Effects of Surroundings Snow Coverage and Solar Tracking on PV Systems Operating in Canada

Mostafa Mehrtash[1,2,a)], Daniel R. Rousse[1,2], and Guillermo Quesada[1,2]
[1]*Department of Mechanical Engineering, École de Technologie Supérieure, Montréal, H3C-1K3, Canada*
[2]*Industrial Research Chair in Energy Technologies and Energy Efficiency (t3e), 201 Boul. Mgr Bourget, G6V- 6Z3, Lévis, QC, Canada*

This paper deals with demonstrating the energy performance of solar tracking photovoltaic (PV) systems in Canada. In this study, a grid connected stand-alone PV system has been designed and coupled with four different tracking systems: fixed horizontal, fixed tilted, single-axis tracking, and dual-axis tracking. The performance analysis of the systems focuses on the variation of array irradiance, electricity generation and efficiency without considerations for economic impacts at this stage. The simulation results show that the dual-axis tracking array provides the best performance over a year. It receives 33% more solar radiation and generates 36% more electricity than the tilted system. On clear winter days, compared to the tilted system, the dual-axis tracking system produces 32% and 29% more electricity in high albedo and low albedo conditions, respectively. High albedo due to surroundings snow coverage has been found to cause an increase of 3.1%, 5.8%, and 7.9% in electricity production of the tilted, single-axis tracking and dual-axis tracking system respectively, over a winter. The results of this research support the idea that tracking the sun is effective on clear days, and could be counterproductive on overcast days. Therefore, in high albedo conditions, it is recommended to track the sun and stay fixed once the sky becomes overcast.

I. INTRODUCTION

The past decade has seen the rapid advancement of solar technology to fulfill the needs for electricity. The quantity of energy produced by PV systems depends on the solar radiation captured by the modules. Tracking the sun allows the PV panels to capture the maximum solar radiation by minimizing the solar incidence angle. Tracking can be basically done along two axes: azimuth or horizontal (from sunrise to sunset) and zenith or vertical (depending on the height of the sun). Solar trackers operate by using a mechanical mechanism (passive) or an electrical mechanism (active).[1, 2] Active trackers can be basically classified as sensor based (electro-optical and bifacial solar cell) and date-and-time (astronomic) based. This study considered the astronomic tracking.[3]

Previous research around the world shows 20% to 50% more solar recovery by using solar trackers as compared to fixed systems.[4-9] Helwa et al.[10] studied four different orientations of PV systems to improve the captured solar radiation: fixed system facing the south and tilted at 40°, vertical-axis tracker, tracker with 6° tilted axis parallel to the north-south direction, and dual-axis tracker. One year measurements of solar radiation and electricity production of these systems shows an increase of 11%, 18%, and 30% in captured radiation by azimuth, north-south, and dual-axis trackers, respectively, over the stationary system. These systems have operated in Germany which is located at 48° latitude.

Salah Abdallah[11] studied four different tracking PV systems operating in Amman, Jordan (latitude of 32°): dual-axis, vertical-axis, east-west, and north-south. These systems have been compared to a fixed system tilted at 32°. The results show 43.9%, 37.5%, 34.4%, and 15.7% more output power for the dual-axis, east-west, vertical-axis, and north-south tracking system, respectively.

In Northern Algeria (latitude of 36.8°), tracking the sun is very effective during clear days. A dual-axis tracking system produced 25%-53% (proportional to radiation intensity) more electricity than a fixed system tilted at yearly optimum angle.[12]

[a)] Corresponding author. E-mail: mostafa@t3e.info. Tel.: (514) 975-5473.

Although dual-axis trackers follow the sun more precisely, they increase the initial cost and complexity of the system. A single-axis tracker is considerably simpler and cheaper than a dual-axis one. Compared with a fixed system tilted at yearly optimum angle in China, a vertical-axis tracking PV system can capture 28% more solar radiation in areas with abundant solar resources and 16% more in areas with inadequate solar resources. In addition, an optimal vertical axis tracker can capture 96% of the annual solar radiation captured by a dual- axis tracker.[13]

Huang and Sun[14] designed a new single-axis three position tracker having a simple structure and low cost. This tracking method adjusts the panels three times in a day: morning, noon, and afternoon. The proposed method produces 24.5% more output power than a fixed system tilted at latitude angle (25°). Daily experiments show that this tracking method can provide an almost similar performance as a dual-axis tracking system in Taiwan. The long-term experiments show that this tracking system can perform very similarly to the single-axis continuous tracking system.[15] However, it could be cumbersome to adjust the system three times per day.

Tomson proposed a daily two-positional tracking method for a high latitude location (Estonia 60°) that is simple and requires minimum energy. The seasonal yield is increased by 10-20% over the yield of a fixed system tilted at an optimum angle.[16]

On the other hand, tracking the sun is not necessary during overcast days. The fixed systems can produce almost the same amount or even 10% more electricity than the tracking systems. During partially clear days, depending on the clearness index, tracking the sun could be useful or counterproductive.[12]

An experimental study[17] at the General Motors Proving Ground in Milford, USA (latitude of 42°) shows that a tracked PV system captures twice as much solar radiation as a horizontal system on sunny days. However, during cloudy periods, tracking the sun is counterproductive since the main part of the solar radiation is diffused. The authors reported that on cloudy days a horizontal PV system can capture 50% more solar radiation than a tracking system.

Kelly and Gibson[18] measured the solar irradiance of PV systems during overcast periods. They utilized six sensors to measure the irradiance upon a horizontal (H) and a dual-axis tracking (DT) system which looks directly toward the sun. The following equation was prepared to define the tracking advantage (TA) of a dual-axis tracking system versus a horizontal system.

$$TA_{DT-H} = \frac{\left(1-\frac{H}{DT}\right)}{\left(\frac{H}{DT}\right)} \tag{1}$$

In 2010, the Canadian Solar Industries Association (CanSIA) published the eagerly expected strategy for the future entitled "Solar Vision 2025".[19] According to this, the total installed PV capacity in Canada was almost 66 MW in 2009 and it could reach between 9 and 15 GW by 2025. Numerous companies participated actively in the Ontario program section entitled "Micro feed-in tariff". The conference mainly focused on sun tracking PV systems and their performance in Canada.

However, there is a lack of studies about the performance of PV tracking systems in Canada. Performance of PV systems also depends on local climate conditions and Canada has particularly severe weather conditions. Several environmental parameters affect the performance of PV systems operating in this geographical position such as very low ambient temperature, frost, ice, and snowfall.

The primary objective of this research is to carry out the performance analysis of sun tracking PV systems operating in Toronto, Canada. Meanwhile, the advantage of tracking is investigated in monthly and daily periods with the purpose of determining the best and worst conditions for sun tracking.

Four different configurations of PV systems are presented in this work: horizontal, inclined, single-axis tracking, and dual-axis tracking. The simulations have been carried out with PVSOL Pro 4.5 for daily and monthly periods. PVSOL is a product of Valentin Energy Software Company. This software is able to use either a linear or dynamic temperature model. In this study, since the wind speed was included in the climate data record, the module temperature has been calculated based on the dynamic temperature model. Performance modeling is available for the following module technologies: c-Si, CdTe, CiS, Ribbon, HIT, and μc-Si. The source of the used irradiation data is coming from synthetically generated hourly values. The program could either useMeteoSyn, Meteonorm, PVGIS, NASA, SSE, and SWERA. The data base used herein is Meteonorm 6.1 embedding at least 5 years of daily data.

This paper is organized as follows. Section 2 introduces some of the fundamentals of incident solar radiation and calculations of solar incidence angles of different surfaces. Section 3 explains the designed systems, assumptions, and simulated scenarios. Section 4 presents and discusses the results of the simulations. Finally, section 5 summarizes the results and presents the conclusions of the study.

II. FUNDAMENTALS OF SOLAR RADIATION INCIDENT UPON PV SYSTEMS

Here, the fundamentals of incident solar radiation are briefly reviewed. The radiation outside the earth's atmosphere is called extraterrestrial radiation (G_{on}). There are several conflicting reports about the accurate amount of extraterrestrial radiation. Duffie and Beckman present an equation that gives an almost accurate amount of extraterrestrial radiation as a function of the day number (n). The solar constant (G_{sc}) has been estimated as 1367W/m^2 with an uncertainty in the order of 1%.[20]

$$G_{on} = G_{sc} \cdot \left[1 + 0.033 \cos\left(\frac{360n}{365} \right) \right] \tag{2}$$

Hourly extraterrestrial solar radiation (Wh/m^2) upon a horizontal surface between sunrise (ω_1) and sunset (ω_2) can be represented by

$$I_o = \frac{12 \cdot G_{sc}}{\pi} \cdot \left[1 + 0.033 \cos\left(\frac{360n}{365} \right) \right] \cdot \left[\cos\varphi \cdot \cos\delta \cdot (\sin\omega_2 - \sin\omega_1) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin\varphi \cdot \sin\delta \right] \tag{3}$$

where φ is the latitude of the location which is equal to 43°40`N for Toronto and δ is the declination angle that can be derived as

$$\delta = 23.45 \sin\left(2\pi \cdot \left(\frac{284 + n}{365} \right) \right) \tag{4}$$

Solar hour angle (ω) is the 15° per hour of angular displacement of the sun from local meridian with positive value in the afternoon and negative value in the morning. The local standard meridians (LSM) are located at 15° intervals from the Greenwich meridian (longitude 0°). The LSM for Toronto is 75°W which means that the local time is 5 hours behind Greenwich Time. LST is the local solar time which can be calculated by using the time corrections.

$$\omega = 15(LST - 12) \tag{5}$$

Incident hourly solar radiation on each surface consisted of three components: direct (beam) radiation, diffuse radiation, and reflected radiation from the other surfaces seen by this plane, that can be expressed as

$$I_T = I_{T,b} + I_{T,d} + I_{T,refl} \tag{6}$$

The incident solar radiation upon a surface is a function of the tilt angle and azimuth angle. The maximum absorption of solar radiation occurs when the panel surface is perpendicular to the direct sun's rays (θ=0). Several attempts have been made to calculate the solar radiation on surfaces. Basically, two main types of models have been presented, isotropic sky and anisotropic sky. In isotropic sky models, like Hottel's (1942), it is assumed that all diffuse radiation is uniformly distributed over the sky dome and that reflection on the ground is diffused. Circumsolar and horizon brightening are assumed to be zero[21].

Liu and Jordan (1963) derived the isotropic diffuse model which is more precise. It illustrates that the radiation on a tilted surface is consisted in three components: direct, isotropic diffuse, and reflected from the ground. This model is easy to understand but it also embeds an underestimation. The isotropic sky model assumes that the intensity of diffuse radiation is uniform over the whole sky. Therefore, the incident diffuse solar radiation on a tilted surface depends on the fraction of sky seen by it. To calculate the incident reflected radiation from the ground, the field of view seen by the surface is considered as a diffuse reflector[22].

Anisotropic sky models take into account the circumsolar diffuse and/or horizon-brightening components. Hay and Davies (1980) estimated an anisotropic sky model in which diffuse radiation from the sky is composed of an isotropic part and circumsolar part, but horizon brightening is neglected[23]. Hence, incident solar radiation on each surface can be presented by

$$I_T = I_b \cdot R_b + I_d \cdot R_d + I \cdot R_{refl} \tag{7}$$

where I_b is the hourly direct solar radiation on a horizontal surface (Wh/m^2), R_b is the geometric factor that is the ratio of direct solar radiation on an inclined surface (**FIG. 1**) to the direct solar radiation on a horizontal surface, and "· " denotes dot product. The geometric factor can be expressed as

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos(\varphi-\beta)\cdot\cos\delta\cdot\cos\omega + \sin(\varphi-\beta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\cos\omega + \sin\varphi\cdot\sin\delta} \tag{8}$$

θ_z (zenith angle) is the angle between the line to the sun and the zenith (**FIG. 1**). R_d is the factor of angle for an inclined surface to the sky at any time that is presented by

$$R_d = \frac{1+\cos\beta}{2} \tag{9}$$

I is the summation of hourly direct and diffuse radiation on a horizontal surface. R_{refl} is the factor of angle for an inclined surface towards the ground that depends on the ground reflection coefficient (ρ_g). It is particularly interesting to account for this factor in the current analysis because the effect of snow on the ground in winter months is investigated by use of a simple model

$$R_{refl} = \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \tag{10}$$

The anisotropic sky model divides the sky into two zones, a zone for part of the sky around the sun (circumsolar area) and one for the remaining portion of the sky. The diffuse solar radiation from the circumsolar area is projected onto the inclined surface in the same manner as direct solar radiation. Therefore, R_d is represented by

$$R_d = \left[(1-A_i)\cdot\left(\frac{1+\cos\beta}{2}\right) + A_i \cdot R_b\right] \tag{11}$$

To compare the circumsolar and isotropic radiation the anisotropic index (A_i) is defined by

$$A_i = \frac{I_b}{I_o} \tag{12}$$

FIG. 1 presents the relations between the sun's angles used to define the amount of solar energy that strikes an arbitrarily oriented surface on earth. In **FIG. 1**, θ is the incidence angle of direct radiation on a fixed surface that can be presented by

$$\cos\theta = \sin\delta \cdot \sin\varphi \cdot \cos\beta - \sin\delta \cdot \cos\varphi \cdot \sin\beta \cdot \cos\gamma + \cos\delta \cdot \cos\varphi \cdot \cos\beta \cdot \cos\omega + \cos\delta \cdot \sin\beta \cdot \sin\gamma \cdot \sin\omega \tag{13}$$

For a single vertical axis tracking (azimuth tracking) plane the incidence angle of direct radiation is

$$\cos\theta = \cos\theta_z \cdot \cos\beta + \sin\theta_z \cdot \sin\beta \tag{14}$$

The slope of the plane is fixed, therefore β is constant. The incidence angle of beam radiation of a tilted axis north-south tracking plane which is parallel to the earth's axis and adjusted continuously can be represented by

$$\cos\theta = \cos\delta \tag{15}$$

The slope that varies continuously can be presented by

$$\tan\beta = \frac{\tan\varphi}{\cos\gamma} \tag{16}$$

Incidence angle of direct radiation of a dual-axis solar tracking plane and its tilt angle variation are represented by the following equations:

$$\cos\theta = 1 \tag{17}$$

$$\beta = \theta_z \tag{18}$$

Eqs. (2-18) altogether form the mathematical description which is used herein to produce the estimates of solar radiation on surfaces arbitrarily oriented anywhere on earth.

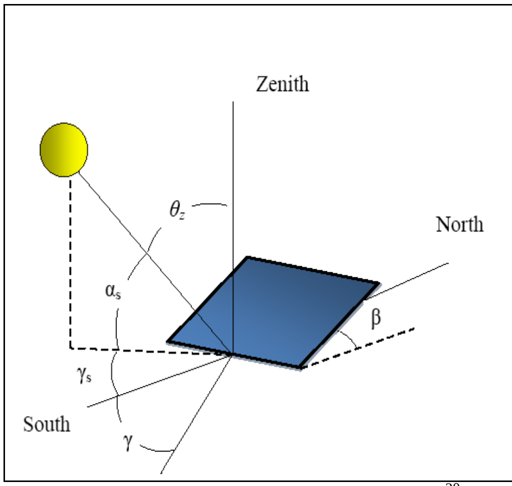

FIG. 1. Sun angles used in the nomenclature.[20]

III. NUMERICAL ANALYSIS DESCRIPTION

Four different grid connected stand-alone PV systems operating under the climate conditions in Toronto have been designed and analyzed. Toronto is located at the latitude of 43° 40´ N and longitude of 79° 24´ W. Its climate is classified as humid continental with warm summers and cold winters.[24]

Each array consists of 48 Si Polycrystalline 300W typical PV modules. They are connected to each other in four series outline and each series consists of 12 modules. The system has four 4.60kW KACO new energy inverters that convert the DC current from the arrays into AC current compatible with electrical appliances. Each system has a total capacity of 14.40kW and total PV area of 92.1m^2. The efficiency of PV panels under standard test conditions (STC) is 15.6%. The module's temperature coefficient of power is -0.45%/K. This data is directly introduced into the model for the four tracking strategies and for different albedos in the winter according to the presence of snow or not.

The performance analysis of the systems focuses on arrays irradiance, electricity generation and efficiency. System efficiency is an essential parameter in demonstrating the systems performance. Efficiency presents the amount of losses involved and how well the system converts solar radiation into electricity. Inefficiencies are attributed to: module mismatch, diodes, wiring and connections, snow cover, air pollution, high operating temperature, and conversion of electricity from DC to AC. This work doesn't consider air pollution and trackers electricity consumption.

The first system is fixed in a horizontal position. The inclined system is a south facing system tilted at the latitude angle which is 43 ° in Toronto. The next system is a single-axis tracking PV system. Modules are adjusted at the tilt angle of 51°, which was calculated as the yearly optimum angle for single-axis tracking PV systems operating in Toronto. The last system is a dual-axis tracking PV system that tracks the sun continuously.

The values of the tracking advantage of a dual-axis tracking system versus the horizontal and tilted systems are calculated from Eqs. (19) and (20), respectively:

$$TA_{DT-H} = \frac{\left(1 - \frac{H}{DT}\right)}{\left(\frac{H}{DT}\right)} \quad (19)$$

$$TA_{DT-T} = \frac{\left(1-\frac{T}{DT}\right)}{\left(\frac{T}{DT}\right)} \tag{20}$$

The tracking advantage of a single-axis tracking system versus the horizontal and the tilted systems can accordingly be represented by

$$TA_{ST-H} = \frac{\left(1-\frac{H}{ST}\right)}{\left(\frac{H}{ST}\right)} \tag{21}$$

$$TA_{ST-T} = \frac{\left(1-\frac{T}{ST}\right)}{\left(\frac{T}{ST}\right)} \tag{22}$$

The above-mentioned anisotropic sky model (Hay and Davies) has been employed to estimate the hourly incident solar radiation upon the PV systems. The radiation has been split into direct and diffuse components according to Reindl's radiation model with reduced correlation[25]. Furthermore, the reflected radiation from the modules is considered in calculations. The performance of a PV system is computed by incoming radiation, module voltage at STC, and the efficiency characteristic curve.

The described PV systems have been analyzed monthly and daily. Each analysis has been done for a clear and an overcast day in both winter and summer. The selected days were chosen near the winter and summer solstices to show the maximum trends or differences between the systems for these periods. In this paper, a clear sky is assumed to involve less than 30% cloud cover, while an overcast sky has a 100% cloud cover.

During the winter in Toronto, significant amounts of snow are accumulated on the ground. Hence, reflected radiation from the ground (albedo effect) could affect the solar irradiance of inclined PV systems in rural areas. In this paper, two typical winters conditions have been simply simulated by introducing a high albedo for snowy grounds and a low albedo for areas into which snow may not play a significant role (downtown or a densely populated suburban area with high density buildings, for instance): the low albedo is set to 0.2 for winter conditions without snow coverage and the high albedo is set to 0.8 otherwise. Basically the albedo value is between 0 and 1. Fresh snow has an albedo of 0.80-0.95. In this work, it is assumed that winter spans from January to the end of March.

IV. RESULTS AND DISCUSSION

A. Annual analysis

This subsection presents the electricity production and efficiency of the systems over a complete year of simulation. The subsection first discusses the comparison of the four tracking strategies when there is no snow on the ground while the second specifically accounts for reflection from it.

1. *Average winter albedo=0.2*

In areas into which snow does not play a preponderant role as a reflector, it is assumed that the albedo has the constant value of 0.2 during the whole year. For such a condition, the annual analysis shows an increase of array irradiance of 11%, 42%, and 47% for tilted, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the fixed horizontal system.

The total electricity production of systems as compared to the horizontal array is 14%, 49%, and 54% more for tilted, single-axis tracking, and dual-axis tracking systems, respectively. The array irradiance percentage increase is not equal to the energy production percentage increase since the correlation between irradiance and relative efficiency of the PV systems is not linear.

Dual-axis tracking and single-axis tracking arrays have the highest efficiencies among these systems. The annual efficiencies are 13.1% and 13.4% for horizontal and tilted arrays, respectively, while the single-axis and dual-axis tracking systems have the efficiency of 13.7% and 13.8%, respectively.

FIG. 2 shows the electricity generation of these systems throughout a year which is the most interesting result to be used in an eventual pay-back analysis. Dual-axis tracking PV array absorbs more radiation than other arrays but, clearly in Toronto, it has an almost similar performance than the single-axis tracking system. The electricity generation of the tilted array is considerably higher than that of the horizontal one, except in summer since the sun moves across the sky through a path nearly overhead while the horizontal plane is closer to the direct radiation for a longer time. In November and December, the minimum amounts of production are observed, while the average of electricity consumption increases in winter. In **FIG. 2**, one can clearly see the poor performance due to cloudy skies in April and November.

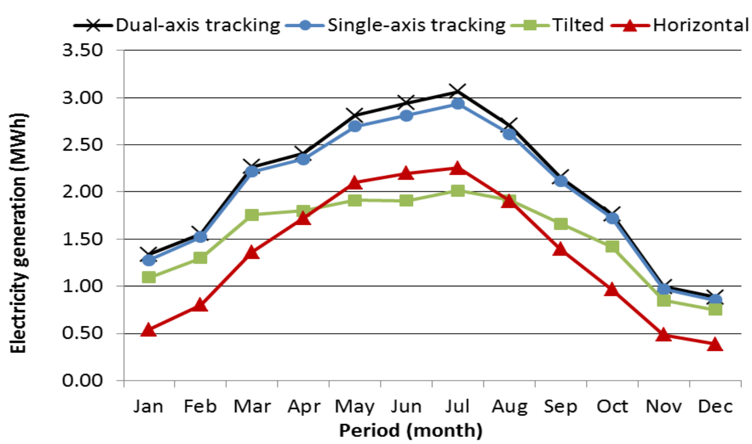

FIG. 2. Monthly electricity generation (albedo=0.2).

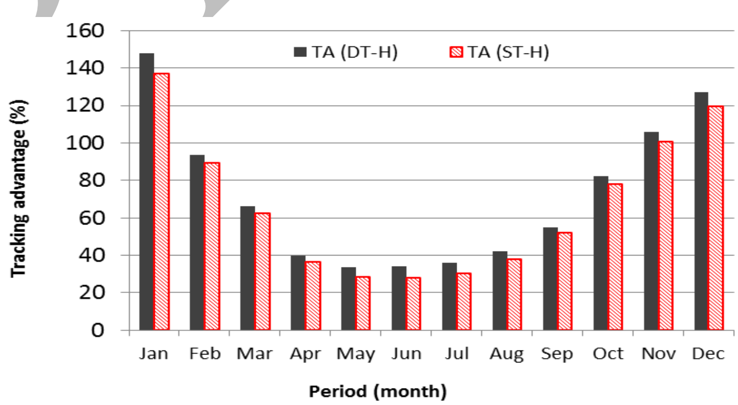

FIG. 3. Monthly tracking advantage versus the horizontal system (albedo= 0.2).

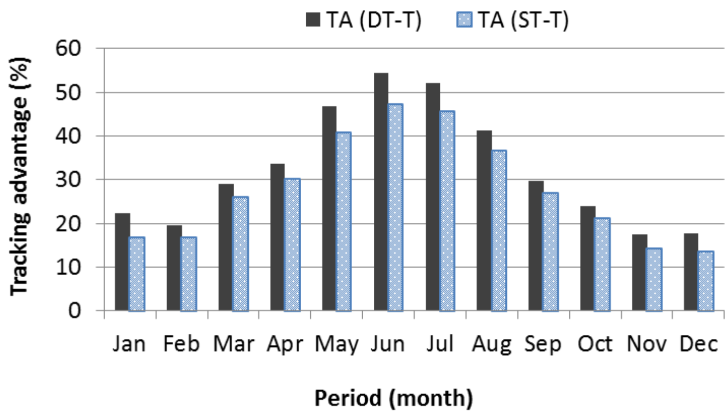

FIG. 4. Monthly tracking advantage versus the tilted system (albedo= 0.2).

FIG. 3 and **FIG. 4** show the monthly tracking advantages versus the horizontal and the tilted systems. In **FIG. 3** significantly larger tracking advantages (up to 150% on January) are observed versus the horizontal system during the winter as the sun remains quite low in the sky over the whole period, even at noon. Consequently, the dual-axis tracking system has a larger tracking advantage for all months. As it can be seen from **FIG. 4**, the tracking advantage is superior during the summer when the comparison is carried out with respect to the fixed tilted system. Hence, the situation is the opposite with a high sun in the sky at noon in June and July. Nevertheless, both figures indicate that there is not much difference between the two tracking strategies, the difference being a couple of percentage points only. The minimum advantage is always superior or nearly 15% for both tracking strategies whether the comparison is against the horizontal or tilted system.

2. Average winter albedo=0.8

This section provides the results of a year for which the average albedo is 0.8 during the winter. During January, February, and March, when the surrounding environment of arrays is covered by snow, the energy production of the systems is expected to increase, except for the horizontal system, as compared to the low albedo winter. The horizontal array is not sensitive to the change in the environment because it is facing the sky and therefore cannot absorb any reflected radiation from the ground. Here, it was assumed that there is no snow accumulation on the systems.

Once again, the dual-axis tracking system captured the highest amount of solar radiation, followed gradually by single-axis tracking, tilted and finally the horizontal system.

The monthly electricity production of the systems is shown in **FIG. 5**. The electricity production of the systems as compared to the horizontal one is 15%, 51%, and 57% more for tilted, single-axis tracking and dual-axis tracking systems, respectively. Obviously, the changes in **FIG. 5** over **FIG. 2** are for the first three months only. As a result, there is not a major change for yearly results.

As shown in **FIG. 6**, the tracking advantage is almost 30% during the summer, while it reaches 170% in January, an increase of more than 15% over what was obtained for albedo=0.2.

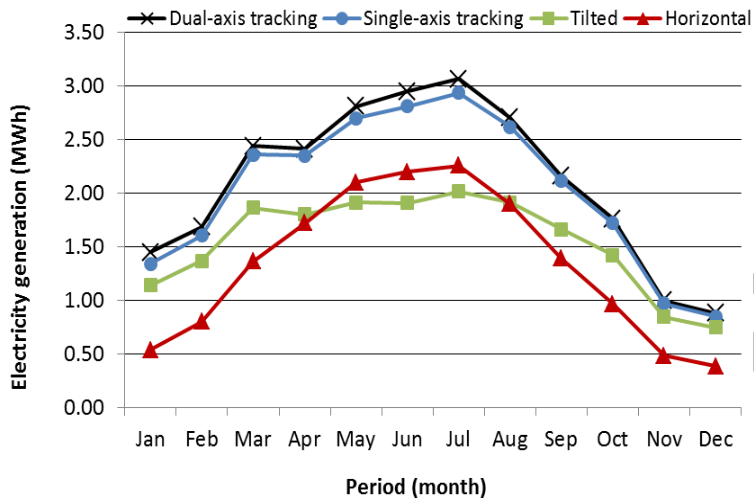

FIG. 5. Monthly electricity generation (winter albedo= 0.8).

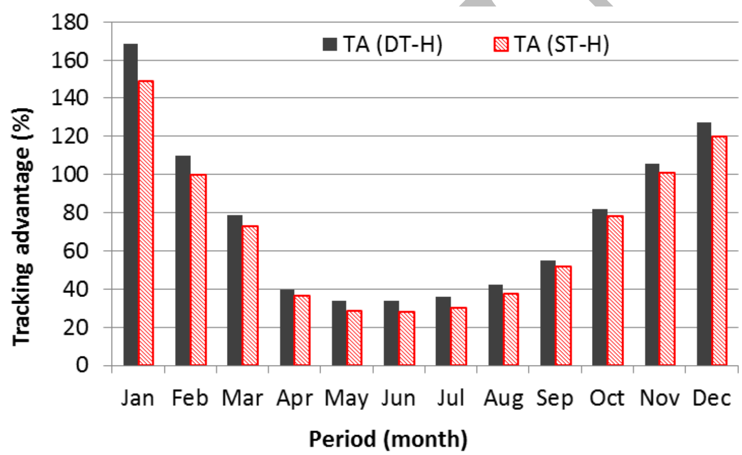

FIG. 6. Monthly tracking advantage versus the horizontal system (winter albedo= 0.8).

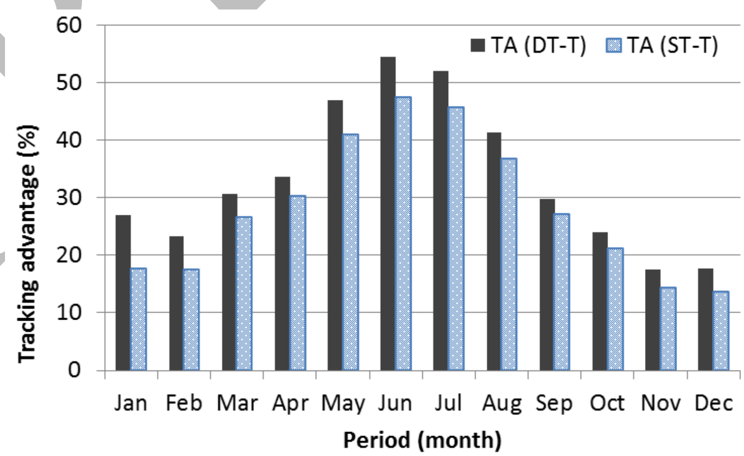

FIG. 7. Monthly tracking advantage versus the tilted system (winter albedo= 0.8).

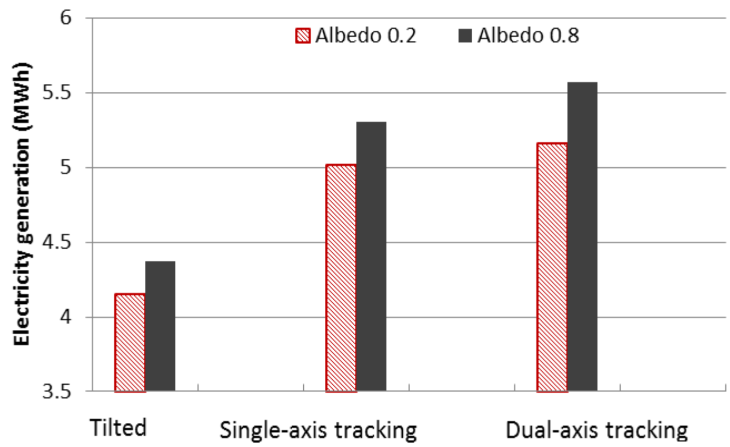

FIG. 8. Electricity generation of different systems over January, February, and March: albedo=0.2, and albedo=0.8.

FIG. 7 shows the tracking advantages versus the tilted system. During the summer we observed a larger tracking advantage, since the tilt angle of the tilted system is not optimum in the summer. **FIG. 7** shows that there is almost no difference between results for albedo=0.8 and albedo=0.2 when it comes to the comparison of tracking strategies with respect to tilted systems. One can only observe a slight (2-5%) increase for January, February, and March.

FIG. 8 summarizes the results of electricity generation during two winters, with high and low albedos. The results of these simulations, valid for the first three months of the year, show that reflected radiation from the snow causes an increase of 3.1%, 5.8%, and 7.9% in energy production over the winter for tilted, single-axis tracking, and dual-axis tracking systems, respectively. According to the results obtained from the simulations, the reflected radiation from the ground should improve the performance of PV systems operating in northern climate countries like Canada. It is worth noting that in several regions in Southern Canada, the snowfalls begin in November and that snow coverage may last until the end of April. Thus increasing the trends reported in **FIG. 8**.

B. Daily analysis

This subsection presents some results obtained from simulations for a typical winter day in the vicinity of the solstice. PV systems have been studied for clear and overcast days. Once again, winter days have been analyzed with albedo of 0.2 and 0.8.

1. Clear day

During a clear winter day with albedo=0.2, as expected, the dual axis tracking system generates more electricity than the others. Daily analysis shows an increase of energy production of up to 145%, 198%, and 218% for inclined, single-axis tracking, and dual-axis tracking arrays, respectively, as compared to the energy produced by the horizontal one (**FIG. 9**).

Large increases are reported here as the amount of energy produced by a horizontal collector is very low in latitudes as high as that of Toronto. As Toronto is located in the south of Canada, **FIG. 9** confirms that horizontal collectors are not the best suited ones for the whole country and this without regards to the possible accumulation of snow on flat surfaces in winter.

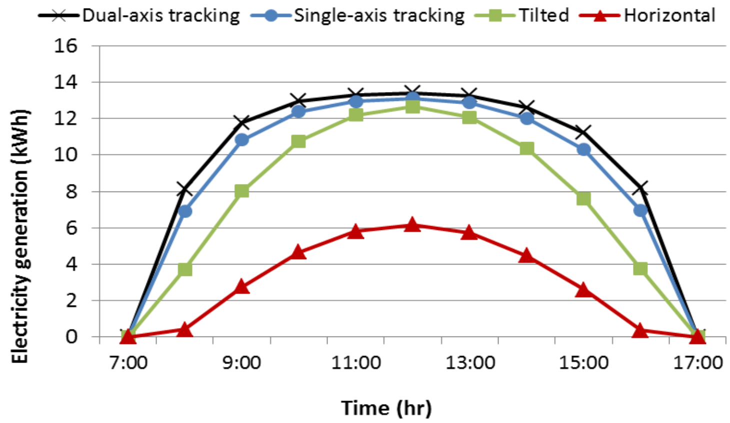

FIG. 9. Electricity generation during a clear winter day (albedo= 0.2).

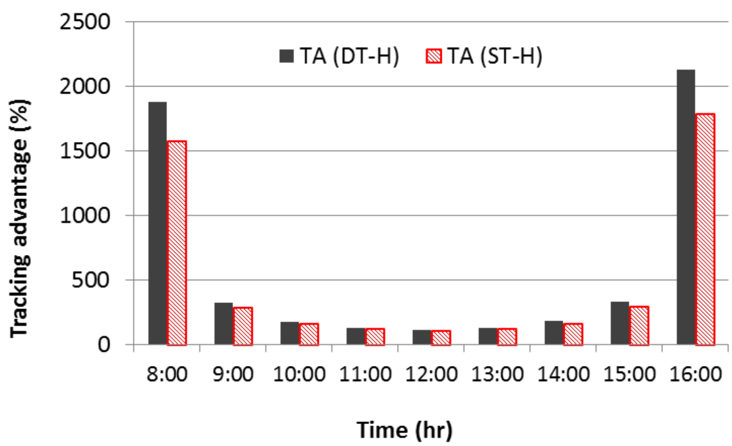

FIG. 10. Tracking advantage versus the horizontal system during a clear winter day (albedo= 0.2).

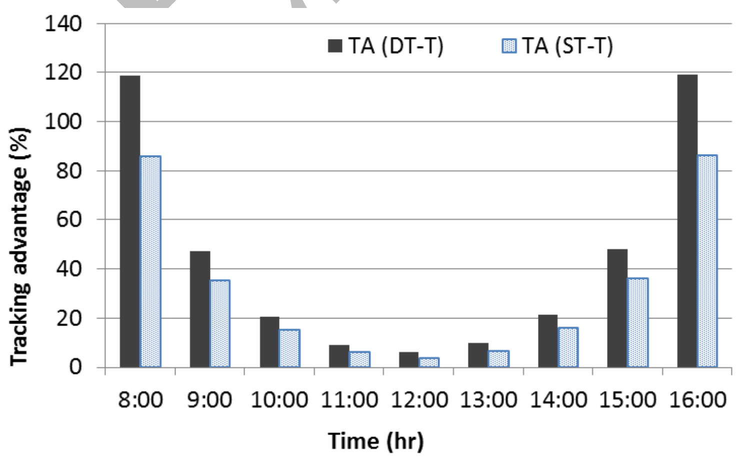

FIG. 11. Tracking advantage versus the tilted system during a clear winter day (albedo= 0.2).

FIG. 10 and **FIG. 11** show the tracking advantage of dual-axis and single-axis trackers versus the horizontal and tilted systems, respectively. Near sunrise and sunset, the tracking advantage has a very large value since the fixed systems do not look towards the sun and their production is negligible. However, at this time of the day the intensity of radiation is very low. As result, although the advantage is large, the actual gain in terms of energy is not quite important. For the rest of the day, the tracking advantage remains above 100% when compared to the horizontal system.

FIG. 12 shows the electricity production of the systems during a clear winter day with the albedo of 0.8. Comparing **FIG. 9** and **FIG. 12**, it can be seen that horizontal system's production has not been affected by the albedo variation. An increase of 3.1%, 3.3%, and 5.2% in electricity production is reported for the tilted, single-axis tracking, and dual-axis tracking systems, respectively, as compared to the clear winter day with albedo of 0.2.

FIG. 13 compares the averages of tracking advantages over a clear winter day with albedo of 0.2 and 0.8. It is apparent from this figure that increasing the albedo improves the tracking advantage versus the horizontal up to 17%. Meanwhile, a minor increase is shown in tracking advantage versus the tilted system.

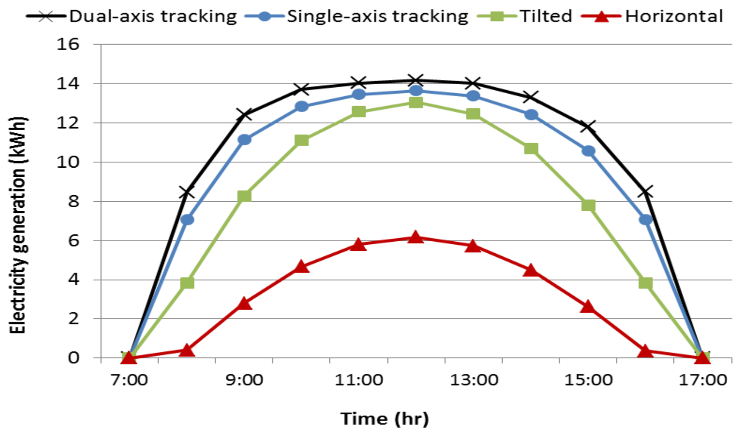

FIG. 12. Electricity generation during a clear winter day (albedo= 0.8).

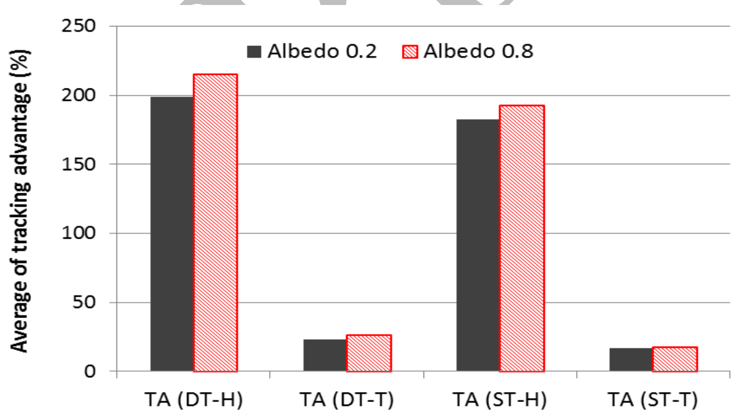

FIG. 13. Average of tracking advantages versus horizontal and tilted systems in a clear winter day.

2. *Overcast day*

FIG. 14 shows the electricity production for an overcast day in which the major part of the radiation is diffuse and the albedo is equal to 0.2. The specific irradiance in this overcast day is almost 10% of that of clear days. On an overcast day, the horizontal position is optimum. However, one should note that although this is true for this specific weather condition, the amount of electricity production for each system is very low. The maximum cumulative energy over a day is 2.5 kWh for the horizontal system. **FIG. 15** and **FIG. 16** present the tracking advantages, versus the horizontal and tilted systems, during an overcast winter day. Tracking advantage has negative values during this day, which means that tracking the sun is counterproductive during overcast days.

As shown in **FIG. 17**, during an overcast winter day with albedo of 0.8, all the systems have more or less similar performance except the horizontal one. The horizontal system captures more diffuse radiation than the others. Here, the reflected radiation from the surrounding surfaces deems the performance differences.

FIG. 18 provides the comparison of tracking advantages during an overcast winter day with albedo of 0.2 and 0.8. The average tracking advantage of dual-axis tracking system versus the horizontal system is -55% when there is no snow. While on a high albedo day the similar advantage is -10%. Single-axis tracking and tilted systems provide almost the same amount of electricity as on a high albedo day. On an overcast day, reflected radiation from the ground covered by snow causes 9%, 39%, and 98% increase in electricity generation of tilted, single-axis tracking, and dual-axis tracking systems, respectively.

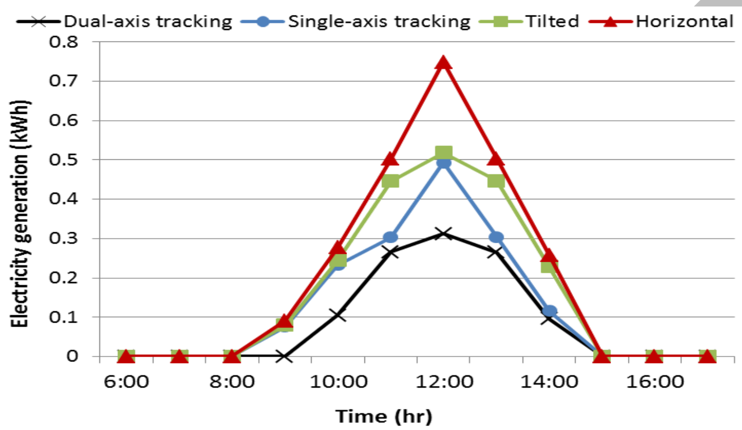

FIG. 14. Electricity generation during an overcast winter day (albedo= 0.2).

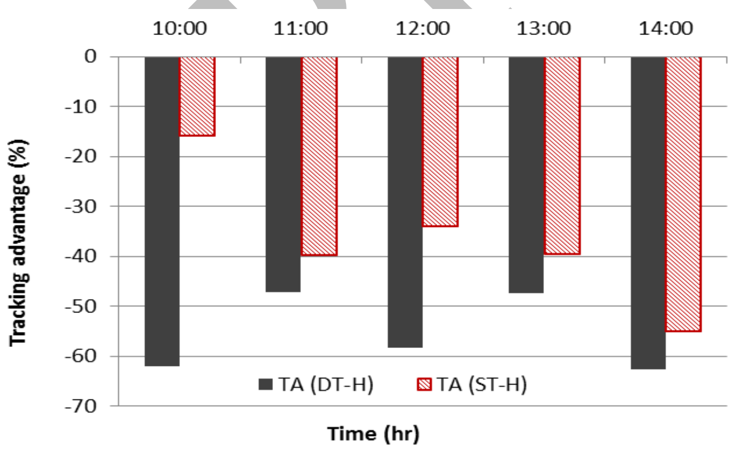

FIG. 15. Tracking advantage versus the horizontal system during an overcast winter day (albedo=0.2).

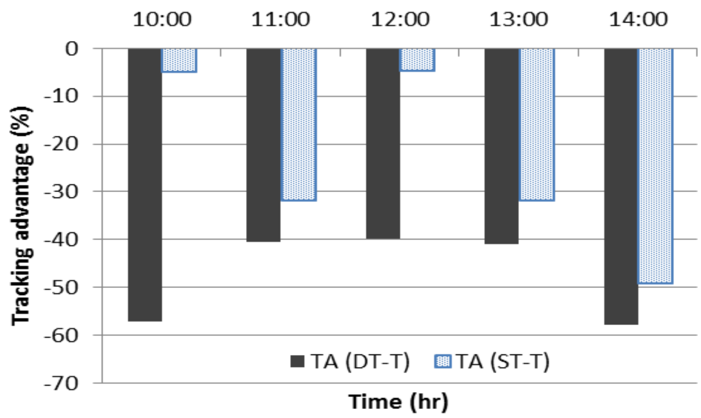

FIG. 16. Tracking advantage versus the tilted system during an overcast winter day (albedo=0.2).

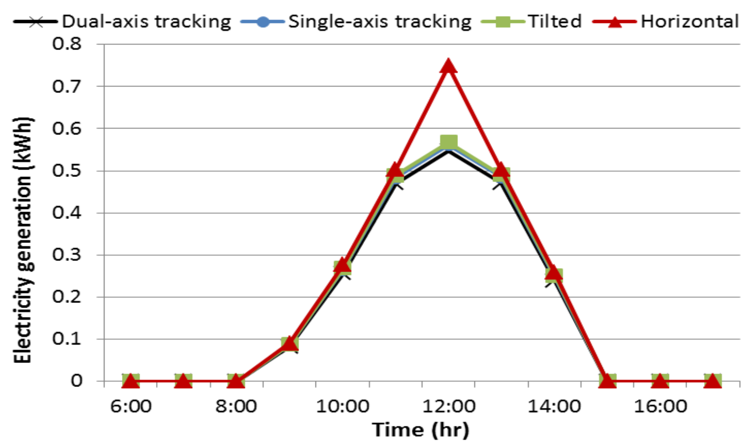

FIG. 17. Electricity generation during an overcast winter day (albedo= 0.8).

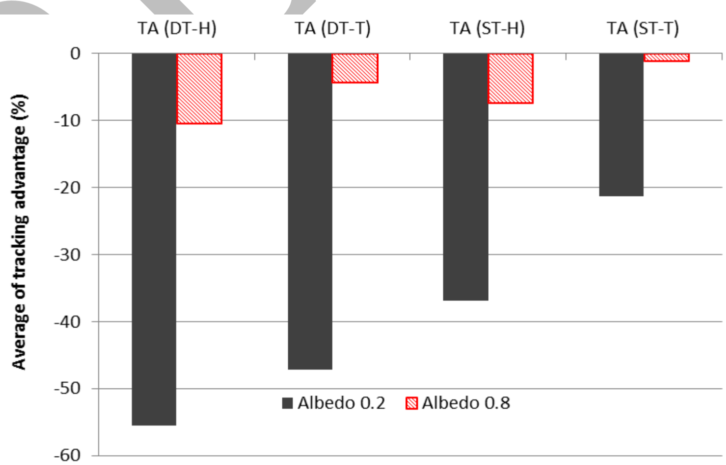

FIG. 18. Average of tracking advantages versus horizontal and tilted systems over an overcast winter day.

Overall the simulations carried out for an overcast winter day near the solstice is showing that the horizontal position should be selected based on its energy increases. This is the opposite of what was observed for a clear day.

TABLE I. Production differences percentage compared to the tilted system in various weather conditions.

Period	albedo	H	ST	DT
Annual	0.2	-12.3	30.9	35.4
	0.8	-13.4	31.0	36.0
Clear winter day	0.2	-59.2	20.9	29.3
	0.8	-60.0	21.7	32.5
Overcast winter day	0.2	21.4	-22.4	-46.9
	0.8	10.4	-1.1	-4.0
Clear summer day	0.2	16.0	64.4	72.4
Overcast summer day	0.2	14.8	-5.0	-0.02

The results obtained from numerous simulations are summarized in TABLE I. This table compares the electricity production of the systems for different periods, with high or low albedo surroundings, with the reference tilted system in terms of percentage. TABLE I also presents results for the summer solstice (last two lines) although these are not formally presented above. The summer results are not explicitly discussed to avoid this paper to become overly lengthy. The first two columns present the period, sky condition, and albedo magnitude under which the results are obtained. Once again, an almost similar performance of single-axis and dual-axis tracking systems can be observed. Furthermore, the horizontal system provides the best performance during both summer and winter overcast days. It is apparent from this table that the effect of albedo on annual electricity production of the systems is very small, while it affects significantly the daily systems production in winter. As it can be seen in an overcast winter day, reflected radiation from accumulated snow on the ground can increase considerably the tracking advantage (21% for single-axis and 46% 42% for dual-axis tracking systems). However, the optimum position for each weather condition can be specified using this table.

V. CONCLUSIONS

A. Content and methodology

This paper has evaluated the performance of sun tracking PV systems for the Toronto metropolitan area in Canada. A typical grid connected stand-alone PV array has been analyzed for daily and monthly periods for four different tracking strategies: fixed horizontal, fixed tilted (at latitude angle), single-axis tracking tilted at yearly optimum tilt angle, and dual-axis tracking. These strategies were also compared for winters involving snow or not as a potential reflector in January, February and March.

Hourly incident solar radiation upon these systems has been estimated based on an anisotropic sky model. The systems performance was computed as a function of arrays irradiance, modules voltage at STC, and an efficiency characteristics curve. Arrays irradiance, electricity production, and tracking advantage have been calculated in different weather conditions.

All results were obtained by means of PVSOL Pro 4.5 simulations. The scope of this first study is limited to energy performance only.

B. Summary of results

The simulation results show that the dual-axis tracking array provides the best electricity production performance over a year in Toronto, Canada. It receives 33% more solar radiation and generates 36% more electricity than the tilted system.

On clear winter days, the average tracking advantage of dual-axis tracking versus the tilted system is 32%. For an overcast winter day, the dual-axis tracking system generates 4% and 13% less electricity compared to the tilted and the horizontal systems, respectively. Hence, tracking the sun on an overcast winter day could be counterproductive. This conclusion also stands for overcast summer days.

This study has also shown that reflected radiation from the ground covered by snow affects the systems performance considerably. The albedo effect basically improves the performance of tilted and tracking systems. It causes an increase of 3.1%, 5.8%, and 7.9% in electricity production of the tilted, single-axis tracking and dual-axis tracking system respectively, over a winter for which snow coverage lasts from January until the end of March.

C. Concluding remarks

The results of this research support the idea that tracking the sun is effective on clear days and counterproductive on overcast days. Consequently, the optimum method of sun tracking, based on the sole energy production analysis, is to use the dual-axis tracker to follow the sun during clear sky conditions and then switch to the horizontal position during overcast conditions. These results are supported by previous studies[26, 18, 3]. However, switching to the horizontal position consumes energy, while during the winter the accumulated snow on PV modules significantly reduces the electricity production. Hence, in high albedo conditions, it is recommended to track the sun in clear sky conditions and stay fixed when the sky becomes overcast.

D. Future work

All results presented for a full year of operation in Toronto indicate that the single-axis system produces nearly as much energy as the dual-axis system. The relative underproduction of the single-axis tracking system could be compensated by a strategy in which, twice or more a year, the tilt angle could be modified. Specifically, it could be set above 51°in the winter and below this threshold in the summer. This would enable the system to grab more energy at its peak at noon in the summer time. Certainly, this would be inappropriate for large farms but could be manageable for smaller systems. A similar strategy could be employed for the tilted system: its zenith tilt angle could be modified twice (or more) a year. This has yet to be investigated in terms of energy production.

Although the dual axis tracking system may produce more electricity than the single-axis tracking system, it is more complicated and thus more expensive. Furthermore, it is a well-documented fact that the electricity consumption of tracking systems is proportional to the tracking accuracy. Then, care should be taken when selecting the best tracking strategy with respect to the initial investment costs, capital cost, and operating costs. The economic analysis has yet to be undertaken.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support. The authors also thank NSERC and the partners of the t3e research chair who support the project: Ville de Lévis, Ecosystem, Valéro Énergie, Conférence Régionale des Élus Chaudière-Appalaches, SDE-Lévis, Roche Groupe Conseil.

NOMENCLATURE

I	hourly solar radiation (Wh/m^2)
G	irradiance (W/m^2)
n	day number
φ	latitude (°)
δ	declination (°)
ω	hour angle (°)
R	geometric factor
θ	incidence angle (°)
θ_z	zenith angle (°)
β	surface slope (°)
γ	surface azimuth angle (°)
ρ_q	ground reflection coefficient
A_i	anisotropic index
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CIS	Copper-Indium-Diselenide
HIT	Heterojunction with Intrinsic Thin-layer
µc-Si	Microcrystalline Silicon
TA	tracking advantage
H	horizontal
T	tilted
ST	single-axis tracking
DT	dual-axis tracking
STC	standard test conditions
LSM	local standard meridian
LST	local solar time
Subscripts	
on	extraterrestrial
sc	solar constant
T	total
b	beam
d	diffused
refl	reflected
o	extraterrestrial upon a horizontal surface

[1]C. L. Archer, and M. Z. Jacobson, 'Evaluation of Global Wind Power', *J. Geophys. Res.*, 110 (2005), D12110.
[2]F. Sick, Erge, T., *Photovoltaics in Buildings* (Freiburg, Germany: XYZ publishing company, 1996), p. 72.
[3]H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, 'A Review of Principle and Sun-Tracking Methods for Maximizing Solar Systems Output', *Renewable and Sustainable Energy Reviews,* 13 (2009), 1800-18.
[4]S. Abdallah, and S. Nijmeh, 'Two Axes Sun Tracking System with Plc Control', *Energy Conversion and Management*, 45 (2004), 1931-39.
[5]M. M. Abu-Khader, O. O. Badran, and S. Abdallah, 'Evaluating Multi-Axes Sun-Tracking System at Different Modes of Operation in Jordan', *Renewable and Sustainable Energy Reviews,* 12 (2008), 864-73.
[6]A. Al-Mohamad, 'Efficiency Improvements of Photo-Voltaic Panels Using a Sun-Tracking System', *Applied Energy,* 79 (2004), 345-54.
[7]M. Lave, and J. Kleissl, 'Optimum Fixed Orientations and Benefits of Tracking for Capturing Solar Radiation in the Continental United States', *Renewable Energy,* 36 (2011), 1145-52.
[8]W. D. Lubitz, 'Effect of Manual Tilt Adjustments on Incident Irradiance on Fixed and Tracking Solar Panels', *Applied Energy,* 88 (2011), 1710-19.
[9]H. Yang, and L. Lu, 'The Optimum Tilt Angles and Orientations of Pv Claddings for Building-Integrated Photovoltaic (Bipv) Applications', *TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF SOLAR ENERGY ENGINEERING,* 129 (2007), 253.
[10]N. Helwa, A. Bahgat, A. El Shafee, and E. El Shenawy, 'Maximum Collectable Solar Energy by Different Solar Tracking Systems', *Energy Sources,* 22 (2000), 23-34.
[11]S. Abdallah, 'The Effect of Using Sun Tracking Systems on the Voltage–Current Characteristics and Power Generation of Flat Plate Photovoltaics', *Energy Conversion and Management,* 45 (2004), 1671-79.
[12]M. Koussa, A. Cheknane, S. Hadji, M. Haddadi, and S. Noureddine, 'Measured and Modelled Improvement in Solar Energy Yield from Flat Plate Photovoltaic Systems Utilizing Different Tracking Systems and under a Range of Environmental Conditions', *Applied Energy,* 88 (2011), 1756-71.
[13]Z. Li, X. Liu, and R. Tang, 'Optical Performance of Vertical Single-Axis Tracked Solar Panels', *Renewable Energy,* 36 (2011), 64-68.
[14]B. J. Huang, and F. S. Sun, 'Feasibility Study of One Axis Three Positions Tracking Solar Pv with Low Concentration Ratio Reflector', *Energy Conversion and Management,* 48 (2007), 1273-80.
[15]B. J. Huang, W. L. Ding, and Y. C. Huang, 'Long-Term Field Test of Solar Pv Power Generation Using One-Axis 3-Position Sun Tracker', *Solar Energy,* 85 (2011), 1935-44.
[16]T. Tomson, 'Discrete Two-Positional Tracking of Solar Collectors', *Renewable Energy,* 33 (2008), 400-05.
[17]N. A. Kelly, and T. L. Gibson, 'Increasing the Solar Photovoltaic Energy Capture on Sunny and Cloudy Days', *Solar Energy,* 85 (2011), 111-25.

[18]N. A. Kelly, and T. L. Gibson, 'Improved Photovoltaic Energy Output for Cloudy Conditions with a Solar Tracking System', *Solar Energy*, 83 (2009), 2092-102.
[19]CanSIA, 'Solar Vision 2025: Beyond Market Competitiveness', (Canada, 2010).
[20]J. A. Duffie, and W. A. Beckman, *Solar Engineering of Thermal Processes*John Wiley & Sons, 2013).
[21]B. Brinkworth, and M. Sandberg, 'Design Procedure for Cooling Ducts to Minimise Efficiency Loss Due to Temperature Rise in Pv Arrays', *Solar Energy*, 80 (2006), 89-103.
[22]P. G. Loutzenhiser, H. Manz, C. Felsmann, P. A. Strachan, T. Frank, and G. M. Maxwell, 'Empirical Validation of Models to Compute Solar Irradiance on Inclined Surfaces for Building Energy Simulation', *Solar Energy*, 81 (2007), 254-67.
[23]A. M. Noorian, I. Moradi, and G. A. Kamali, 'Evaluation of 12 Models to Estimate Hourly Diffuse Irradiation on Inclined Surfaces', *Renewable Energy*, 33 (2008), 1406-12.
[24]Environment Canada, 'Canadian Climate Normanls 1971-2000', 2012).
[25]D. T. Reindl, W. A. Beckman, and J. A. Duffie, 'Diffuse Fraction Correlations', *Solar Energy*, 45 (1990), 1-7.
[26]T. P. Chang, 'Performance Analysis of Tracked Panel According to Predicted Global Radiation', *Energy Conversion and Management*, 50 (2009), 2029-34.