An Experimental Validation of the Concept Critical Solar Radiation for Solar Tracking Systems

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Abstract

This work involves an experimental validation of a concept to be used in optimal tracking strategy for a dual-axis tracking PV panel during cloudy conditions in Canada or any high latitude locations. The work presents an experimental study of incident solar radiation and electrical production of two PV panels in various configurations. The measurements were carried out during several seasons for the city of Montréal, Canada. One of the panels is continuously directed toward the zenith (horizontal position) while the second is equipped with a dual-axis solar tracker allowing it, according to the stages of the experimentation, to fix its surface at a specific angle or to track the sun. Results confirmed that on sunny days, the solar tracking surface is more irradiated than the other. Conversely, on cloudy days a horizontal PV panel receives more diffuse solar radiation and therefore produces more electricity (up to 25%) than one tracking the sun. The experimental results presented here have validated the method that uses the concept of "hourly critical solar radiation" to determine whether or not the panel should follow the sun. The theory and measurements were found to be in agreement 96% of the time.

Keywords: Solar energy, photovoltaic, solar tracker, tracking strategies

Nomenclature

E	hourly electrical energy produced by the solar PV array (Wh)
G	solar irradiance on a surface (W/m^2)
G_{sc}	extraterrestrial solar irradiance, solar constant = 1353 W/m^2
I	hourly solar radiation (Wh/m^2)
k_t	hourly clearness index
PV	photovoltaic panels
R_b	geometric factor
SC	short-circuit current (A)
TA	tracking advantage (%)
$MPPT$	maximum power point tracking

Greek symbols

β	surface slope (°)
δ	solar declination (°)
ξ, γ	dimensionless parameters used in Eq. (21)
ω	solar hour angle (°)
□	latitude (°)
ρ_g	ground reflection coefficient
θ	incidence angle (°)
θ_z	zenith angle (°)

Subscripts

0	extraterrestrial
c	critical
d	diffuse
DTS	pointing directly towards the sun
H	horizontal
net	net
T-57°	titled 57°
T	titled

1. Introduction

In their review paper, Mousazadeh et al, (2009) demonstrated that tracking the sun with solar panels largely increases the average yearly energy production with respect to panels set in a fixed position. This was also reported more recently by Lazaroiu et al. (2015) and Ismal et al. (2013). Nevertheless, because in overcast or cloudy conditions more than 90% of the solar radiation may be diffused (Orgill and Hollands, 1977), tracking the sun could be ineffective as the albedo of the environment is generally lower than that of the clouded sky itself. Hence, in partially cloudy conditions, as a function of the clearness index, tracking the sun could be either effective or unnecessary. Knowing for which conditions it is more advantageous to track the sun is an important issue for the optimisation of the operation of solar panels under any climatic conditions. But this is especially relevant under Canadian weather conditions as the presence of snow, both on the ground and on the panel itself, influences the performance.

Under cloudy conditions, normally a low amount of energy is produced. Hence, studies of the tracking strategy optimization under cloudy conditions are sparse and are relatively recent. The oldest reported work on this topic is a study carried out about 20 years ago by Appelbaum et al. (1994) on the performance of solar arrays on Mars. While there are no significant clouds on Mars, dusty atmospheric conditions are somewhat similar to an overcast sky on Earth. This theoretical study demonstrated that in dusty conditions (optically thick atmosphere) dual axis tracking and horizontal surfaces provided almost the same power. Later, Badescu (1998) created a more refined model for the PV cells working under Martian conditions. He also concluded that there is little difference between the electrical power output of the PV array when different strategies (horizontally oriented, south-facing tilted and dual axis tracking) are considered to collect solar radiation, mainly consisting of diffuse radiation. However, it is the seminal work of Kelly and Gibson (2009) which is the best known starting point for the current research. The authors made measurements of the solar irradiance during cloudy periods. They measures solar irradiance on the horizontal position (G_H) and on a surface pointing directly towards the sun (G_{DTS}). Kelly and Gibson (2009) suggested the following equation to define the tracking advantage (TA) of a dual-axis tracking panel versus a fixed horizontal panel:

$$TA = \frac{G_{DTS} - G_H}{G_H} = \frac{1 - \dfrac{G_H}{G_{DTS}}}{\dfrac{G_H}{G_{DTS}}} \qquad (1)$$

Here the right-hand side of Eq.(1) is the original formulation of Kelly and Gibson (2009) whereas it can be written more concisely as shown by the middle term. Although Eq.(1) is written in terms of power (instantaneous energy), in this study the concept will be extended to the energy recovered during a period of time.

Since all measurements were performed on overcast days, the authors obtained negative values for TA (a tracking disadvantage) ranging from -0.17 to -0.45 with an average of -0.31 (31%). These results led Kelly and Gibson (2009) to conclude that orienting solar panels toward the zenith allows to capture more energy than with moving panels that simply track the sun's path every day regardless of the sky conditions.

Two years later, Kelly and Gibson (2011) reported an extensive set of measurements for solar irradiance at noon. They used four identical PV solar arrays and associated silicon-photodiode pyranometers with different tilt angles (57°, 42°, 27° and 0°) relative to the earth's surface. Their objective was to determine an optimal tracking algorithm for capturing solar radiation. The data was collected at Milford, Michigan (42°35' N).

Over an overcast day, they estimated that the horizontal orientation of a PV panel can collect up to 50% more solar energy than a system that moves with the sun hidden behind the clouds.

Koussa et al. (2011, 2012a, 2012b) studied the effect of eight different tracking configurations on the performance of solar PV panels. The evaluation was performed on the basis of hourly measurements of direct normal, horizontal global and diffuse solar radiation as well as the ambient temperature. Data was collected at Bouzareah (36°47' N) (Koussa et al. (2012a) and Ghardaïa location (32.4°N) (Koussa et al. (2012b), situated in the desert in the North of Algeria. A theoretical model was used to calculate the energy performance of each PV panel configuration. They reported that, during an overcast day, the horizontally oriented PV panel provides the best performance, compared to the other configurations.

Although the above mentioned papers indicate a disadvantage of sun tracking on cloudy days, none of them investigated the hourly and seasonal results as well as the influence of ground albedo on *TA*.

2. The Critical Hourly Global Solar Radiation

Hence, Quesada et al. (2015) proposed a simple yet efficient way to determine whether or not a PV panel should be set horizontally on cloudy days. The paper suggests a theoretical approach, based on an isotropic sky model (Hay and McKay, 1985; Reindtl, Beckman and Duffie, 1990; Noorian, Moradi, and Kamali, 2008), for any PV panel. This methodology estimates the theoretical value of global or integrated solar radiation incident on a horizontal plane under which a PV panel, horizontally oriented, receives and produces more energy than one following the sun. This value has been called "critical hourly global solar radiation" (I_c). This “critical hourly global solar radiation” (I_c) can be defined as the hourly global solar radiation incident on the horizontal surface (I_H) for which the value is equal to the global solar radiation incident on a tilted surface (I_T). This threshold is reach when the following equation equals unity (Quesada et al. (2015)).

$$\frac{I_T}{I_H} = \left(1 - \frac{I_{H,d}}{I_H}\right) \cdot R_b + \frac{I_{H,d}}{I_H} \cdot \left(\frac{1+\cos\beta}{2}\right) + \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

Where R_b is defined such as:

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos(\phi-\beta)\cdot\cos\delta\cdot\cos\omega + \sin(\phi-\beta)\cdot\sin\delta}{\cos\phi\cdot\cos\delta\cdot\cos\omega + \sin\phi\sin\delta} \tag{3}$$

And all angles pertain to standard solar geometry that can be found in a standard textbook such as that of Duffie and Beckmann (2006) or in Quesada et al. (2015).

When I_H is below this threshold ($I_H < I_c$), a tilted surface would receive less energy that a horizontal one.

Then, for the condition $I_H = I_T = I_c$, the ratio of $I_{H.d} / I_c$ is calculated by modifying Eq. (3) as follows,

$$\frac{I_{H,d}}{I_c} = \frac{I_{H,d}}{I_H} = \frac{1 - \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) - R_b}{\left(\frac{1+\cos\beta}{2}\right) - R_b} \tag{4}$$

Now, Orgill and Hollands (1977) presented a correlation equation between the $I_{H.d} / I_H$ ratio and the hourly clearness index (k_t) based on meteorological data collected over four years. Their results lead to formulate an expression for I_c that depends upon the threshold for $k_t = k_{tc}$ corresponding to cloudy days accounting for more than 90% of global incident solar radiation being diffuse.

$$I_c = k_{t_c} \cdot I_{H,0} \tag{5}$$

where the extraterrestrial solar radiation on a horizontal surface ($I_{H,0}$) for an hour period between hour angles ω_1 and ω_2 ($\omega_2 > \omega_1$) is provided by Duffie and Beckmann (2006)

$$I_{H,0} = \frac{12 \cdot G_{sc}}{\pi} \cdot \left[1 + 0.033 \cos\left(\frac{360 \cdot n}{365} \right) \right] \times \left[\cos\phi \cdot \cos\delta \cdot \left(\sin\omega_2 - \sin\omega_1 \right) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin\phi \cdot \sin\delta \right] \tag{6}$$

3. Numerical Validation of the Concept

In Quesada et al. (2015) the authors use the data provide d by Orgill and Hollands (1977) to fist estimate the monthly clearness index ($\bar{K}_T$) while the monthly average radiation impinging on a horizontal surface in Montreal was obtained from the PV-Sol Pro 4.5's (Valentin, 2010) meteorological database.

Then, the calculation of the critical hourly global solar radiation for a two axis solar tracking PV panel operating in Montreal was performed. The calculations were made considering a ground reflection coefficient value of 0.2 for the summer season (June, July, August) and values of 0.2 (without ground snow coverage) and 0.8 (with snow on the surrounding ground) for the winter season (December, January, February). The values of I_c were compared to that a tracking advantage, TA, now based on hourly averages of the cumulative irradiation (that is energy) on the tilted (or DTS) and horizontal surfaces instead of irradiation (power).

$$TA_H = \frac{I_{DTS} - I_H}{I_H} \tag{7}$$

I_c was found to constitute an excellent criterion to determine whether or not the panel should be horizontal or not on cloudy days. That is whenever for an hour $I_H < I_c$, there is no tracking advantage, that is a tilted (or following) surface receives less energy than a horizontal one. Nevertheless, the advantage of producing electricity by fixing the PV panels horizontally has to be demonstrated because at low levels of solar radiation, the PV photosensitive properties (current-voltage characteristic curve) and the operating parameters of the other PV system components (charge regulator, electric battery, and inverter) may provide significant constraints to the transformation of the incident solar energy into useful electrical energy (Abdallah and Nijmeh, 2004; Mamlook et al., 2006; Abu-Khader et al., 2008; Poulek, 1994; and Poulek et Libra, 1998). Hence, it was found mandatory to compare the above conclusions with the electricity production of a panel. To do that, Quesada et al. (2015) introduced the distinction between the "rough" tracking advantage and the "net" tracking advantage. While TA_{rough} is define with respect to the hourly incident radiant energy on a tracking PV panel compared to a horizontal panel, Eq.(7), TA_{net} is based on the hourly electrical energy produced by a tracking PV panel compared to a horizontal panel for the same conditions.

$$TA_{H,net} = \frac{E_{DTS} - E_H}{E_H} \tag{8}$$

Then, a PV system performance was simulated to determine the effective usefulness of the I_c concept. PV-Sol Pro 4.5 (Valentin, 2010) was used to analyse the performance of a typical grid-connected PV system operating under cloudy sky conditions. To carry out the simulation, a PV system connected to Montreal's electrical grid was chosen. The system had a total power of 10.8kW and is composed of 48 PV panels of 225W each (Type PV panel: CS6P-225P) and 3 inverters (Inverter type: Powador 5300). Similar ground reflection coefficients were used.

For June 25th, 2014, an overcast day in Montreal, all values of TA reported by Quesada et al. (2015) were negative (ranging from -24.7% to -2.3%) suggesting that orienting PV panels toward the zenith on such days produces more electricity than tracking the sun. In all cases, that is for each of the 13 hours of sun reported, $I_H < I_c$.: the theoretical concept could eventually enable one to adopt the appropriate strategy for the control of the panel based on weather forecast.

One of the shortcomings of the above mentioned study (Quesada et al. 2015) is that no experimental validation was available to confirm these results.

The main objective of the current work is then to determine experimentally whether the strategy of setting PV panels horizontally during cloudy days increases the performances of a dual-axis solar tracker or not.

First, the work verifies that similar experimental results to that of Kelly and Gibson's study (2009) could be obtained for the city of Montreal. Then, measurements are used to validate the theoretical methodology proposed by Quesada et al. (2015) estimating the availability of solar energy for a city in the northern hemisphere.

4. Experimental Validation of the Concept

4.1 Experimental Set-Up

The experimental set-up involved in the study is located in Montréal (latitude = 45° 29'N, longitude = 73° 33'W). It is composed of two polycrystalline photovoltaic panels which characteristics, in standard conditions of operation, are reported in Table 1.

Table 1: Characteristics of the PV Panels

Type	SG210P
Rated power	210 W
Short-circuit current	7.9 A
No-load voltage	36.8 V
Rated voltage	28.7 V
Rated current	7.3 A
Area	1.66 m^2

As shown in Fig. 1, the left panel is fixed horizontally while the second, on the right, is powered by a dual-axis solar tracker "SDE3B-62MHC-24H01-RC" from Kinematics Company. The right panel was used in a tilted fixed position (stage 1) and with a dual-axis tracker (stages 2 and 3).

Fig.1: Picture of the experimental set up : (left) overview of both PV panels with the fixed and horizontal panel on the left and the solar tracking panel on the right ; (right) close-up of the motors of solar tracker

The incident solar radiation on the PV panel surface is measured by Kipp & Zonen SP Lite 2 pyranometers. The accuracy of the measurements is ±10% for an incident angle of sun lower than 80 degrees. Such pyranometers were installed on each PV panel structure; Fig. 2 explicitly indicates the location of each sensor on the panels.

Fig.2: Picture showing details on the mounting of the pyranometers (left) on the two PV panels, and (right) close-up of the sensor support

To protect the solar tracking mechanism, a Davis Vantage Pro2 6410 anemometer continuously measures the wind speed near the experimental set-up. When wind speed exceeds 60km/h, the control system places the tracking PV panel in safety horizontal position.

Voltage and current generated by the panels are measured by using voltage dividers and CR5210-10 current transducers, respectively.

A National Instruments USB-6218 card connected to a computer via USB and LabVIEW software are used for acquisition, data processing and for the operation and control of the solar tracking system. All sensor signals (unit: mV) are converted with conversion factors integrated in LabVIEW to obtain reference units, like W/m^2. All parameters are retrieved each second. This acquisition frequency enabled to examine motor movements and calculated their electrical consumption. MATLAB was used to analyze experimental data and to present results. To facilitate the comparison of results regardless of the location, they are expressed in solar time rather than local time.

The LabVIEW program continuously calculates elevation and azimuthal angles of the sun from the location, date and time according to the standard theory presented by Duffie and Beckman (2006). In automatic mode, during solar tracking, both motors have to fit their angles to match with the sun angles.

4.2 Threefold Testing Procedure

4.2.1 Stage 1: 57° Titled and Horizontal Positions

The first step of the experiment was to reproduce the experiment conducted by Kelly and Gibson (2006) to ensure that similar results could be obtained in Montreal. Measurements took place between the February 11th and 18th 2014 and between February 28th 2014 and March 6th 2014. As this test was conducted in winter, the panel with a solar tracker was tilted 60 ° to the horizontal and facing south. The second PV panel was horizontal and fixed.

Contrary to the study of Kelly and Gibson (2009), incident solar radiation on the two panels was measured between 12 h and 13 h (solar time) and not by the civil time. By integrating these values over a period of one hour, it is possible to calculate the experimental hourly solar energy incident on each panel and to estimate the “rough” tracking advantage, *TA*, with a similar equation than the one proposed above:

$$TA = \frac{I_{T-60^\circ} - I_H}{I_H} \tag{9}$$

4.2.2 Stage 2: Solar Tracking in Short-Circuit

In the second step of the experiment, the dual-axis solar tracker was used to compare the benefit of a solar tracking system with a fixed horizontal panel. PV panels were connected in short-circuit and measurements of current have been carried out between April 23rd and May 5th and between May 28th and June 8th 2014. The tracking advantage, *TA*, was calculated from the short-circuit currents generated using a modified Eq.(9).

$$TA_H = \frac{SC_{DTS} - SC_H}{SC_H} \tag{10}$$

4.2.3 Stage 3: Solar Tracking with Resistive Loads

The last step of the experiment took place between May 6th and 26th and between June 10th and July 4th 2014. In order to be close to real conditions of use of PV panels, electrical resistive loads have been installed to each PV panels. Their characteristics are detailed in Table 2.

Table 2: Characteristics of Resistive Loads

Manufacturer	Vishay Dale
Type	HLZ30007Z8R000KJ
Resistance	8 Ω
Power	300 W
Tolerance	±10%

Since voltages and currents were measured, the power dissipated in each of the resistive loads has been calculated. Tracking advantage has been estimated with energy produced by the two PV panels with Eq.(8).

The use of resistive loads allows to quickly and simply calculating an energy production, however, this production is by far not optimized as it is far from the maximum power point of the panels that would be possible to meet with a MPPT circuit. As a result, the energy produced and reported here is low, especially as the days chosen are overcast. But these low values do not impair the whole test procedure. Fig. 3 illustrates how the dissipative resistance are far from the maximum power tracking point.

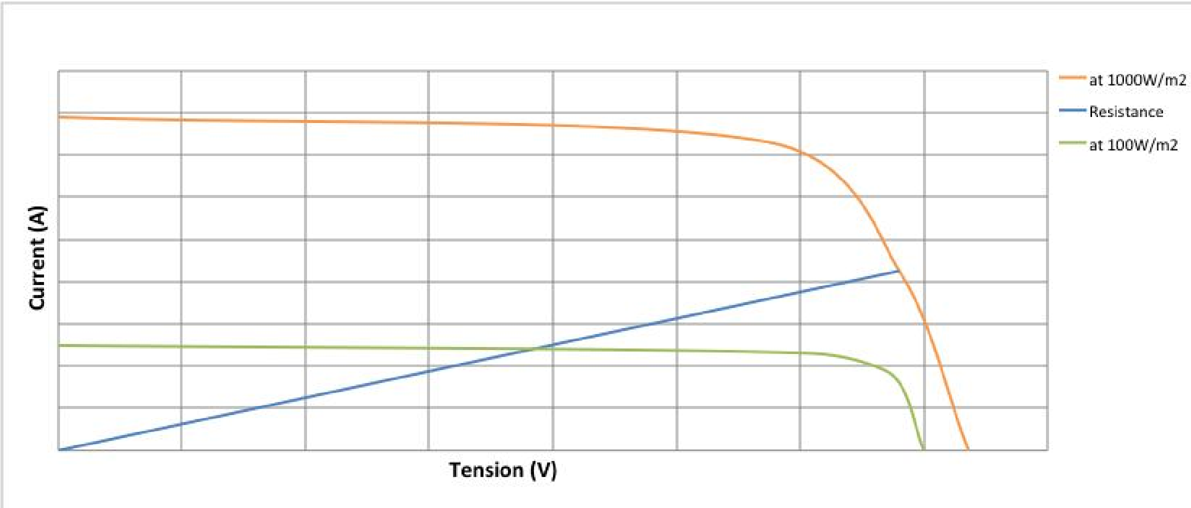

Fig.3: Example of IV Curve with Resistive Load

5. Results and Discussions

5.1 Stage 1: 60° Titled and Horizontal Position

In Table 3, columns labeled “I_H” and “$I_{T\text{-}57°}$” indicate, respectively, the experimental values of hourly global radiation on horizontal and on tilted surfaces integrated between 12h and 13h (solar hour). The column “*TA*” indicates the tracking advantage calculated from these parameters with Eq. (9).

Table 3: Tracking Advantage for Global Hourly Solar Radiation at Solar Noon for an Inclination of 57° and Several Cloudy Days of Early 2014

Day	I_H (Wh/m^2)	$I_{T\text{-}57°}$ (Wh/m^2)	*TA* (%)
12/02	215.9 ± 1.4	181.4 ± 1.2	-16.0 ± 0.8
14/02	295.2 ± 1.4	247.3 ± 1.2	-16.2 ± 0.6
15/02	78.8 ± 1.4	63.5 ± 1.2	-19.4 ± 2.1
27/02	95.6 ± 1.4	72.9 ± 1.2	-23.8 ± 1.7
28/02	344.7 ± 1.4	304.2 ± 1.2	-11.7 ± 0.5
02/03	232.7 ± 1.4	179.0 ± 1.2	-23.1 ± 0.7
04/03	454.3 ± 1.4	437.8 ± 1.2	-3.63 ± 0.40

For cloudy days, results presented in Table 3 clearly show that it was disadvantageous to tilt the PV panel surface at 60 ° between 12 h and 13 h (solar time). Indeed, during this test, horizontal PV panel received between 3.63% and 23.8% more solar radiation than the tilted PV panel.

5.2 Stage 2: Solar tracking in short-circuit

In Table 4, columns “I_c” and “I_H” show, respectively, the critical hourly solar radiation obtained by the theoretical method and the incident solar radiation on the horizontal surface measured experimentally. Columns "SC_H” and “SC_{DTS}” correspond, respectively, to the average values of short-circuit current generated in one hour by the fixed horizontal and the tracking panels. Then, the tracking advantage, in the last column, is calculated directly from the short-circuit currents with the Eq. (10).

Table 4: Tracking Advantage for Average Hourly Short-Circuit Current for May 28th 2014 Based on Solar Time

Day	Hour	I_c (Wh/m^2)	I_H (Wh/m^2)	SC_H (A)	SC_{DTS} (A)	TA (%)
	6h	131.2	30.3 ± 1.4	0.2533 ± 0.0026	0.1871 ± 0.0020	-26.1 ± 1.1
	7h	223.9	32.9 ± 1.4	0.3264 ± 0.0033	0.2522 ± 0.0026	-22.7 ± 1.1
	8h	318.1	47.2 ± 1.4	0.4903 ± 0.0049	0.4152 ± 0.0042	-15.3 ± 1.2
	9h	404.0	91.4 ± 1.4	0.790 ± 0.008	0.739 ± 0.007	-6.5 ± 1.3
	10h	472.6	73.1 ± 1.4	0.639 ± 0.006	0.612 ± 0.006	-4.4 ± 1.4
	11h	516.8	89.3 ± 1.4	0.798 ± 0.008	0.766 ± 0.008	-4.1 ± 1.4
	12h	532.1	88.6 ± 1.4	0.786 ± 0.008	0.742 ± 0.007	-5.6 ± 1.3
	13h	516.8	235.9 ± 1.4	2.039 ± 0.020	1.892 ± 0.019	-7.2 ± 1.3
	14h	472.6	378.4 ± 1.4	3.149 ± 0.032	2.8886 ± 0.029	-8.4 ± 1.3
	15h	404.0	188.7 ± 1.4	1.585 ± 0.016	1.273 ± 0.013	-19.7 ± 1.1
	16h	318.1	76.1 ± 1.4	0.643 ± 0.007	0.435± 0.0044	-32.3 ± 1.0
	17h	223.9	119.7 ± 1.4	0.975 ± 0.010	1.221 ± 0.012	25.1 ± 1.8
	18h	131.2	44.2 ± 1.4	0.3592 ± 0.0037	0.3228 ± 0.0034	-10.1 ± 1.3
	Total	**4665.3**	**1511.5 ±19.6**			

Table 4 confirms again that it is disadvantageous to follow the Sun during cloudy days. Indeed on May 28th, the horizontal panel has produced, most of the time, more current than the solar tracker (between 4.1% and 32.3%). In overcast days, the most important disadvantages are obtained at sunrise and sunset when the tracking PV panel is much tilted and "sees" just a part of the sky. Conversely, at solar noon, the sun is at its highest position, and the tracking PV panel tilt is low and similar to that of the horizontal one; the minimum value of the disadvantage is obtained near solar noon.

According to the I_c value, tracking advantage should always be negative on May 28th; yet this is not the case between 17 and 18h. Between 17h and 18h, the positive value for the tracking advantage (25.1%) was obtained due to scattered sunny periods although the cumulated values of I_H were below I_c. Indeed, the theoretical model is based on the hypothesis of an isotropic sky and therefore is only valid in cloudy periods. I_H was 119,7 Wh/m^2 for the hour comprised between 17h and 18h while it was only 76,1 Wh/m^2 for the previous hour and 44,2 Wh/m^2 for the next.

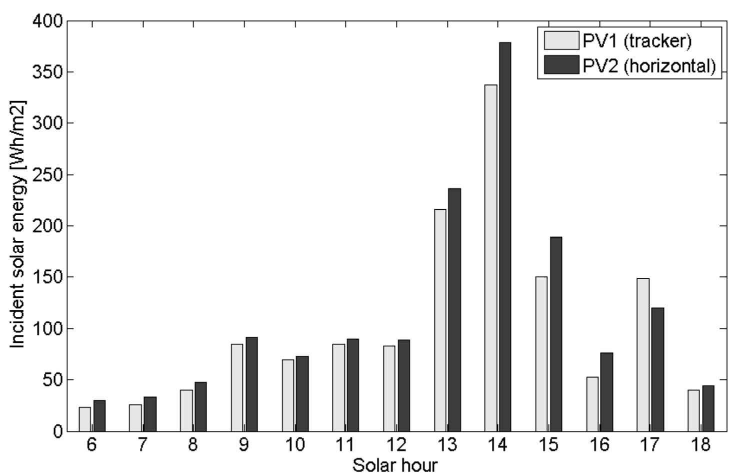

Fig.4: Incident solar Energy on the PV Panel Surfaces for Cloudy Day (28/05/2013)

Fig. 4 shows the amount of incident solar energy received by each PV panel for May 28th. The results for the hourly integrated solar radiation on the tracking and fixed surfaces confirm those expressed in terms of energy production reported in Table 4. The amount of incident solar energy on the horizontal surface (dark vertical bars) is higher than that on the tracking surface (light vertical bars) except between 17h and 18h.

Tests were carried out for a total period of two months with the short-circuit currents. Over that period, four completely overcast days were selected to assess the validity of the theoretical methodology. Comparison between the calculated critical hourly solar radiation, I_c, and measured incident solar radiation on the horizontal surface, I_H, were done over a 51 hours period. Whenever $I_c > I_H$, a negative *TA* was found and that 98% of the time.

5.3 Stage 3: Solar Tracking with Resistive Loads

Table 5 shows the calculated hourly values of critical solar radiation, I_c, and experimental values of the solar radiation on the horizontal panel, I_H, for each solar hour of the day. In addition, columns 5 and 6 indicate the energy production of the two PV panels connected to the dissipative resistances. This energy production is used to estimate the "net" tracking advantage with Eq. (5) during this third series of tests.

Table 5: Tracking Advantage for Global Hourly Energy Production, with Resistive Loads, For June 11th 2014 Based on Solar Time

Day	Hour	I_c (Wh/m^2)	I_H (Wh/m^2)	E_H (Wh)	E_{DTS} (Wh)	*TA* (%)
	6h	130.6	27.4 ± 1.4	0.321 ± 0.010	0.147 ± 0.007	-54.0 ± 2.7
	7h	223.5	47.3 ± 1.4	1.193 ± 0.023	0.069 ± 0.016	-42.4 ± 1.7
	8h	317.9	56.4 ± 1.4	1.907 ± 0.031	1.364 ± 0.025	-28.5 ±1.7
	9h	404.0	51.0 ± 1.4	1.583 ± 0.027	1.460 ± 0.026	-7.8 ± 2.3
	10h	472.8	50.0 ± 1.4	1.472 ± 0.026	1.444 ± 0.026	-1.9 ± 2.5
	11h	517.1	59.5 ± 1.4	2.072 ± 0.033	2.008 ± 0.032	-3.1 ± 2.2
	12h	532.4	48.8 ± 1.4	1.515 ± 0.026	1.375 ± 0.025	-9.2 ±2.3
	13h	517.1	57.0 ± 1.4	1.049 ± 0.033	1.621 ± 0.028	-20.9 ± 1.9
	14h	472.8	77.1 ± 1.4	3.61 ± 0.05	2.440 ± 0.037	-32.4 ± 1.4
	15h	404.0	64.8 ± 1.4	2.454 ± 0.037	1.379 ± 0.025	-43.8 ± 1.3
	16h	317.9	40.2 ± 1.4	0.872 ± 0.019	0.364 ± 0.011	-58.3 ± 1.6
	17h	223.5	28.2 ± 1.4	0.376 ± 0.012	0.131 ± 0.007	-65.1 ± 2.0
	18h	130.6	16.4 ± 1.4	0.091 ± 0.005	0.0299 ± 0.0031	-67.0 ± 3.9
	Total	**4664.2**	**639.7±19.6**	**17.10±0.31**	**12.42±0.25**	**-27.37±0.15**

As shown in Table 5, on June 11th 2014, there was no advantage to track the sun position. Indeed, the horizontal PV panel produced 27.4% more electrical energy than the solar tracking one. As expected, the most important disadvantage (67.0%) was obtained between 18 h and 19 h and the lowest (3,1%) between 11h and 12h. The value between 10h and 11h (-1.9 ± 2.5%) impedes any conclusion on the advantage because the measurement uncertainty is higher than the measurement. Here one should recall that the amount of energy produced by the panels is not representative of that obtained with an inverter as the working point is very different than optimum. Nevertheless, the set-up allows concluding of the relative production of each panel. The hourly critical incident solar radiation is always higher than the incident solar radiation on the horizontal surface. Here again, whenever $I_c > I_H$, a negative *TA* was found.

There were eight overcast days during the third test stage involving the dissipative resistances as a load, during 90 hours of these days, the value of critical incident solar radiation was higher than the total incident solar radiation on the horizontal surface ($I_c > I_H$). According to the theoretical methodology, 96% of this ratio coincides with a predictive negative value of the tracking advantage.

Study of radiation measurements permitted to find out that discrepancies between the experimental results and the theoretical method (in this case, 4% of measurements) occurred mainly in the early morning or late afternoon. These differences could be due to the fact that the theoretical method assumes that the entire hour is cloudy (isotropic sky). However, in reality the differences could be caused by sunny periods that had been observed. These sunny breaks play an important role during sunrise and sunset because for these periods of the day there is a high difference between the two PV panel angles.

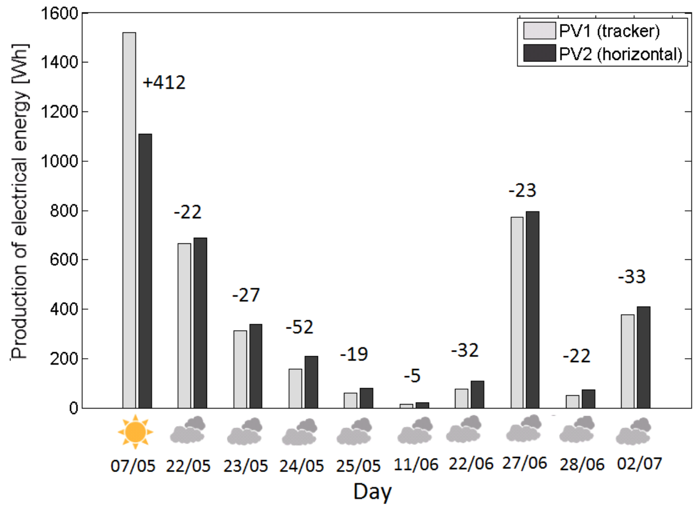

Fig.5: Electricity Generated by the two Panels and Difference between these Two Productions for Several Days

Fig. 5 shows the amount of electrical energy produced by the two panels and the difference between them for several days of the third part of the experiments. May 7th, 2014 was a completely sunny day and the solar tracker produced 1521Wh. That is 412Wh more than the production of the fixed horizontal panel. These values provide an overview of the magnitude of the difference in electricity production during sunny days. However, in general, fixed PV panels are tilted and not in horizontal position, so this difference should be a little bit less on a real setup where the fixed panels are tilted. The other results shown in Fig. 5 are all for cloudy days. For some of them (22 May and 27 June), the amount of energy produced is about half that produced during a sunny day, while for others this amount is very small. Detailed analyses of the results have shown that when the power generation exceeds the 200Wh, it is due to sunny periods during the day. During very low electrical production days (24/05, 25/05, 11/06, 22/06, 28/06), the sky was overcast without any sun apparitions along the day. On cloudy days, the horizontal PV panel produced between 5Wh and 52Wh more electricity than the solar tracker. According to the first observations, the type of clouds predominant could cause this variation (for example: cumulus, nimbus, stratus, cirrus, etc.).

When these results are extrapolated to a typical installation of 10kW, like these installed in Ontario (composed of 48 PV panels), the surplus electricity production would be between 240Wh and 2.5 kWh, equivalent to at least one additional PV panel.

6. Conclusion

The main objective of this work was to validate, with a real PV system, the relevance of the concept of critical hourly solar radiation. In this paper, three different experiments were carried out in Montreal to measure the incident radiation and the production of electrical energy of two PV panels. One PV panel was always in a fixed horizontal position and the other one was used in a tilted fixed position (stage 1) and with a dual-axis tracker (stages 2 and 3).

Results obtained in the first stage of tests confirmed the statements of the study realized by Kelly and Gibson (2009), that horizontal surfaces are more irradiated than tilted surfaces on cloudy days at solar noon. In this study, the tilted PV panel is between 3.63% and 23.8% less irradiated than the horizontal PV panel. This percentage depends of the type of clouds present during tests.

Then, second phase results shown that short-circuit current generated by PV panel tracking is up to 14% lower than those produced by horizontal PV panel, during cloudy days. Once again, it is better to fix PV panel in horizontal position on overcast conditions.

Lastly, thirst stage results, which are the nearest of actual conditions of PV use, confirm that solar tracking panels could produce up to 25% less than fixed horizontal panels during cloudy days in the spring study period.
In winter, disadvantage would probably be higher because of the lower altitude of the sun and the high tilt angle of the panel.

In summary, all data confirmed the interest of the theoretical methodology since when the experimental cumulated incident solar radiation was lower than the critical radiation I_c, the advantage of solar tracking was negative in 96% of the cases. However, there are limits to this method utilization because it applies only in cases where, for an hour, the sky can be considered isotropic (completely overcast day). It would be necessary to test is application more extensively during sun apparition periods when disadvantage have been observed.

Future experiments will be conducted with the PV solar tracker connected on Hydro-Québec network. These will determine, during one year, if the proposed strategy significantly increases the amount of electrical energy produced.

Finally, work is also underway to develop a predictive algorithm based on weather forecasts, which orient the PV panels in the position that maximizes electrical energy production.

Acknowledgements

The authors gratefully acknowledge Michel Drouin as well as company Dyco Solar for their participation in this project and the partners of the t3e research chair for their financial support.

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