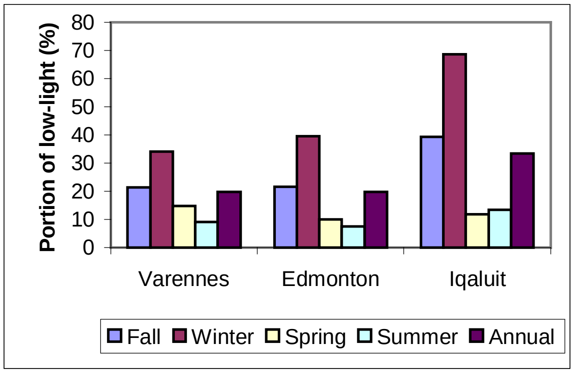

Figure 1A: Seasonal portion of horizontal low-light global insolation

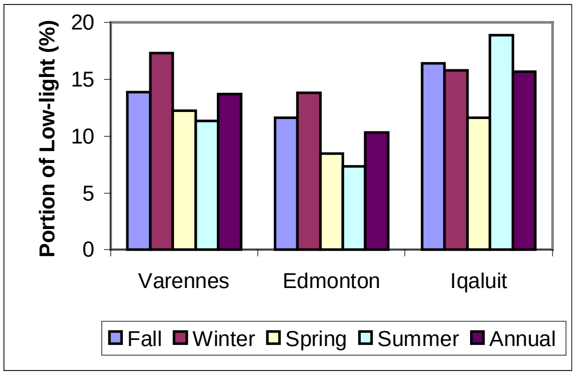

Figure 1B: Seasonal portion of tilted low-light global insolation

3.2 PV array efficiency

The array efficiency, as a function of insolation, of the Edmonton system is shown in Figure 2. Similar plots have been obtained (not shown here) for the other systems. If the efficiency of a PV array is not influenced by any climatic factors, one would have expected a single line of data parallel to the X-axis of the plot. The scattering of the data in this plot clearly indicates that the array efficiency is influenced by climatic factors. These factors are: module temperature, level of irradiance, angle of incidence (reflectance effect) and spectral changes.

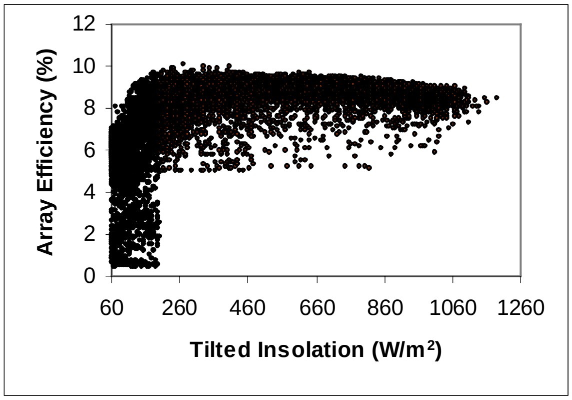

Figure 2: PV array efficiency of Edmonton system as a function of irradiance

In order to identify the extent of negative influence of any one factor, for example level of irradiance factor, it becomes necessary to account for the influences of the three other factors.

Since the module temperature of all the systems are measured and the temperature coefficient for power is well established for the crystalline silicon technologies (-0.5%/C), the influence of module temperature can easily be accounted for. As the direct-light and spectral irradiance data are not measured for the systems, it is not possible to quantitatively account for the extent of influences of these two factors individually. However, the extent of cumulative influence of these two factors can be quantitatively identified if the data in Figure 2 are presented as seasonal efficiencies under high-light (above 200 W/m^2) and low-light (below 200 W/m^2) conditions.

3.2.1 Seasonal efficiency at high-light conditions

The array's high-light efficiencies are shown in Figure 3A. In all three systems, the efficiencies in summer are lower than in the other seasons because of higher module temperatures. The temperature-corrected (to 25°C) high-light efficiencies are shown in Figure 3B.

Under high-light conditions, in Figure 2, the highly populated region is nearly parallel to the X-axis of the plot. Therefore, it can be stated that the variations in the seasonal efficiency shown in Figure 3B are influenced by the angle of incidence and spectral factors only, and not by the level of irradiance factor, i.e., fill factor (FF) is constant for the high-light conditions.

The seasonal efficiencies shown in Figure 3B indicate that angle-of-incidence and spectral factors can cumulatively decrease the efficiencies, at high-light conditions, to a maximum of 13% for the Varennes system, 11% for the Edmonton system and 15% for the Iqaluit system.

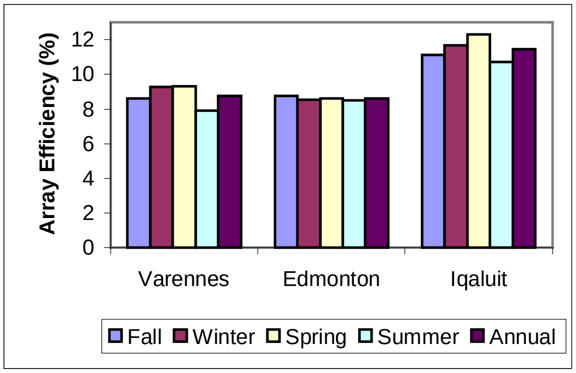

Figure 3A: Seasonal variation of high-light PV array efficiency

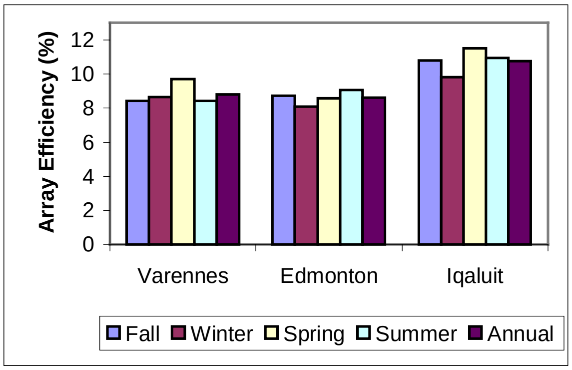

Figure 3B: Seasonal variation of temperature-corrected high-light PV array efficiency

The extent of influence of individual factors on the seasonal efficiencies of Figure 3B is qualitatively discussed in the following paragraphs.

For the Edmonton system, considering the latitude (53.3° N) and module tilt angle (27^o), one would expect, based on the angle of incidence only, the following order of seasonal efficiency: summer>fall≈spring>winter. Due to considerable loss of blue photons during the cold months (higher air-mass values), one would expect, based on the spectral effect only, the following order of seasonal efficiency: summer>spring≥fall>winter. Since the effects of these two factors are closely in-phase for all the seasons, one would expect the following overall order of seasonal efficiencies: summer>spring≥fall>winter. The observed results for this system indicate that this is indeed the case.

For the Iqaluit system, again based on the latitude (63.75° N) and module tilt angle (90^o), one would expect the following order of seasonal efficiency: winter>spring≈fall>summer for the angle of incidence effect and summer>spring≥fall>winter for the spectral effect. Since the effects of the two factors are near in-phase for the fall and spring seasons and totally out-of-phase for the other seasons, one would expect the following overall order of seasonal efficiency: spring≥fall>winter and spring≥fall>summer. The observed results for this system indicates that this is indeed the case. More importantly, higher summer-to-winter and spring-to-fall efficiency ratios indicate that the spectral effect is more dominant than the angle of incidence effect. It is to be noted that this conclusion is derived assuming that there is no spectral response mismatch error between the silicon cell used in LiCor pyranometer and the silicon cells used in the PV array.

For the Varennes system (latitude of 45.2^o N and module tilt angle of 45^o), the variations in the seasonal efficiencies can be explained by applying the arguments similar to the other two systems. Thus, one would expect the following overall order of seasonal efficiency: spring≥fall>winter and spring≥fall>summer. The observed results generally follow these trends. Moreover, higher spring-to-fall efficiency ratio indicates that the spectral effect again plays a more dominant role than the angle of incidence effect.

3.2.2 Seasonal efficiency at low-light conditions

The low-light efficiencies, without and with temperature correction, are shown in Figure 4A and 4B, respectively.

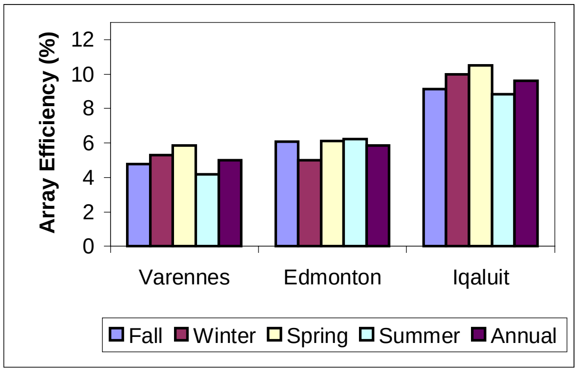

Figure 4A: Seasonal variation of low-light PV array efficiency

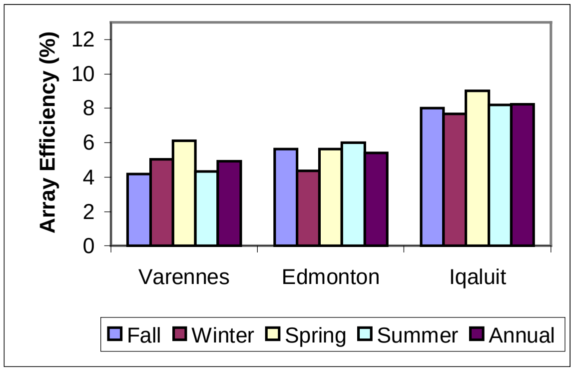

Figure 4B: Seasonal variation of temperature-corrected low-light PV array efficiency

The seasonal efficiencies shown in Figure 4B are influenced by three factors: angle of incidence, spectral change and level of irradiance. These factors can cumulatively decrease the efficiencies, at low-light conditions, to as high as 57% for the Varennes system, 52% for the Edmonton system and 33% for the Iqaluit system (these percentage decreases are calculated from the highest efficiency at high-light conditions and lowest efficiency under low-light conditions). This indicates that the drop in efficiency due to the three cumulative factors is excessively higher (33-57%) than the cumulative drop due to angle of incidence and spectral factors only (11-15%) (see Section 3.2.1). If we reasonably assume that the extent of influence of angle of incidence and spectral effects, for the low-light conditions, would be only marginally higher than 11-15%, then it can be concluded that the seasonal efficiency, at low-light conditions, is influenced predominantly by the level of irradiance.

Poor efficiencies of the modules at low-light conditions are attributed to poor cell manufacturing processes that include the presence of impurities, such as iron, and/or induced defects, such as scratches, at the junction plane. The efficiency under low-light conditions can also be decreased by the presence of defects along the outer edges of the cell.

At higher photon fluxes (high-light conditions), increased carrier traffic begins to saturate these centres/defects and hence their influence is negligible; but at lower photon fluxes (low-light conditions), these centres/defects are not saturated with charge carriers and the photocurrent becomes comparable to the shunt/diode current. If the densities of these centres/defects are abnormally high, then one would expect a drop in efficiency even in the lower end of high-light range.

As a consequence of predominant effect of level of irradiance, the efficiencies of individual modules in a large array may differ from each other, and hence the performance of a series connected array is also affected by the compounded problem of module mismatch along with angle of incidence and spectral effects. This problem becomes much worse if an array, consisting of modules from different manufacturers, is tracked by a power conditioner using a single maximum power point tracker (MPPT).

3.3 Performance prediction by WATSUN-PV

Using the measured tilted irradiance and measured module temperature, the seasonal efficiency of each system can be predicted by the power model of the WATSUN-PV simulation program [8,9]. This model utilizes the following translation equations:

$$I_{SC} = I_{SC\text{-}REF}(H_T/H_{T\text{-}REF})(1 + \alpha(T_C - T_{C\text{-}REF}))$$

$$V_{OC} = V_{OC\text{-}REF}(l - \gamma(T_C - T_{REF}))\ln[e + \beta\{(H_T/H_{T\text{-}REF}) - 1\}]$$

$$P_{max} = P_{max\text{-}REF}\{(I_{SC}V_{OC})/(I_{SC\text{-}REF}V_{OC\text{-}REF})\}$$

Where:
I_{SC} = short circuit current [A]
$I_{SC\text{-}REF}$ = short circuit current under reference conditions, eg., STC [A]
H_T = insolation level for the hour [W/m^2]
$H_{T\text{-}REF}$ = reference insolation level [W/m^2]
α = temperature coefficient for neutered short circuit current [1/C]
T_C = cell temperature [^{o}C]
$T_{C\text{-}REF}$ = reference cell temperature [^{o}C]
V_{OC} = open circuit voltage [V]
$V_{OC\text{-}REF}$ = open circuit voltage under reference conditions [V]
γ = temperature coefficient for neutered open circuit voltage [1/C]
β = insolation coefficient for open circuit voltage [unitless]
P_{max} = module power at maximum power point [W]
$P_{max\text{-}REF}$ = module power at maximum power point under reference conditions [W]

The predicted and measured annual high-light and low-light efficiencies are shown in Figure 5A and 5B, respectively. The predicted efficiency is slightly higher than the measured ones for the high-light conditions, whereas it is too high for the low-light conditions. Therefore, it may be concluded that the power model of WATSUN-PV is appropriate for high-light conditions, but is less accurate for low-light conditions. The lower accuracy under low-light conditions arises because the power model of WATSUN-PV assumes a single efficiency/fill factor/β value, which is equal to the one obtained at high irradiance levels. The analysis of the results obtained at high-light (Figure 3B) and low-light (Figure 4B) conditions clearly demonstrates that it is not the case, and hence it becomes necessary to define the β value as a function of irradiance, rather than a single value, as is currently used by WATSUN-PV.

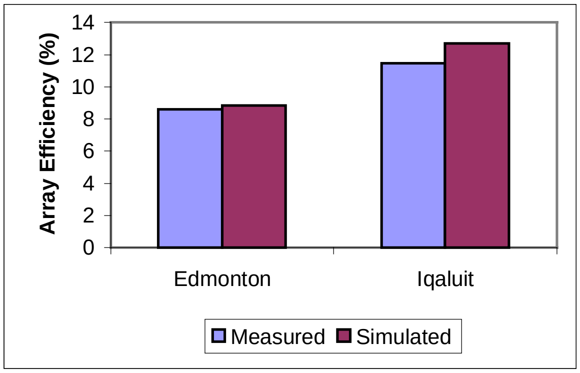

Figure 5A: Simulated vs measured annual high-light efficiency

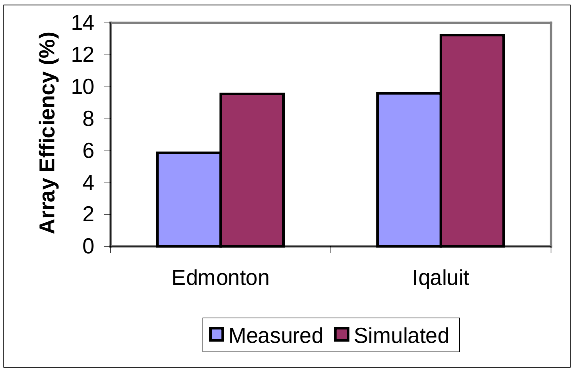

Figure 5B: Simulated vs measured annual low-light efficiency

4. CONCLUSIONS

Based on the analysis of the performance of three Canadian grid-connected systems, it can be concluded that: (i) the efficiencies of the PV modules are significantly lower at low-light conditions than at high-light conditions; therefore, energy prediction based on the product of STC power rating and sunhours would be misleading, (ii) the efficiency at low-light conditions should be used as one of the selection criteria of the PV modules in Canada, (iii) the spectral factor is predominantly responsible for the extent of variations in the temperature-corrected high-light seasonal efficiencies and, (iv) the level of irradiance factor is predominantly responsible for the extent of variations in the temperature-corrected low-light seasonal efficiencies.

From the comparison of measured array efficiencies with the WATSUN-PV simulated efficiencies under low- and high-light conditions, it is concluded that the insolation coefficient for the open circuit voltage, β, should be defined as a function of irradiance, rather than a single value as is currently used in the translation equation of WATSUN-PV.

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