# Optimal PV orientation and geographic dispersion: a study of 10 Canadian cities and 16 Ontario locations

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**Abstract**

The purpose of this article is two-fold. The first is to model the output of a photovoltaic panel for 10 Canadian cities to determine the optimal orientation to maximise energy production. In all instances, the desired tilt angle is slightly less than latitude with the average optimal tilt angle being 9.6$^\circ$ less than latitude. The average optimal azimuth angle was found to be 1.9$^\circ$ west of due south. Secondly, to determine whether geographic dispersion of photovoltaic panels reduces the variability in energy production. If so, how much dispersion is required?; and does the dispersion affect the correlation of production with system-wide grid demand? Simulations were conducted for 1 000 kW of photovoltaic panels over three years for 16 locations across Ontario. The results indicate geographic dispersion can: decrease variability with minimal penalty to total energy production; increase or decrease correlation with demand depending on dispersion distance and location.

## 1 Introduction

Electricity is a necessary, though not sufficient, condition for modern societal development, for a range of electricity services have been shown to be critical for advancing well-being (e.g., (IEA 2010, UNDP 2005)). While systems of electricity delivery during the past century have produced many benefits, it is increasingly recognized that a singular reliance upon centralized generators, particularly when largely powered by fossil fuels, is no longer sustainable. A range of environmental, economic, and social challenges have revealed the importance of developing alternative means of providing electricity services (UNDP 2004).

Increased use of renewable resources is a key element of this alternative means of electricity service delivery (del Río & Burguillo 2009). Within that portfolio, greater use of solar energy deployed by means of photovoltaic (PV) panels is often identified as pivotal (Arvizu, Balaya, Cabeza, Hollands, Jäger-Waldau, Kondo, Konseibo, Meleshko, Stein, Tamaura, Xu & Zilles 2011). Many have shown that solar-PV offers numerous benefits to society (e.g., very low life-cycle emissions; modular, and flexible means of deployment; contribution to sustainable livelihoods; and coincidence of peak generation with high-demand periods (e.g., (Arvizu et al. 2011, Brown & Rowlands 2009, Fthenakis 2009)). While still modest in terms of worldwide contribution (in 2008, 0.06% of all of the world's electricity was generated by solar-PV (IEA 2011)), the use of solar-PV is growing. Between 2005 and 2010, for instance, installed capacity rose at an average annual rate of 49% to reach 40 GW worldwide in 2010 (REN21 2011, p. 18,22)

Given the costs of electrical energy storage and transmission, markets are increasingly placing a higher value on electricity that is available at peak times in congested areas. As such, knowledge about the time-specific and location-specific characteristics of electricity production is valuable for planning decisions. Discussions about electricity produced by photovoltaic (PV) panels (henceforth called 'solar electricity') have increasingly been concerned with these issues. The coincidence of peaks in solar electricity production with peaks in system-wide electricity demand in many grids has led some to suggest that solar electricity is actually more 'valuable' than conventionally estimated (Borenstein 2007, Borenstein 2008, Hoff & Margolis 2004, Mills, Wiser, Barbose & Golove 2008, Rowlands 2005, VanGeet, Brown, Blair & McAllister 2008, Watt, Partlin, Oliphant, Outhred, MacGill & Spooner 2008). The fact that solar electricity can be more easily generated on rooftops in urban areas (which are often part of electrically-congested load centres) adds to its value (Borenstein 2008, Brown & Rowlands 2009). Indeed, this encourages planners to investigate the optimal orientation and location of their PV panels. While it has traditionally been common practice to tilt PV panels at an angle equal to the latitude with an azimuth of due south (in the northern hemisphere) in an area of maximum annual solar radiation, this conventional wisdom has been accepted in the absence of market considerations. When the temporal and locational value of electricity enters the calculation, decisions about orientation and location may differ.

Challenges to solar electricity as a contributor to a sustainable energy future have arisen ((Foster 2010, Hughes 2011) for a more comprehensive assessment, see (Evans, Strezov & Evans 2009)). One particular challenge is variability (also called 'intermittency'), which refers to the fact that solar-PV panels are not 'firm' suppliers of energy, but instead only produce power 'when the weather activates them' (Everett & Boyle 1996, p. 408) (See, also, (Laughton 2007, p. 4-5)). The challenge of variability is raised with respect to other renewable resources as well (particularly, wind) (for an overview, see (Milborrow 2007); for a solar-PV-relevant discussion, see (Denholm & Margolis 2007)). While the development of storage technologies may, at one point in the future, make this point moot, the question is one that nevertheless affects renewable electricity deployment and associated policy discussions now. Levels of variability (perceived and real), and strategies to reduce the same clearly have the potential to affect future electrical development paths.

One proposal to reduce variability levels is to broaden the geographic distribution of solar-PV panels. Effectively accepting the old adage that 'the sun is always shining somewhere', the argument is that deployment of, for instance, five 1 000 kW groupings of solar-PV panels across geographically-dispersed locations will have a lower level of variability, across time, than one 5 000 kW grouping of solar-PV panels (located contiguously to each other). While total energy generated, the argument continues, may not be different between the two arrangements, it is more likely that the collective generation profile, across time, of the five 1000 kW groupings will be smoother than that of the single 5 000 kW location generation peaks may be smaller, but generation troughs will also be shallower. This strategy could thus address, at least partially, the challenge of variability.

This article focuses on two aspects. The first is to determine the optimal tilt angle and azimuth for a PV panel such that the annual energy production is maximised for a given location. This is investigated for 10 Canadian cities of varying geographic location and climates using simulated PV panel performance and statistically derrived representative climate files. The article's second aspect focuses on Ontario where modelled PV panel production is further explored to answer the key question: Does geographic dispersion of solar-PV panels reduce variability? Related to this key question, we aim to answer two sub-questions: 1) If geographic dispersion reduces variability, how dispersed should the panels be?; and 2) How are the answers affected by consideration of system-wide demand? The following sections will provide a brief review of methodology, results and discussion on these investigations.

## 2 Methodology

### *Weather data, including solar radiation*

The electrical production of a PV panel is a function of both the solar radiation incident upon the panel as well as its temperature. Furthermore, the temperature of a PV panel is determined by the panel's optical and thermal properties, the incident solar radiation, the ambient air temperature, and the prevailing wind conditions. Consequently, data on solar radiation, air temperature, and wind velocity were required for the present study.

For the optimal PV orientation investigation, Canadian Weather year for Energy Calculation (CWEC) climate data made available by Environment Canada for 10 Canadian cities were utilised. These are intended to provide data consistent with a 'typical' weather year. To achieve this, 12 months are selected from 30 years of real-time weather data, statistically compared, weighted, and concatenated (Environment Canada 2010*a*).

For the geographic dispersion analysis, ESP-r simulations were conducted for 16 geographical locations, and for three years of weather data (2003, 2004, and 2005). The 48 weather files required for these simulations (16 locations times three years) were drawn from the Canadian Weather Energy and Engineering Data Sets (CWEEDS) (Environment Canada 2010*b*). CWEEDS provides both measured and modelled data on an hourly basis for a number of geographic locations, and covering a time period greater than five decades, up to 2005.

### *Modelling methods*

The radiation on a tilted surface can be calculated if the horizontal diffuse and direct components are known (Duffie & Beckman 2006, Clarke 2001). The climate files include this information and ESP-r uses these data to calculate the direct, ground reflected, and sky diffuse components for a surface tilted at a given angle. The direct radiation on an inclined surface is related to the direct normal radiation by the angle between the normal vector of the surface and the incident radiation beam, and the angle of inclination of the direct radiation beam. The ground reflected radiation is a function of the diffuse and direct beam radiation on a horizontal surface as well as a view factor. The view factor between a vertical plate and the sky is 0.5. This is multiplied by the difference between unity and the cosine of the angle of tilt of the surface and the ground reflectivity (an input from the ESP-r user) (Clarke 2001). The sky diffuse component was calculated using the Perez sky model, which considers three components, namely, isotropic, circumsolar, and horizon brightening. The isotropic component is non-directional radiation received from the entire sky. Circumsolar is the result of forward scattering of the radiation in the atmosphere, the origin of which is assumed to be a point source located at the sun. Circumsolar factors account for the incidence angle of this component on the horizontal and tilted surfaces. Horizon brightening is concentrated at the horizon and becomes a greater factor on clear sky days. Brightness coefficients are derived statistically to account for this component (Duffie & Beckman 2006).

The ESP-r simulation program (ESRU 2005), which was employed in this analysis, is a comprehensive building simulation program that can predict the electrical production of PV systems using an approach based upon the WATSUN-PV model (Motillo, Beausoleil-Morrison, Couture & Poissant 2006). The interested reader is referred to Clarke (2001) for a comprehensive treatment of the methodologies employed by ESP-r.

The WATSUN-PV model is a one-diode equivalent photovoltaic model incorporated into ESP-r. The one-diode model determines the power output of the PV cell using the short circuit current and open circuit voltage at reference conditions. It accounts for the temperature dependence of these two variables. The model is defined by equations for short-circuit current, open-circuit voltage, and maximum power (Motillo et al. 2006) given here,

$$I_{sc} = I_{sc,ref}\left(\frac{E_{T,eff}}{E_{ref}}\right)[1+\alpha(T_c - T_{c,ref})] \tag{1}$$

$$V_{oc} = V_{oc,ref}[1-\gamma(T_c - T_{c,ref})]\cdot max\left[0, 1+\beta\left(\frac{E_{T,eff}}{E_{ref}}\right)\right] \tag{2}$$

$$P_{mp} = I_{mp,ref}\cdot V_{mp,ref}\left(\frac{I_{sc}\cdot V_{oc}}{I_{sc,ref}\cdot V_{oc,ref}}\right) \tag{3}$$

where,

| | |
|---|---|
| $\alpha$ | Coefficient of short circuit current ($K^{-1}$) |
| $\gamma$ | Coefficient of open circuit voltage ($K^{-1}$) |
| $\beta$ | Coefficient of logarithm of irradiance for open circuit voltage (-) |
| $E_{ref}$ | Irradiance at reference conditions ($W\cdot m^{-2}$) |
| $E_{T,eff}$ | Effective irradiance incident on the panel ($W\cdot m^{-2}$) |
| $I_{sc,ref}$ | Short circuit current at reference conditions for the panel ($A$) |
| $I_{sc}$ | Short circuit current ($A$) |
| $I_{mp,ref}$ | Current at maximum power point at reference conditions for the panel ($A$) |
| $V_{oc,ref}$ | Open circuit voltage at reference conditions for the panel ($V$) |
| $V_{oc}$ | Open circuit voltage ($V$) |
| $V_{mp,ref}$ | Voltage at maximum power point at reference conditions for the panel ($V$) |
| $P_{mp}$ | Electrical power output at maximum power point ($W$) |
| $T_{c,ref}$ | Reference temperature ($K$) |
| $T_c$ | Temperature ($K$) |

To model the performance of a specific PV system, the coefficients required by these equations are input to ESP-r via a special materials (SPM) file. These data are, for the most part, available directly from the manufacturers' data sheets. The only exception is the coefficient of logarithm of irradiance for open circuit voltage ($\beta$), which is not typically provided. In this case, the method recommended by Thevenard was used to establish $\beta$ (Thevenard 2008).

### *Solar panel selection*

A number of PV panel distributors in Ontario were contacted to determine which products currently lead the market. They suggested panels for different requirements, economy, performance and availability. Based on these recommendations, three representative panels were chosen: SHARP ND-198UIF 198W; SUNTECH STP200-18/Ub-1 200W; and SANYO HIT Series, HIP-200BA3 200W. The manufacturers' specifications for these three panels were used to provide the necessary data to the ESP-r model.

The Suntech panel was chosen as the subject for further investigation for three key reasons. First, Suntech is, according to one report, the world's second-largest supplier of PV panels (2009 data from (REF 2010)); Sharp ranked third, Sanyo ranked tenth, and First Solar was in first position). Second, this panel's annual electrical production figures fell between those of the Sanyo and the Sharp panels. And third, its production was not particularly skewed to summertime or wintertime production. (The Sanyo panel was found to perform relatively better in the summertime, and the Sharp panel relatively better in the wintertime.) Therefore, the Suntech panel is a reasonable 'middle choice' to take. In any case, note that the differences are relatively modest, with relative annual production figures between the highest producer (Sanyo) and the lowest producer (Sharp) being less than 3%.

### *Inverter efficiency*

PV systems produce direct-current (DC) electrical power. Most household utilities and applications operate on alternating-current (AC) electrical power. As a result, most applications will require an inverter to convert the power produced by the solar array into AC power. Losses are associated with this process and can be accounted for with an inverter efficiency factor. The DC electrical power output predicted by ESP-r is multiplied directly by this factor to calculate the AC power production.

The power-dependant efficiency of the inverter converting the PV panel's DC production to AC was modelled using the method described by Rowlands et al (Rowlands, Kemery & Beausoleil-Morrison 2011). A single 200 W nominal solar-PV panel connected to a nominal 200 W inverter was modelled in each of the ESP-r simulations and these results were linearly scaled in the subsequent analysis. Although the assumption of linear output scaling does introduce some uncertainty into the analysis, it is felt that these effects are minor and do not affect the conclusions drawn about geographic dispersion.

### *Optimal PV orientation investigations*

Preliminary investigations were conducted to determine the possible range of tilt and azimuth angles that maximised the annual energy production. This allowed subsequent analyses to focus the study upon a particular range of variables. More specifically, it became clear that the optimal values for all locations lay within a fairly restricted range of orientations – namely, tilt angles between 30$^\circ$ and 44$^\circ$; and azimuth angles between 15$^\circ$ east of due south and 15$^\circ$ west of due south. Therefore, increments of 1$^\circ$, for both tilt angles and azimuth angles, were subsequently investigated.

### *Analysis of geographically dispersed location groups*

In each of the 48 simulations conducted to examine the effects of geographic dispersion (16 locations, 3 years), the solar-PV panel was oriented due south and at a tilt angle of 8$^\circ$ less than the location's latitude. In a previous study (Rowlands et al. 2011), this orientation was found to maximise the annual electricity production for Ontario locations.

Initially, the solar-PV production was contrasted for each pair of the 16 locations (i.e. 120 pairs). This contrasting was conducted for the summer 'on-peak' period, i.e., non-holiday weekdays from May 1 through October 31, from 11h00 to 17h00 local time. This was accomplished by calculating the Pearson correlation coefficient ($r_{x,y}$) for the solar-PV production for each of the 120 location pairs. This gives an indication of how well two time-series of data correlate, where $X$ is the time-series solar-PV production from one location and $Y$ is from another location,

$$r_{x,y} = \frac{\sum_{i=0}^{n}(X_i - \bar{X}) - (Y_i - \bar{Y})}{\left[\sum_{i=0}^{n}(X_i - \bar{X})^2\right]^{\frac{1}{2}} - \left[\sum_{i=0}^{n}(Y_i - \bar{Y})^2\right]^{\frac{1}{2}}} \tag{4}$$

where $\bar{X}$ is the annual average solar-PV production (W) for one location and $\bar{Y}$ is the average annual production for the other location in the pair. $X_i$ and $Y_i$ represent the production (W) at hour $i$. The summations of 4 are taken over $n$ hourly time-steps, where $n$ represents all hours of the year during which there was electrical production from the PV system.

Values of $r_{x,y}$ tend to 1 when the two time-series are closely correlated, i.e., when the fluctuations in solar-PV production of location $X$ closely follow the fluctuations in solar-PV production of location $Y$. Negative values would indicate that the two time series are negatively correlated, i.e., the production of location $X$ tends to increase when the production of location $Y$ decreases.

An indication of variability amongst the various groupings analysed were calculated using standard deviation,

$$\sigma_k = \sqrt{\frac{\sum_{j=0}^{m} (X_i - \bar{X})^2}{m}} \tag{5}$$

where $\sigma_k$ is the standard deviation of the production during a 1-hour period (e.g. 11am-12noon) over each of the non-holiday weekdays between May 1 and October 31.

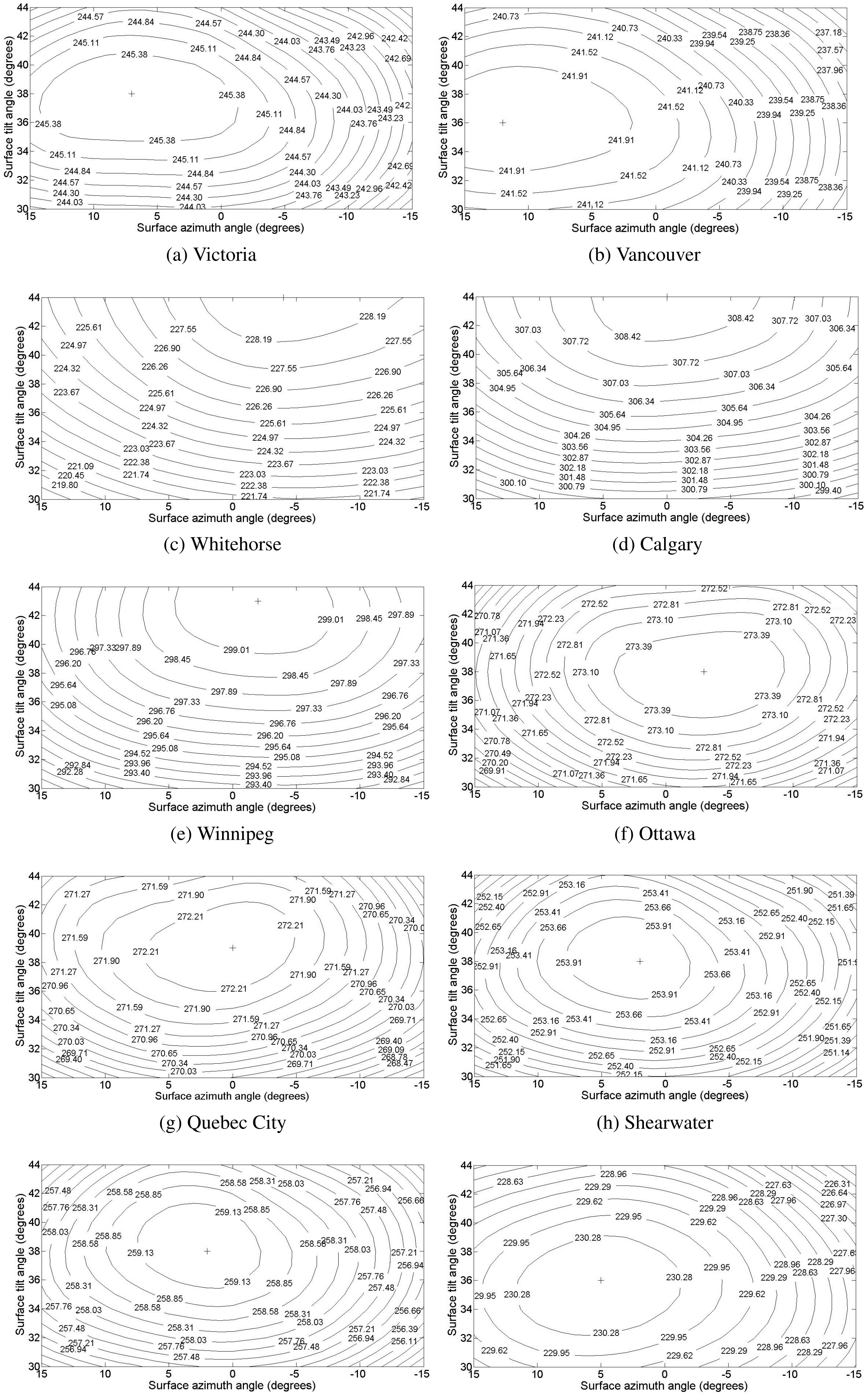
# 3 Results

***Optimal PV-tilt angle for numerous Canadian cities***

The methodology laid out in the previous section was used to generate hourly solar electricity production figures (for 465 different orientations: 15 tilt angles times 31 azimuth angles) for 10 cities using CWEC weather data. These simulations were conducted using a single Suntech panel whose nominal output is 200 W. Consequently the results that follow correspond to the electrical output that would be produced by a single panel. These results (in Table 1) could be easily scaled to larger systems (as is done for the geographically dispersed arrangements in following sections).

**Table 1: Orientation for maximum annual energy production in 10 Canadian cities**
**Note: SW denoted as (+), SE azimuth denoted as (-)**

| city | latitude (degrees) | tilt angle (degrees) | azimuth angle (degrees) | latitude - tilt (degrees) |
|---|---|---|---|---|
| Shearwater | 44.6 | 38 | 2 | 6.6 |
| Winnipeg | 49.9 | 43 | -2 | 6.9 |
| Calgary | 51.1 | 44 | 0 | 7.1 |
| Ottawa | 45.5 | 38 | -3 | 7.5 |
| Quebec City | 46.8 | 39 | 0 | 7.8 |
| Charlottetown | 46.3 | 38 | 2 | 8.3 |
| Victoria | 48.7 | 38 | 7 | 10.7 |
| St John's | 47.5 | 36 | 5 | 11.5 |
| Vancouver | 49.2 | 36 | 12 | 13.2 |
| Whitehorse | 60.7 | 44 | -4 | 16.7 |
| average | | | 1.9 | 9.6 |




(a) Victoria (b) Vancouver

(c) Whitehorse (d) Calgary

(e) Winnipeg (f) Ottawa

(g) Quebec City (h) Shearwater

(i) Charlottetown (j) St John's

**Figure 1: Annual energy produced (kWh) from a nominal 200W panel (+ indicates maximum)**

Figures 1a through 1j show the annual output energy for the 465 different orientations for Whitehorse, Victoria, Vancouver, Calgary, Winnipeg, Ottawa, Quebec City, Shearwater, Charlottetown, and St John's. For all locations, the optimal tilt angle is less than the city's latitude. The results can be divided into two categories: 1) cities whose optimal tilt is 6.6° to 8.3° less than latitude; and 2) cities whose optimal tilt is 10.7° to 16.7° less than latitude. These results indicate that the cities in group 2 tend to have less solar energy available in the winter, and hence have a preference for a more shallow tilt angle to favour summer collection. It is interesting to note that all group 2 cities – with the exception of Whitehorse – are coastal locations. Further, all these cities – again, with the exception of Whitehorse – favour an azimuth angle west of due south.

It should be noted that due to the simulation model's treatment of convective heat transfer, results for tilts of 45° and higher were not be examined as part of this analysis. This was deemed to have no impact on the results for all of the cities with the exception of Whitehorse and potentially, albeit to a lesser extent, Calgary. Calgary's optimal tilt of 44° might increase if the analysis was extended but as Calgary is already at the lower end of the average latitude minus tilt, it is unlikely to be a significant difference. However, Whitehorse has a significantly higher latitude than all other cities analysed. Consequently, although the optimal angle for Whitehorse was found to be 44° in this analysis, it may be that the optimal angle is actually greater than 44°. Hence, the seemingly incongruous result of latitude minus tilt of 16.7° may be unduly inflated and thus artificially increasing the average latitude minus tilt angle from 8.8° (Whitehorse excluded) to 9.6° (Whitehorse included).

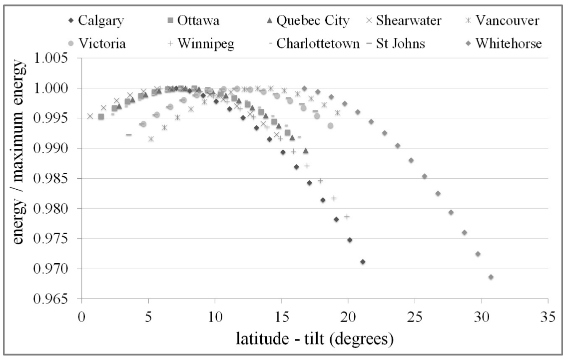



**Figure 2: Normalized due south energy production (kWh) for latitude - tilt (degrees)**

In any case, for the 10 cities analysed, the average tilt angle was found to be slightly higher than the value found by (Rowlands et al. 2011) regardless of whether the Whitehorse results are discounted or not. However, for a change of +/- 5° in tilt angle – at the optimal azimuth – the resulting difference in annual energy production is less than 1%, and the average is less than 0.5%. Whitehorse and Calgary were found to have the first and second greatest sensitivity to tilt angle respectively.This is further illustrated for a single azimuth of due south in Figure 2. This same insensitivity is evident in the azimuth angle where there are differences less than 4% seen across the range of investigated azimuths (i.e., 15° east of due south and 15° west of due south), with the average being only slightly higher than 2%. Whitehorse and Calgary were also found to have the first and second greatest sensitivity to azimuth angle respectively.

***Geographic dispersion for numerous Ontario cities***

Figure 3 contrasts the PV production for each pair of locations for the three years analysed (2003, 2004, and 2005). As can be seen, the Pearson correlation coefficient is relatively high for locations that are relatively close together. For instance, consider Buttonville and Toronto

– 31 km apart, the two locations in our sample that are closest to each other. The Pearson correlation coefficients are 0.925, 0.928, and 0.941, for 2003, 2004, and 2005, respectively. In the literature, it is generally accepted that a coefficient of more than 0.8 represents a ‘very strong relationship’ (Salkind 2001, p. 85). By contrast, Kenora and Ottawa are 1 481 km apart. Their Pearson correlation coefficients are 0.480, 0.387, and 0.489 for the same three years, respectively. Values between 0.4 and 0.6 are considered to represent a ‘moderate relationship’, while values between 0.2 and 0.4 represent a ‘weak relationship’ (Salkind 2001, p. 85). In between, the size of the Pearson’s correlation coefficient falls as the distance increases.

But that decline is not linear. A visual inspection of Figure 3 suggests that as the distance approaches 800 – 1 000 kilometres, the change in the Pearson correlation coefficient becomes much smaller, to virtually nothing. As such, any increased distance beyond this range may not produce any further reduction in the association between PV production at these locations.

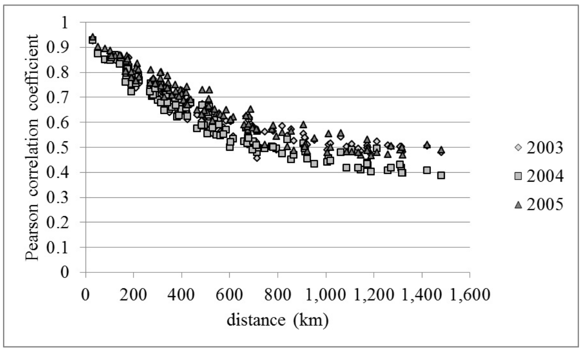



**Figure 3: Pearson correlation coefficients for pairs of Ontario locations.**

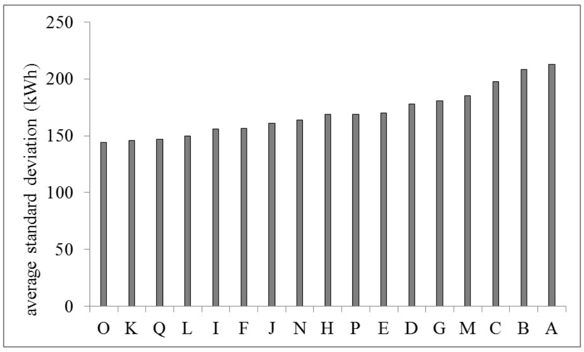



**Figure 4: Average annual standard deviation values (on-peak periods), 2003, 2004, and 2005, by grouping.**

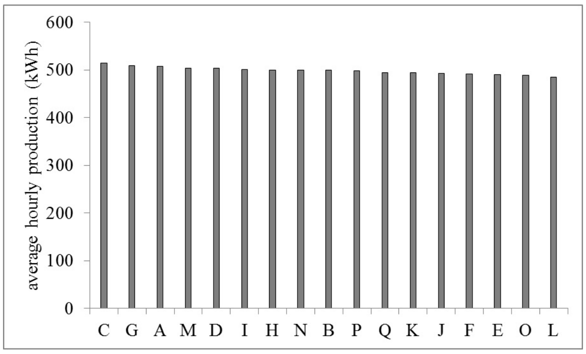



**Figure 5: Average hourly energy production (on-peak periods), 2003, 2004, and 2005, by grouping.**

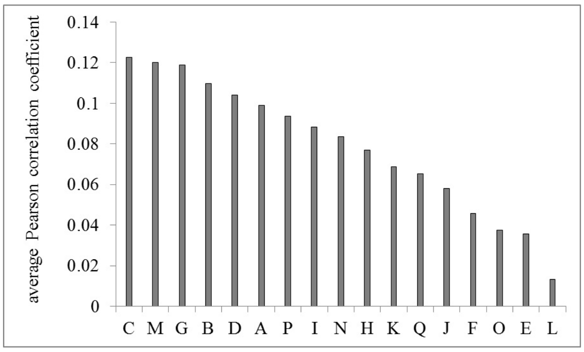



**Figure 6: Average Pearson correlation coefficient (solar-PV production and Ontario system-wide demand), 2003, 2004, and 2005, by grouping.**

The above explored the extent to which PV-panel production across locations in Ontario is ‘in-step’ with each other by calculating Pearson correlation coefficients. Implicit in this work has been the sentiment that decreasing coefficient values (with increasing distance) is a desirable outcome. This is only the case, however, if this distribution of panels is not serving to sacrifice electricity production. To clarify, consider the following simplistic – and extreme – example. Two 200 W panels, 100 km apart, could have hourly energy production values of 160 Wh and 150 Wh from 13h00 to 14h00 and then 140 Wh and 130 Wh from 14h00 to 15h00. If such a pattern were to continue over time, then these two panels' production profiles would generate a high Pearson correlation coefficient. Alternatively, two other 200 W panels, 1 000 km apart, could have hourly energy productions of, for those same hours, 80 Wh and 60 Wh followed by 70 Wh and 90 Wh, respectively. If repeated over time, then their Pearson correlation coefficient would be much lower. An incomplete analysis might suggest that the second combination of solar-PV panels – 1 000 km apart, not the ones that are 100 km apart – is the preferred, for it has a lower Pearson correlation coefficient. What would not be revealed by singular reflection upon the Pearson correlation coefficient, however, would be that the second combination's electricity production would also be much lower. Thus, while the lower Pearson correlation coefficient might be hailed as something positive – serving to smooth out aggregate electricity generation values over time – the 'something negative', i.e., lower overall electricity generation levels would have been overlooked. This issue is examined in the analysis that follows.

The investigation is continued by clustering the 16 locations into six different groups. Toronto was assigned to its own 'group' – because of its importance as a congested load centre. The other 15 locations were then gathered into five different groups, categorized on the basis of similar distance from Toronto. Table 2 provides details.

**Table 2: Descriptions of groups used in analysis**

| group identifier | location | distance from Toronto (km) |
|---|---|---|
| T | Toronto | - |
| G1 | Buttonville | 31 |
| | Hamilton | 53 |
| G2 | London | 142 |
| | Wiarton | 168 |
| | Trenton | 176 |
| G3 | North Bay | 301 |
| | Windsor | 313 |
| | Sudbury | 341 |
| | Ottawa | 374 |
| G4 | Sault Ste. Marie | 494 |
| | Timmins | 561 |
| | Kapuskasing | 675 |
| G5 | Thunder Bay | 912 |
| | Sioux Lookout | 1 173 |
| | Kenora | 1 310 |

A series of solar-PV panel arrangements were then conceived, each consisting of 1 000 kW of panels. The 'baseline' was a 1 000 kW system located in Toronto. As a comparator, half the panels (500 kW) were located in Toronto and the other half in the group of locations labelled 'G1' (see Table 2). Accordingly, this second half (the remaining 500 kW) were divided equally between Buttonville and Hamilton. In another example alternative, Toronto was examined with groups G3 and G4. With this 333 kW were assigned to each of T, G3, and G4. Within G3 and G4, the panels were equally allotted among the members of each group. Therefore, North Bay, Windsor, Sudbury, and Ottawa (G3 members) each had 83 kW, and Sault Ste. Marie, Timmins, and Kapuskasing (G4 members) each had 111 kW. The extension of this logic led to an examination of the full range of possibilities laid out in Table 3.

**Table 3: Descriptions of group combinations used in analysis**

| grouping | combinations | grouping | combinations | grouping | combinations |
|---|---|---|---|---|---|
| A | T | G | T, G2, G3 | M | T, G1, G2, G3 |
| B | T, G1 | H | T, G2, G4 | N | T, G2, G3, G4 |
| C | T, G1 | I | T, G2, G5 | O | T, G3, G4, G5 |
| D | T, G3 | J | T, G3, G4 | P | T, G1, G2, G3, G4 |
| D | T, G4 | K | T, G3, G5 | Q | T, G2, G3, G4, G5 |
| F | T, G5 | L | T, G4, G5 | | |

Key results are summarised in order to identify those combinations that might achieve multiple goals: smooth out intermittency, maximize energy production, and be ‘in-step’ with system-wide electricity demand. Figures 4, 5, and 6 identify key indicators for each of these three measures: standard deviation (on-peak periods), energy production (on-peak periods), and Pearson correlation coefficient (solar-PV production and Ontario system-wide demand). Preferred combinations would have shorter bars in Figure 4 (representing less variability), taller bars in Figure 5 (representing more electricity generated), and taller bars in Figure 6 (representing solar-PV production that was more ‘in-step’ with the province’s demand patterns).

What is clear from Figures 4, 5, and 6 is that no single strategy should be recommended unequivocally. For instance, there is not one strategy that ranks among the top five in every one of the three indicators. Nevertheless, the options that appear to be most attractive – here defined as notable reductions in variability (measured by a value of under 160 kWh for standard deviation), coupled with no major reduction in energy production (average value stays within 2% of that of group A), and a positive contribution to Ontario’s demand requirements (an average Pearson correlation coefficient of at least 0.08). On these criteria, group I – i.e., a combination of 333 kW of PV-panels in Toronto and 111 kW of PV-panels in each of London, Wiarton, Trenton, Thunder Bay, Sioux Lookout, and Kenora – ranks highest; indeed, it is the only one that satisfies the three criteria. Different relative emphases among these three characteristics (variability, electricity generation, and timing of production) would yield different candidates. Nevertheless, three key observations – and associated recommendations – are important to make following the results in shown in Figures 4, 5, and 6.

First, it is noteworthy that at least one of the 16 combinations fares ‘better’ than Toronto on its own. Initially, ‘better’ is defined as having lower variability, more energy production, and a higher correlation value with the Ontario-wide system as a whole. Group C (i.e., 500 kW of solar-PV panels in Toronto, coupled with 166 kW of solar-PV panels in each of London, Wiarton, and Trenton), and group G (i.e., 333 kW of solar-PV panels in Toronto, coupled with 111 kW of solar-PV panels in London, Wiarton, and Trenton, as well as 83 kW of solar-PV panels in North Bay, Windsor, Sudbury, and Ottawa) achieve this high standard. If we change the criteria somewhat, and look for a standard deviation value under 165 kWh (Toronto on its own is 212.8 kWh), an average energy value of at least 500 kWh (Toronto on its own is 508 kWh) and a Pearson correlation coefficient of at least 0.070 (Toronto is 0.099), then distribution that emerges is again group I. Finally, if we look for lower variability than Toronto’s, an energy value of at least 500 kWh and a correlation value of at least that of Toronto’s, four groupings emerge: C, D, G and M. On this kind of evidence, therefore, there is an argument for a dispersed placement of solar-PV panels across Ontario. Thus, continued research into the potential benefits of distributed generation is justified. Indeed, with a significant amount of solar-PV being deployed across Ontario – spurred by the province's feed-in tariff arrangements – our investigation of modelled data will soon be able to be supplemented by actual panel production data, from across the province.

Second, our results do not point towards a particular distribution of solar-PV panels across the province. In other words, one of our 17 groupings has not unequivocally emerged as 'best'. Indeed, the discussion above reveals that groupings that are relatively closer to Toronto (groups C and D, for instance) as well as groupings that include locations relatively further from Toronto (e.g. group I) both do well. This, combined with the results from Figure 3 suggests that there may be some trade-off between reduced variability and improved performance, with perhaps the 800-1 000 km distance being an important inflection point: deployment beyond that distance does not deliver ongoing reductions in variability, but performance continues to be sacrificed. Increased analysis of such options – including 'breaking down' our groups to determine where particularly valuable collections of locations may exist is warranted.

It is worth noting that the analysis presented here merely serves to initiate discussion on this topic. Three metrics were used here to evaluate proposed arrangements (namely, decreased variability, increased energy generation, and higher correlation with system-wide demand). Other metrics should be introduced into the analysis – the transmission capacity (and cost) of solar-PV generation in additional locations and the increased land-use ease of locating a smaller number of solar-PV panels in a greater number of places are but two such examples.

# 4 Conclusions

The optimal PV-panel orientation (for maximum energy production) analysis of 10 Canadian cities is in line with previous findings for Ontario. Firstly, that the energy production for a PV panel is 'by and large' insensitive to azimuth and tilt for a reasonably large spectrum. This holds true from coast-to-coast for numerous climates and a range of latitudes. Secondly, while the analysis herein resulted in an average of 9.6°, further analysis for cities at very high latitudes – such as Whitehorse – warrant an extended study for tilts greater than 44°.

Motivated by increasing interest solar-PV's role in contributing to a sustainable energy future, this article investigated the extent to which geographical dispersion of solar-PV panels can reduce variability. Using the Pearson correlation coefficient and standard deviation as indicators, the findings indicate increased dispersion does reduce variability.

While there is usually a modest reduction in energy generation with increased dispersion, we also found instances in which dispersed panels can serve to increase the correlation coefficient between PV-panels' generation and system-wide demand. Improvements in system performance appear to be possible with increased dispersion of PV-panels, but future research considering additional panel production data and transmission issues could potentially generate more specific recommendations.

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# 6 References

Arvizu, D., Balaya, P., Cabeza, L., Hollands, T., Jäger-Waldau, A., Kondo, M., Konseibo, C., Meleshko, V., Stein, W., Tamaura, Y., Xu, H. & Zilles, R. (2011), IPCC special report on renewable energy sources and climate change mitigation, Technical report, Cambridge University Press, Cambridge, UK.

Borenstein, S. (2007), Electricity rate structures and the economics of solar PV: Could mandatory time-of-use rates undermine California's solar photovoltaic subsidies?, Technical report, University of California Energy Institute, CSEM WP 172, Berkeley.

Borenstein, S. (2008), The market value and cost of solar photovoltaic electricity production, Technical report, University of California Energy Institute, CSEM WP 176, Berkeley.

Brown, S. & Rowlands, I. H. (2009), 'Nodal pricing in Ontario, Canada: Implications for solar PV electricity', *Renewable Energy* **34**, 170–178.

Clarke, J. A. (2001), *Energy simulation in building design*, 2nd edn, Butterworth-Heinemann, Oxford, UK.

del Río, P. & Burguillo, M. (2009), 'An empirical analysis of the impact of renewable energy deployment on local sustainability', *Renewable and Sustainable Energy Reviews* **13**, 1314–1325.

Denholm, P. & Margolis, R. M. (2007), 'Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems', *Energy Policy* **35**, 2852–2861.

Duffie, J. A. & Beckman, W. A. (2006), *Solar engineering of thermal processes*, 3rd edn, John Wiley and Sons, Inc., Hoboken, NJ.

Environment Canada (2010*a*), CWEC Files updated user's manual, Technical report, Meteorological Service of Canada (MSC) and The National Research Council of Canada, Ottawa, ON.

Environment Canada (2010*b*), CWEEDS Files updated user's manual, Technical report, Meteorological Service of Canada (MSC) and The National Research Council of Canada, Ottawa, ON.

ESRU (2005), *The ESP-r system for building energy simulations User guide version 10 series*.

Evans, A., Strezov, V. & Evans, T. J. (2009), 'Assessment of sustainability indicators for renewable energy technologies', *Renewable and Sustainable Energy Reviews* **13**, 1082–1088.

Everett, B. & Boyle, G. (1996), *Renewable Energy: Power for a Sustainable Future*, Oxford University Press, Oxford.

Foster, P. (2010), The solar robber barons, Technical report, The Financial Post (Toronto) October 21.

Fthenakis, V. (2009), 'Sustainability of photovoltaics: The case for thin-film solar cells', *Renewable and Sustainable Energy Reviews* **13**, 2746–2750.

Hoff, T. E. & Margolis, R. (2004), Are photovoltaic systems worth more to residential consumers on net metered time-of-use rates?, American Solar Energy Society, Portland.

Hughes, G. (2011), The myth of green jobs, Technical report, The Global Warming Policy Foundation, GWPF Report 3, London.

IEA (2010), World energy outlook 2010, Technical report, International Energy Agency, Paris.

IEA (2011), 'Electricity/heat in world in 2008',
**URL:** *http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=29*.

Laughton, M. (2007), *Renewable Electricity and the Grid: The Challenge of Variability*, Earthscan, London.

Milborrow, D. (2007), *Renewable Electricity and the Grid: The Challenge of Variability*, Earthscan, London.

Mills, A., Wiser, R., Barbose, G. & Golove, W. (2008), 'The impact of retail rate structures on the economics of commercial photovoltaic systems in California', *Energy Policy* **36**, 3266–3277.

Motillo, M., Beausoleil-Morrison, I., Couture, L. & Poissant, Y. (2006), A comparison and validation of two photovoltaic models, Technical report, CETC-Ottawa, Natural Resources Canada, Ottawa, ON.

REF (2010), First Solar tops PV module suppliers list in 2009, Technical report.

REN21 (2011), Renewables 2011 global status report, Technical report, Renewable Energy Policy Network for the 21st Century Secretariat, Paris.

Rowlands, I. H. (2005), 'Solar PV electricity and market characteristics: Two Canadian case-studies', *Renewable Energy* **30**, 815–34.

Rowlands, I. H., Kemery, B. P. & Beausoleil-Morrison, I. (2011), 'Optimal solar-PV tilt angle and azimuth: An Ontario (Canada) case-study', *Energy Policy* **39**, 1397–1409.

Salkind, N. J. (2001), *Statistics for People Who (Think They) Hate Statistics*, Sage Publications Inc., Thousand Oaks, CA.

Thevenard, D. (2008), Validation of ESP-r's equivalent one-diode PV model with data from NIST, Technical report, CETC-Ottawa, Natural Resources Canada, Ottawa, ON.

UNDP (2004), World energy assessment: 2004 update, Technical report, United Nations Development Programme, New York.

UNDP (2005), Energizing the millennium development goals: A guide to energy's role in reducing poverty, Technical report, United Nations Development Programme, New York.

VanGeet, O., Brown, E., Blair, T. & McAllister, A. (2008), Solar San Diego: The impact of binomial rate structures on real PV systems, Conference Paper, NREL/CP-670-42923, National Renewable Energy Laboratory, Golden CO, Presented at Solar 2008, San Diego.

Watt, M., Partlin, S., Oliphant, M., Outhred, H., MacGill, I. & Spooner, T. (2008), The value of PV in summer peaks, 19th European Photovoltaic Solar Energy Conference, Paris.