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THE DEVELOPMENT OF PHOTOVOLTAIC RESOURCE MAPS FOR CANADA

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ABSTRACT

We describe the development of new, Web-based maps of insolation and photovoltaic energy potential across Canada. The maps will be made available on the Natural Resources Canada website. They are presented for each month and summed for the entire year, for five different surface orientations: a sun-tracking orientation and four fixed South-facing orientations with latitude, vertical and latitude ± 15° tilts. The models used to generate the maps are based on 1974-1993 (CERES, Environment Canada) monthly mean daily global insolation data. Insolation values were interpolated over the country in a regular grid (grid size: 300 arc seconds ~10km grid) using thin-plate smoothing splines. The models used are based on position (longitude, latitude) and precipitation (used as a surrogate for cloudiness). Photovoltaic (PV) electricity generation potential for grid-connected photovoltaic systems (in kWh per kilowatt of photovoltaic installed power capacity) was estimated from the radiation models for all fixed surface orientations for each grid cell using standard international values for the performance ratio of grid-connected photovoltaic systems. To demonstrate the value of the models beyond the maps we also developed a database of the photovoltaic production potential of over 3500 municipalities across Canada and produced a ranking of provincial capitals and major cities in terms of PV production potential, and a list of the best "PV hotspot" for each province.

1. INTRODUCTION

As demand for renewable energy grows, so does the need for accurate, readily available resource data and maps. However, in Canada, as in most countries, relatively few meteorological stations collect the solar radiation data required to assess the potential and performance of solar energy systems, and in particular of photovoltaics (solar-based electricity).

Other than the insolation map sources mentioned in this paper, there are currently four other radiation maps for Canada: Canada's solar radiation atlas [McKay and Phillips 1984], a set of maps presented in Natural Resources Canada's "Photovoltaic Systems Design Manual" [Energy, Mines and Resources Canada 1991], NASA's Surface Solar Energy (SSE) worldwide maps [NASA SSE website, June 28, 2006] and maps produced by Natural Resources Canada, Canadian Forest Service (CFS), at the Great Lakes Forestry Centre [Great Lakes Forestry Centre website, June 28, 2006]. Other maps have been constructed for individual provinces, including a satellite-based radiation map for Québec [Lemieux et al., 2000] and a map for Nova Scotia [Green Power Labs website, June 28, 2006]. However, none of the radiation models/maps mentioned above assesses photovoltaic electricity generation potential.

The models and maps presented in this paper are extensions of the CFS models to include insolation on non-horizontal surfaces. They differ from the models mentioned above in that they provide an assessment of photovoltaic production potential for grid-connected systems. Likewise, the choice of surface orientations is also geared towards photovoltaic applications.

This paper is organized as follows: In section 2, we describe the data and methodology used to generate the maps and the municipalities database. Section 2.1 describes the data on which the models are based and section 2.2 the surface orientations for which insolation data was analyzed. Section 2.3 describes the radiation model used to interpolate the insolation data over Canada , while section 2.4 explains how electricity production potential values (in kWh/kW) were calculated using the insolation data from the radiation model. The following two sections describe how the maps (section 2.5) and the municipalities database (section 2.6) were generated. Section 3 presents and discusses the results: the maps (section 3.1) and the municipalities database (section 3.2). Finally, section 4 gives concluding comments.

2. DATA AND METHODOLOGY

2.1 Data

The source for the monthly and annual mean values of global solar radiation used to compile the maps is the Environment Canada CERES CD (*le disque* *canadien des énergies renouvelables éolienne et solaire, The Canadian Renewable Energy Wind and Solar Resource CD*). CERES provides data for 144 Canadian locations for the 1974-1993 period, including global, direct beam, and diffuse solar radiation on a horizontal surface and 31 tilted surface orientations including one sun-tracking surface, referred to below as FTS (follow the sun).

Global horizontal radiation was measured at only about a quarter of the 144 locations, and modeled at the remaining stations using the MAC3 model [Davies et al., 1984]. Global radiation on non-horizontal surfaces was modeled from horizontal radiation for all locations using the HAY model [Hay, 1979]. Mean bias errors for the HAY model typically ranged from 5 to 10% for a variety of tilted surface orientations.This gives an appropriate measure to judge the upper bound of errors in the monthly and annual totals from CERES.

Data for eight meteorological stations in Alaska was also added due to concerns over data sparsity in the far north. This data was extracted from the U.S. National Solar Radiation Database which covers a similar period (1961-1990) and provides monthly and annual mean radiation data for all the orientations of interest in the current study. The database is described fully in Marion et al., 1994.

A map of all the meteorological stations used is shown in Figure 1.

2.2 Choice of orientations

The orientation of a PV array has a significant impact on the amount of electricity it can generate, and on how this amount varies throughout the year. The array's production is maximal when its surface is perpendicular to the sun's rays. However, since the sun moves across the sky on a daily and seasonal basis, fixed surfaces cannot maintain a perpendicular orientation. Instead, an optimal orientation must be chosen based on intended use and on practical considerations such as the orientation of the surface (ex: rooftops, façades) on which the array is to be mounted.

In the Northern hemisphere, PV arrays are often South-facing, since the sun is due South at solar noon, when insolation is typically maximum. Meanwhile, the angle of inclination of a PV array away from the horizontal and toward the South, also known as its tilt or slope, can be chosen depending on the intended use (year-long vs. summer use, for example), as discussed below for the surface orientations examined here.

Five surface orientations of particular relevance for photovoltaic applications were selected for analysis among the 32 orientations presented in the CERES database. Four of the five orientations considered are fixed, while one tracks the sun along both the East-West and North-South axes. The four fixed surfaces are South (Equator)-facing, while their tilts are as follows: 90° tilt (vertical), latitude tilt (L), tilt = L-15°, tilt = L+15°

An example of the evolution of monthly mean daily insolation throughout the year is shown in Figure 2 for these 5 surface orientations. The sun-tracking surface orientation (FTS) receives the maximum insolation at any time, and is relevant for sun-tracking systems such as solar concentrators. As shown in the figure, the surfaces with higher tilts (90°, L+15°) receive less radiation on a yearly basis, but the irradiance received is more constant than for the surfaces with L and L-15° tilts. If a PV system user/designer seeks to ensure a more constant output, then higher tilts (L+15° or other) would be favourable since they maximize output in winter when insolation is minimum. Meanwhile, the yearly electricity production is maximized for tilts of a few degrees less than latitude tilt, so latitude tilt is often used as a rule-of-thumb. Finally, the L-15° tilt and lower tilts would be suitable for PV systems used predominantly in the summer. As for the 90° tilt, it applies to PV systems integrated into building façades or other vertical structures.

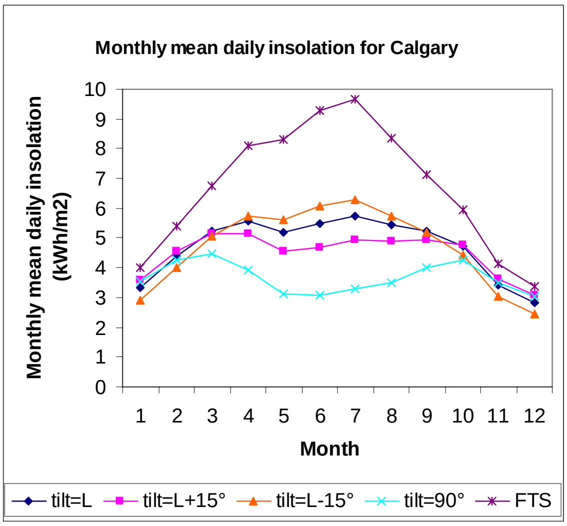

Figure 2: Yearly evolution of mean daily insolation for Calgary for five surface orientations

For a more detailed account of optimal surface orientations and PV system design in Canada, see the "Photovoltaic Systems Design Manual" 1991. Estimates of optimal surface tilts for each month and for the year can also be found in the NASA SSE data tables for individual locations [NASA SSE website, June 28, 2006]

2.3 The ANUSPLIN model

Details on the methods and model testing can be found in McKenney et al., (in preparation) and hence are only briefly described here.

We used the thin plate smoothing spline algorithms as implemented by the ANUSPLIN model [Australian National University website, June 28, 2006; e.g. Hutchinson 1995]. ANUSPLIN provides a practical means to rapidly develop and test alternative models incorporating different dependencies and resolve the final fitted models into useful map products. The software draws on thin plate smoothing splines as described by Wahba (1979), with an extension to partial models based on Bates et al. (1987). A comprehensive description of thin plate smoothing splines, including a number of extensions, has been given by Wahba (1990). ANUSPLIN calculates and optimizes full and partial thin plate smoothing splines fitted to data sets distributed across an unlimited number of climate station locations.

A number of models for interpolating radiation over the country were tested. Ultimately the radiation models selected were based on longitude, latitude and on a separate elevation-dependent spatial model of monthly precipitation. The dependence on precipitation allows for the known dependence of solar radiation on clouds associated with precipitation and gives rise to somewhat more complex solar radiation patterns than other models tested, especially in terrain where precipitation is closely tied to topography [Hutchinson, 1995]. This approach follows the modeling of solar radiation for Australia [Hutchinson et al., 1984]. The models presented in this paper made use of previously published precipitation surfaces (1971 to 2000 averages) that overlap the period of record for the insolation data [see McKenney et al 2001, 2006 for a description of the precipitation models].

Two different accuracy assessments were performed. The first was a (stringent) withheld data test where models were run with 30 stations withheld, and the second was a cross-validation analysis which basically assesses the error in the interpolation at each station when that station (and no other) is withheld [McKenney et al., in prep]. The generalized cross validation error (RTGCV, akin to a spatially averaged standard error) on monthly mean daily insolation in the final models that included all data ranged from 0.10-0.46 kWh/m^2 (3 to 14% of the network means) and root mean square model errors (RTMSE) ranged from 0.048 to 0.23 kWh/m^2 (1.6-7.3% of the network means). The mean RTGCV and RTMSE were 0.26 kWh/m^2 (7.1%) and 0.13 kWh/m^2 (3.4%), respectively.

Spatially explicit Baysian standard error maps were generated to provide users with a visual sense of the 95% confidence limits in the values.

The level of accuracy achieved compares very favorably to that obtained in other radiation maps of Canada. Reported RMSEs for the NASA satellite maps, for instance, are of 13 to 16% for horizontal insolation [NASA SSE website, June 28, 2006]. Meanwhile, RTGCV for the horizontal Canadian Forest Service maps akin to the ones in this study were of the order of 4 to 9% [Great Lakes Forestry Centre website, June 28, 2006].

2.4 Estimating PV electricity generation potential from the spatial radiation models

Photovoltaic modules are rated by manufacturers according to their nominal power, which is the power output corresponding to standard testing conditions (STC): 1000 W/m^2 irradiance with normal incidence, 25°C module temperature, air mass 1.5. Under these conditions (and assuming no losses), a 1 kW PV system is expected to produce 1 kW of electric power. However, actual operating conditions are typically quite different from standard testing conditions, and power losses occur both at the level of the PV arrays and at the level of the balance of system components: electric cables, power conditioning, etc. (In the scope of this paper only grid-connected systems with no batteries are considered). The losses and overall system performance are specific to each PV system, and depend on the type of PV module used (crystalline, polycrystalline, thin film), on its performance under different operating conditions (solar radiation intensity, angle of incidence, temperature, spectral distribution, etc.) and on overall system design [Poissant et al., 2003].

The overall system losses can be quantified by a performance ratio (PR), which is the ratio of actual system yield (kWh/kW) to the reference or nominal yield, which is numerically equal to the insolation in the plane of the PV array (kWh/m^2). The overall system efficiency is obtained by multiplying the PV module efficiency by the performance ratio. According to worldwide monitoring of 395 grid-connected PV systems by the International Energy Agency [IEA PVPS report T2-05:2004], yearly average performance ratios for photovoltaic systems built between 1996 and 2002 range from 0.4 to 0.85, with an average value of 0.702 and a peak (most common) value around 0.75.

In order to estimate the monthly/yearly electricity production per kilowatt of a typical PV system with the orientations examined here, a performance ratio of 0.75 was assumed, in which case the monthly/yearly electricity production per kW E/P is given by multiplying the monthly/yearly insolation by the overall system efficiency and the PV array area:

$$\frac{E}{P} = (H\ N) * (0.75\eta) * \left(\frac{1}{\eta}\frac{m^2}{kW}\right) = 0.75\, H\ N\, \frac{m^2}{kW} \qquad (1)$$

where H is the monthly/yearly mean daily insolation in the plane of the PV array, η is the rated or nominal PV array efficiency and N is the number of days in the month/year. Equation (1) was applied to the monthly insolation values H generated in the spatial radiation models to obtain the monthly PV electricity generation potential (in kWh/kW) on which the PV potential maps were based.

The corresponding electricity generation for a nominal power of P kilowatts is then simply:

$$E = P * \frac{E}{P} = 0.75\, H\, N\, P \frac{m^2}{kW} \qquad (2)$$

This can be used to estimate the PV electricity generation potential of photovoltaic systems with a given power rating. The PV electricity generation potential for PV systems mounted on buildings was calculated in another paper for all Canadian residential and commercial/institutional buildings in this way [Pelland and Poissant, in prep].

The approach based on performance ratios gives a quick and convenient way of obtaining a first estimate of the potential output of a PV system at a particular location. The approach is also reasonably accurate: more than two thirds of systems built in the 1996-2002 period monitored by the International Energy Agency had average annual performance ratios within 15% of 0.75. Of course, for the design of actual photovoltaic systems, technology specific performance assessments will yield a more accurate estimate.

It should be noted that the electricity production estimates above were not applied to the FTS surface orientation, since the 0.75 performance ratio may not accurately reflect the performance of tracking systems (e.g. higher operating temperature, lower reflection losses, mechanical failures).

2.5 Photovoltaic potential and insolation maps

All the insolation models were resolved (i.e. mapped), using a 300 arc second (~10km) Digital Elevation Model of Canada [Great Lakes Forestry Centre website, June 28, 2006]. This generated a set of 60 maps (5 orientations times 12 months). The monthly maps were also summed to obtain 5 yearly maps, for a total of 65 insolation maps. For the four fixed surfaces, the monthly insolation maps were transformed to photovoltaic power potential using equation (1) and also added together to generate annual photovoltaic power. This produced another 52 maps (4 orientations times 12 months and one year).

All these maps will be available over the internet to allow users to zoom and query any location in the country.

2.6 Photovoltaic power potential of Canadian municipalities

A useful attribute of the models is that they are spatially continuous, allowing for estimates at specific locations, rather than queries at the nearest grid cell. This added convenience of ANUSPLIN models is useful for quickly appending estimates of climate variables to, for example, field survey locations, farms or in our case Canadian municipalities. We used longitude and latitude coordinates and model estimates of mean monthly precipitation to generate PV potential estimates for 3540 municipalities in Canada [coordinates obtained from Géogratis website, June 28, 2006]. These values provide photovoltaic potential of Canadian municipalities for each fixed surface orientation, on a monthly and yearly basis. This database can be used by photovoltaic system designers to quickly assess photovoltaic potential at their location of choice. We demonstrate this by comparing and ranking municipalities and provincial “PV hotspots”.

3. DISCUSSION AND RESULTS

3.1 Maps

Five of the available maps are presented in Figures 3 to 7. The annual PV potential map for South-facing PV systems with latitude tilt is shown in Figure 3 and monthly PV potential maps for December, April, June and October are shown in Figures 4 to 7 respectively.

The Canadian average annual PV potential for latitude tilt is about 1130 kWh/kW. As shown in Figure 3, the maximum PV potential occurs in the Prairies, reaching the 1300-1400 kWh/kW range. This is comparable to the yearly potential in Miami (around 1395 kWh/kW for latitude tilt). Meanwhile, the lowest yearly PV potential range for Canada is around 700-800 kWh/kW (for certain regions in the North and on the West coast).

As expected, the annual PV potential values for the other fixed surfaces are slightly lower than for latitude tilt.

The monthly PV potential maps for latitude tilt show the progression of PV potential throughout the year. For latitude tilt, the average Canadian PV potential peaks in April. This reflects the fact that the sun’s rays are more nearly perpendicular to a latitude-tilted surface in the spring than in the summer (when irradiance is highest), with the impact of the surface orientation being dominant for most Canadian locations. For other surface orientations, the maximum is reached in different months: June for the FTS and tilt=L-15° surfaces, and March for the tilt=L+15° and tilt=90°surfaces. All the orientations have their lowest mean value over Canada in December. It should be noted that these results apply to mean values over Canada. The monthly evolution in a particular location can be somewhat different (see for instance Calgary results in Figure 2, which show a peak in July for PV systems with latitude tilt). Also, it should be noted that the 0.75 performance ratio used is an annual mean. The monthly variations in climatic factors from this mean are therefore not reflected on the monthly maps.

The higher latitudes near the poles exhibit the greatest seasonal variations in the amount of radiation received and the associated photovoltaic production potential, corresponding to the fact that these latitudes have the shortest days in the winter (polar nights) and the longest in the summer.

3.2 Photovoltaic potential of Canadian municipalities

The full results of the PV potential database for Canadian municipalities will be made available on the Internet. This database allows users to quickly estimate the output of a PV system at their location for any time of year, for the four fixed orientations.

An application of the models is presented in Table 1, which gives a ranking of the provincial and national capitals and of major cities in terms of the yearly photovoltaic production of 1 kW latitude tilted systems. The results are compared to photovoltaic production potential (for latitude tilt) in major cities worldwide (Table 2) (RETScreen insolation data was used, and PV potential was calculated using the methodology described in this paper).

Yearly PV potential for Canadian capitals and major cities ranges from 933 kWh/kW in St. John's, Newfoundland to 1361 kWh/kW in Regina, Saskatchewan. As expected from the yearly PV potential map (Figure 3), capitals and major cities in the Prairies (Regina, Calgary, Winnipeg) have the highest PV potential, while the lowest values occur in Newfoundland/Labrador (St. John's), the Yukon (Whitehorse) and British Columbia (Vancouver). As indicated in Table 2, the photovoltaic potential of all Canadian capitals compares favourably to those of major cities in Germany (Berlin) and Japan (Tokyo), the two world leading countries in terms of photovoltaic installed capacity. Meanwhile, the photovoltaic potential of Regina is slightly greater than that calculated for Sydney, Australia!

We have also mapped the location of the top "PV hotspots" in each province, i.e. the municipality in the database with the highest yearly photovoltaic production potential at latitude tilt (see Figure 3). As shown on the map, many of the PV hotspots (Regway, Rainy River, Waskada, Wild Horse) are located very close to the Canada/U.S. border. The best overall PV hotspot is Regway, Saskatchewan , which has a calculated yearly potential of 1384 kWh per kW of PV power installed.

It is useful to note that the location of the best Canadian PV potential hotspot changes from month to month. For instance, consider the case of Chesterfield Inlet in Nunavut that is North of the 60^{th} parallel. This region has very long daylight hours in the summer, therefore for a 4 month period Nunavut would be one of the PV hotspots in Canada if the period between March and June were considered.

4. CONCLUSION

New maps of global insolation and photovoltaic energy potential have been generated for all of Canada. They present yearly and monthly mean daily global insolation and PV production potential for a variety of different surfaces. Models dependent on position and precipitation as a surrogate for cloudiness were based on measured and modeled insolation data, at 144 locations in Canada and an additional 8 stations in Alaska. In addition to the maps, a PV potential database for over 3500 communities in Canada has been created.

The maps will be made available on the Natural Resources Canada website. It will be possible to "query" the maps at any chosen location in Canada. The map format produced by Natural Resources Canada allows for simple comparisons and integration with other spatial data. This is an important new tool to help Canadians gain an overall perspective of Canada's photovoltaic potential, and estimate photovoltaic system electricity production at any chosen location.

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TABLES AND FIGURES

Figure 1: Location of the 144 Canadian and 8 U.S. meteorological stations used as sources of insolation data

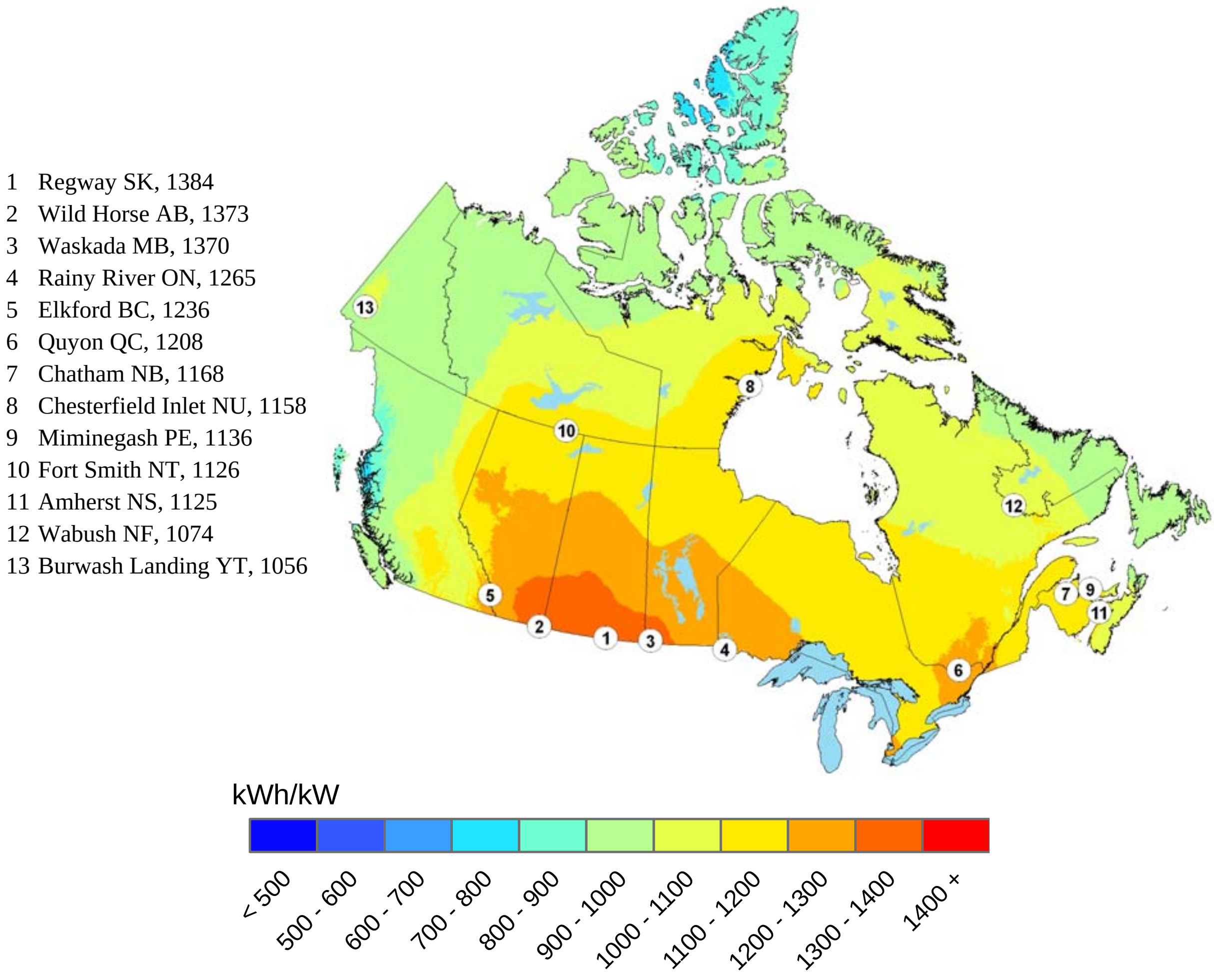
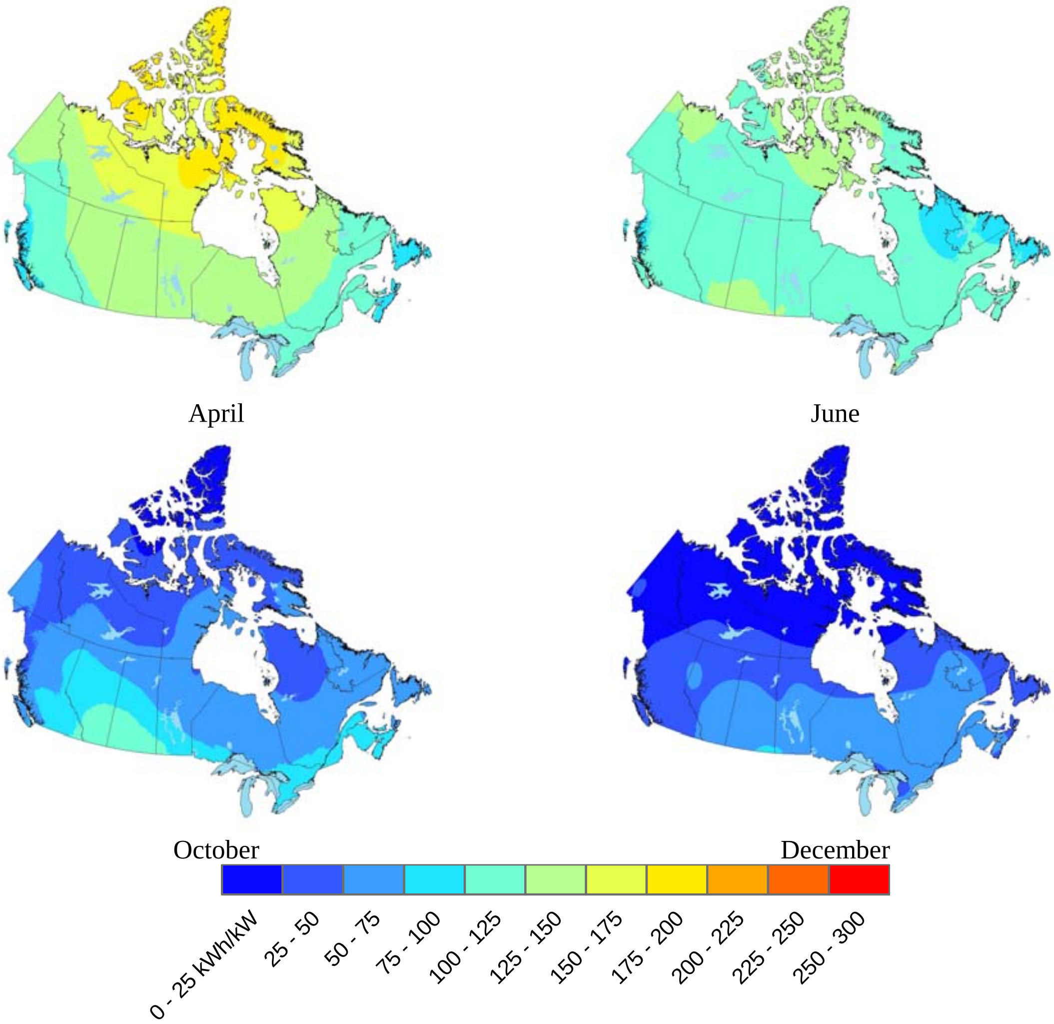


Figure 3: Yearly PV potential map for latitude tilt and the 13 "PV hotspots" in each province and territory in Canada.



Figures 4-7: Monthly PV potential maps at latitude tilt for April, June, October and December.

Table 1: Ranking of major Canadian cities and capitals in terms of yearly PV potential (latitude tilt)

Capital or major city	**Yearly PV potential (kWh/kW)**
Regina (Saskatchewan)	1361
Calgary (Alberta)	1292
Winnipeg (Manitoba)	1277
Edmonton (Alberta)	1245
Ottawa (Ontario)	1198
Montréal (Québec)	1185
Toronto (Ontario)	1161
Fredericton (New Brunswick)	1145
Québec (Québec)	1134
Charlottetown (Prince Edward Island)	1095
Yellowknife (Northwest Territories)	1094
Victoria (British Columbia)	1091
Halifax (Nova Scotia)	1074
Iqaluit (Nunavut)	1059
Vancouver (British Columbia)	1009
Whitehorse (Yukon)	960
St. John's (Newfoundland/Labrador)	933

Table 2: Ranking of major cities worldwide in terms of yearly PV potential for latitude tilt

City	**Yearly PV potential (kWh/kW)**
Cairo, Egypt	1635
Capetown, South Africa	1538
New Delhi, India	1523
Los Angeles, U.S.A	1485
Mexico City, Mexico	1425
Regina (SK), Canada	1361
Sydney, Australia	1343
Rome, Italy	1283
Rio de Janeiro, Brazil	1253
Ottawa (ON), Canada	1198
Beijing, China	1148
Washington, D.C., U.S.A.	1133
Paris, France	938
St. John's (NL), Canada	933
Tokyo, Japan	885
Berlin, Germany	848
Moscow, Russia	803
London, England	728