Maximizing Power Generation of a Solar PV System for a Potential Application at Musselwhite Gold Mine Site in Northwestern Ontario, Canada

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Abstract: Increasing global concern for greenhouse gas emission, air pollution, fossil fuel prices, and electricity demand has generated a significant increase in research of promising renewable energy technologies for green electrical power generation. Solar photovoltaic (PV) systems are known for their capabilities to directly convert renewable solar energy into electrical energy for locations with abundant solar energy where there is a desperate need and demand for electrical power. This includes mining industries in remote locations. Solar PV systems generate more power if they are installed and operated efficiently. The inclination angle at which a PV panel is tilted from the horizontal plane is one of the most influential system parameters that affect the amount of electrical power output from the PV system and the system's overall efficiency. Typically, the variation in the PV tilt angle determines the amount of incident solar radiation received on a PV panel to be utilized by a connected electrical load for use at a given site. In this paper, a mathematical model with numerical simulations are used to determine the total solar radiation incident on a tilted PV surface and to predict the optimum tilt angle for maximizing power generation from a solar PV system for potential application in Musselwhite Mine located in the remote northwestern region of Ontario, Canada. The total solar energy received on the optimally tilted PV surface is computed for all months in a year at the Musselwhite mine site. The results show that the monthly average optimum tilt angle of the PV system varied from a minimum value of 4° in the month of June to a maximum value of 74° in the months of January and December. It was also found that the highest maximum incident radiation of approximately 22.89 MJ/m2 for the whole year occurred in the month of April, whereas approximately 43.9% of this value (the lowest in the year) occurred in the month of December. The numerical simulation results suggest that PV systems are best be installed directly facing south at a fixed optimum tilt angle of 43° throughout the year at the Musselwhitemine site. This will improve the overall efficiency and save operating cost of the proposed PV system which in turn improves the commercial feasibility for the mining industry as an example of application.

Keywords: Northwestern Ontario, Renewable energy, Musselwhite gold mine, Solar PV systems, Maximum power generation, PV tilt angle, Remote locations, Canada.

1. INTRODUCTION

Solar photovoltaic systems are known for their capabilities and have been used in many applications, including various industries, to directly convert the renewable solar energy into electrical energy for locations with abundant solar energy where there is a desperate need and demand for electrical power. There are enormous citations on the use of Solar PV systems for different applications. This includes mining Industries in remote locations. Solar PV systems generate more power if they are installed and operated efficiently. The Musselwhite mine (latitude = 52.6^{o} N and longitude = 90.4^{o} W) is one of the largest gold mines in Canada and in the World [1]. It is located in northwestern Ontario in a fly-in, fly-out operation on the southern shore of Opapimiskan Lake, about 480 km north of Thunder Bay city in North West Ontario, Canada. The Musselwhite property is approximately 175 km^2, entirely on First Nations Land. It has 300-500

workers at the mine site. The all-weather road connects the mine to the nearest community of Pickle Lake, which is about 200 km to the south [1]. A photograph showing an aerial view of Musselwhite gold mine is shown in Figure **1(a)** [1], and the map location of the mine is shown in Figure **1(b)**.

At the Musselwhite mine site, the maximum and minimum average monthly temperatures of 17.1 ^{o}C and -20.6 ^{o}C occur in the months of July and January, respectively [2]. In Canada, Solar PV technology has become one of the preferred forms of renewable energy technology for direct electrical power generation due to a number of economic and social factors, including the need to reduce greenhouse gas (GHG) emissions, deregulation, and the restructuring of electric power generating companies. The rapid growth in the installation of solar PV systems recently indicates that the technology is rapidly gaining ground in Canada [3]. The utilization of solar PV systems for electrical power generation is a useful and convenient technology at Musselwhite mine due to its relatively remote location, the increasing demand due to increase in population and industrial consumption of electrical

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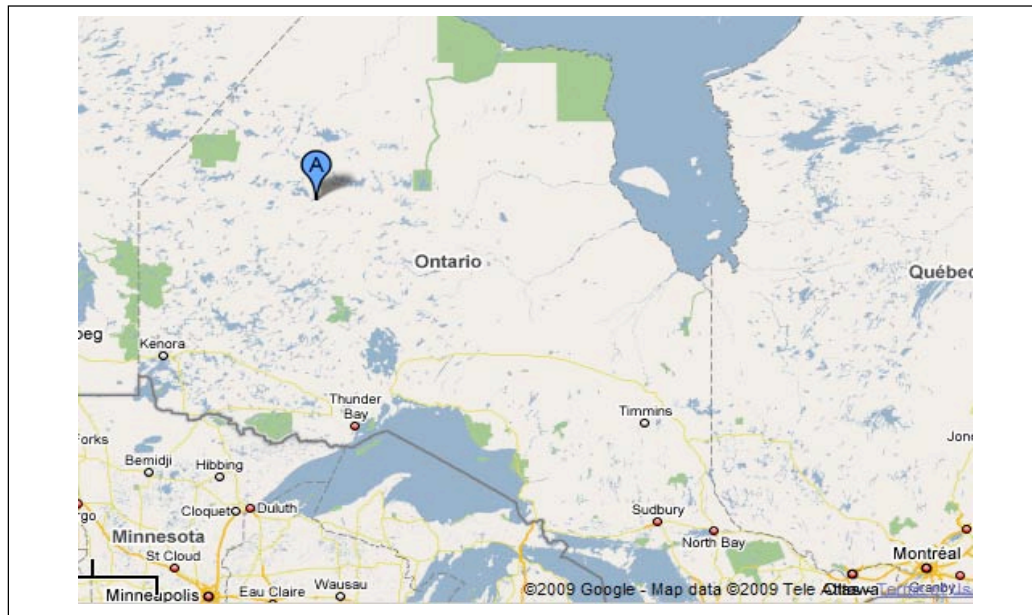**Figure 1(a):** A photograph showing an aerial view of the Musselwhite mine site [1].

Figure 1(b): Location of Musselwhite Mine, Ontario, Canada (labeled as "A"). Google maps.

power, the limitation on the existing power sources of electricity, and the abundance of renewable solar energy. Musselwhite mine site has annually averaged daily sunshine hours of approximately 12.0 hours, and a monthly average daily insolation incident on a horizontal surface of approximately 11.748 MJ/m^2 [4]. It would be more efficient to optimize the performance of PV systems potentially installed at the Musselwhite mine site in order to maximize their electrical power production and justify their economics.

The tilt angle at which a PV panel is tilted from the horizontal plane is one of the most detrimental system parameters that affect the amount of electrical power output from the PV system and the system's overall efficiency [5,6]. Therefore, in order to maximize the overall power production of a PV system throughout a year, the tilt angle of the PV system should be optimized for a given geographical site, considering PV systems fixed at a certain tilt angle throughout the year in that site. In addition, positioning the PV system at an

optimum tilt angle leads to an appreciably lesser PV array area required to match a fixed electrical load, thus reducing the capital cost and improving the economics of the PV system. This also applies to thermal solar collectors used for heating applications in general. Hence, it will be more efficient to maximize the utilization of the incident solar energy on PV systems by optimizing the tilt angle of PV systems installed at the Musselwhite mine site. There are many papers and investigations which involved experimental and/or numerical studies related to optimization of the orienta-tion of PV systems. A number of examples are given in references [7-10]. In this paper, a widely used mathe-matical model, developed by Liu and Jordan (1962) [11] and extended by Klein (1977) [12], is used to estimate and predict the total solar radiation incident on an inclined PV surface and to determine the optimum tilt angle for maximizing power generation from a solar PV system installed at Musselwhite mine site. Detailed numerical simulations were performed using this mathematical model and the total solar energy received on the optimally inclined PV surface was computed for all months in a year and presented for the four seasons in a year; namely, winter, spring, summer, and autumn. Also, the yearly averaged optimum tilt angle for the PV system installation at the Musselwhite mine site was determined. This work provides practical insights for improving the overall efficiency and saving the operating cost of the proposed PV system which in turn improves the commercial feasibility for the mining industry as an example of application, especially when implemented on a large scale as improving economics becomes more pronounced.

2. MATHEMATICAL MODEL AND COMPUTATION METHODOLOGY

The monthly average daily solar radiation, $\bar{H}_T$, impinging on an unshaded inclined (tilted) surface with an angle β from a horizontal plane on a site at a latitude ϕ north of Equator and directly pointed towards the Equator (so that the solar azimuth angle $\gamma = 0$) can be estimated using the widely used mathematical model developed by [11,12] given by:

$$\bar{H}_T = \bar{H}_{b,T} + \bar{H}_{d,T} + \bar{H}_{g,T} \tag{1}$$

In Equation (1), $\bar{H}_T$ (MJ/m^2) is modeled as the sum of three solar radiation components: (1) the beam (direct) radiation incident on the tilted surface, $\bar{H}_{b,T}$, (2) the sky-diffuse radiation received on the tilted surface $\bar{H}_{d,T}$, and (3) the ground-reflected radiation

received on the tilted surface $\bar{H}_{g,T}$. Mathematically, these three components of solar radiation are expressed using the following equations:

$$\bar{H}_{b,T} = \bar{H}\left(1 - \frac{\bar{H}_d}{\bar{H}}\right)\bar{R}_b \tag{2}$$

$$\bar{H}_{d,T} = \bar{H}_d \left(\frac{1 + \cos\beta}{2}\right) \tag{3}$$

$$\bar{H}_{g,T} = \bar{H}\,\bar{\rho}_g\left(\frac{1 - \cos\beta}{2}\right) \tag{4}$$

It should be noted that the sky-diffuse and ground-reflected components of radiation on the tilted surface are each assumed to be isotropic (i.e. this model is referred to as the isotropic sky model). Figure **2** shows the basic solar angles used in the above model [13]. In the above equations, the term $\bar{H}$ (MJ/m^2) is the monthly average daily total terrestrial radiation incident on a horizontal surface (i.e. $\beta = 0$); $\bar{H}_d$ (MJ/m^2) is the monthly average daily sky-diffuse radiation incident on a horizontal surface; and $\bar{\rho}_g$ is the monthly average daily ground reflectivity (also known as albedo). The ratio $\dfrac{\bar{H}_d}{\bar{H}}$ is computed using the following correlations [11,12]:

(a) For $\omega_s \le 81.4^o$ and $0.3 \le \bar{K}_T \le 0.8$, the following correlation is used:

$$\left(\frac{\bar{H}_d}{\bar{H}}\right) = 1.391 - 3.560\,\bar{K}_T + 4.189\left(\bar{K}_T\right)^2 - 2.137\left(\bar{K}_T\right)^3 \tag{5}$$

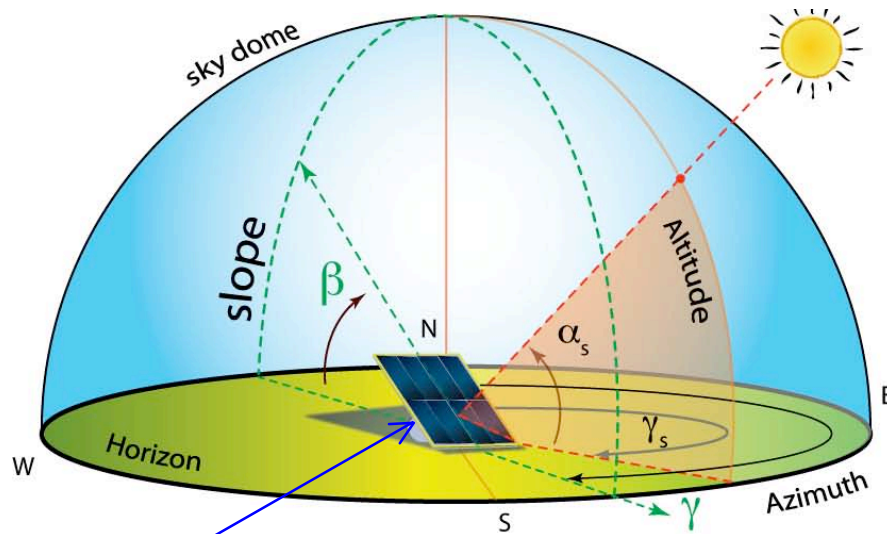(b) For $\omega_s > 81.4^o$ and $0.3 \le \bar{K}_T \le 0.8$, the following correlation is used:

$$\left(\frac{\bar{H}_d}{\bar{H}}\right) = 1.311 - 3.022\,\bar{K}_T + 3.427\left(\bar{K}_T\right)^2 - 1.821\left(\bar{K}_T\right)^3 \tag{6}$$

In both correlations above, the sunset hour angle ω_s can be computed using:

$$\omega_S = \cos^{-1}\left(-\tan\phi\tan\delta\right) \tag{7}$$

where the solar declination angle δ as a function of the day in the year *n* is computed using:

$$\delta = 23.45\sin\left[360\frac{(284 + n)}{365}\right] \tag{8}$$

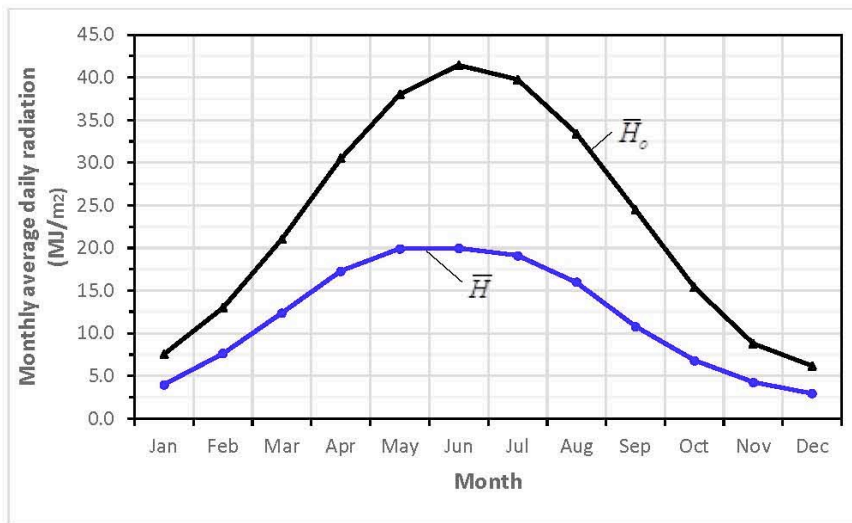**Figure 2:** A conceptual illustration showing basic solar angles used in this study [9].

Figure 3: Comparison of the monthly average daily solar radiation (extraterrestrial vs. terrestrial) incident on a horizontal PV module at Musselwhite mine site.

The monthly average daily clearness index $\bar{K}_T$ appearing in Equations (5) and (6) above is defined using:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} \tag{9}$$

where, $\bar{H}_o$ (MJ/m^2) is monthly average daily extra-terrestrial radiation received on a horizontal surface, estimated by:

$$\bar{H}_o = \frac{24*3600*1367}{\pi}\left(1+0.033\cos\frac{360*n}{365}\right)* \tag{10}$$
$$\left(\cos\varphi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right)$$

In this work, $\bar{H}$ values for Musselwhite location (based on monthly averaged values over 22 years of data [4]) and the estimated $\bar{H}_o$ (using Equation 10) are compared and shown in Figure **3**. In Equation (2), the

parameter $\bar{R}_b$ is known as the beam geometric factor for the mean day of the month, expressed by:

$$\bar{R}_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\ \omega_s'\sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\pi/180)\ \omega_s\sin\varphi\sin\delta} \quad (11)$$

where ω_s' is the sunset hour angle for the tilted surface for the mean day of the month, which is given by:

$$\omega_s' = \min \begin{bmatrix} \cos^{-1}\left(-\tan\varphi\tan\delta\right) \\ \cos^{-1}\left(-\tan(\varphi-\beta)\tan\delta\right) \end{bmatrix} \quad (12)$$

where "min" means the smaller of the two terms in the brackets. The monthly average daily number of sunlight hours can be computed using:

$$N = \frac{2}{15}\cos^{-1}\left(-\tan\varphi\tan\delta\right) \quad (13)$$

The yearly average monthly optimum tilt angle for the PV system installed at Musselwhite mine site can be determined using the simple mathematical relationship given by:

$$\left(\bar{\beta}_{opt}\right)_{year} = \frac{\Sigma_{Jan}^{Dec}\beta_{opt}}{12} \quad (14)$$

A schematic diagram showing a flowchart summarizing the computation process is shown in Figure **4**. In this study, the computation procedure was implemented systematically using the set of Equations (1) to (12) and by varying the inclination (tilt) angle β from 0^0 to 90° with an increment of 3° for every month in the year considering the mean day for every month. The results of $\bar{H}_T$ pertaining to all sets of angles for a particular month were compared and the tilt angle that produces the maximum value for $\bar{H}_T$ (thus, called $\bar{H}_{T,\max}$) was assigned as the optimum tilt angle for that month in the year. As shown in Figure **4**, the computation procedure was repeated for all months in
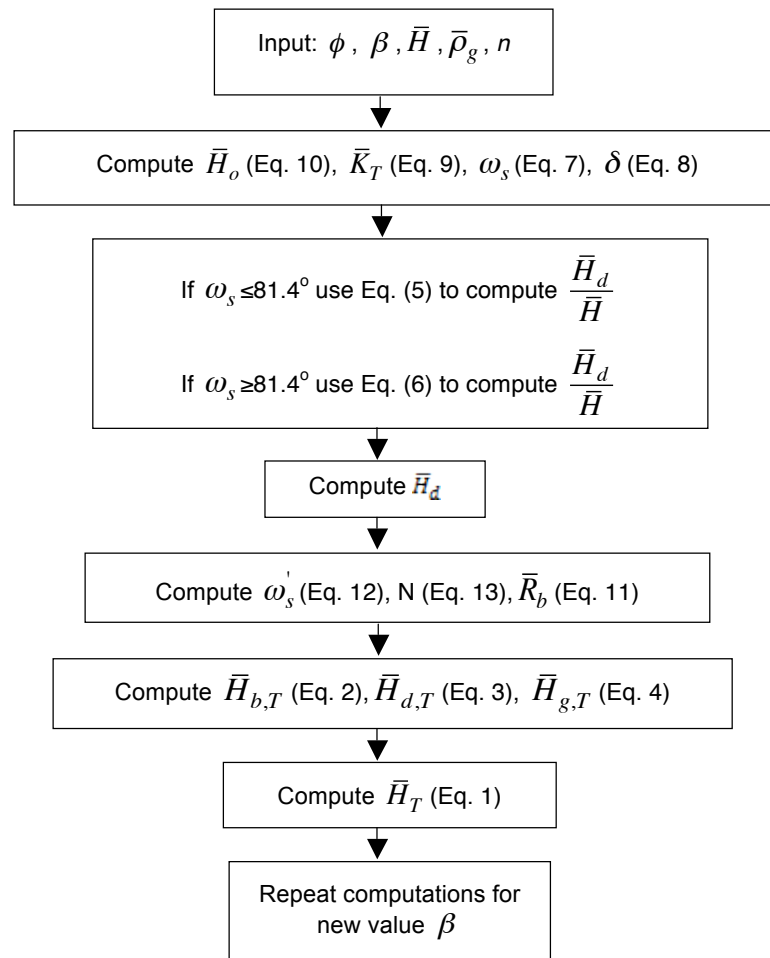
Input: ϕ, β, $\bar{H}$, $\bar{\rho}_g$, n

Compute $\bar{H}_o$ (Eq. 10), $\bar{K}_T$ (Eq. 9), ω_s (Eq. 7), δ (Eq. 8)

If $\omega_s \le 81.4^\circ$ use Eq. (5) to compute $\dfrac{\bar{H}_d}{\bar{H}}$

If $\omega_s \ge 81.4^\circ$ use Eq. (6) to compute $\dfrac{\bar{H}_d}{\bar{H}}$

Compute $\bar{H}_d$

Compute ω_s' (Eq. 12), N (Eq. 13), $\bar{R}_b$ (Eq. 11)

Compute $\bar{H}_{b,T}$ (Eq. 2), $\bar{H}_{d,T}$ (Eq. 3), $\bar{H}_{g,T}$ (Eq. 4)

Compute $\bar{H}_T$ (Eq. 1)

Repeat computations for new value β

Figure 4: A schematic showing a flowchart for performing numerical simulations used in this study.
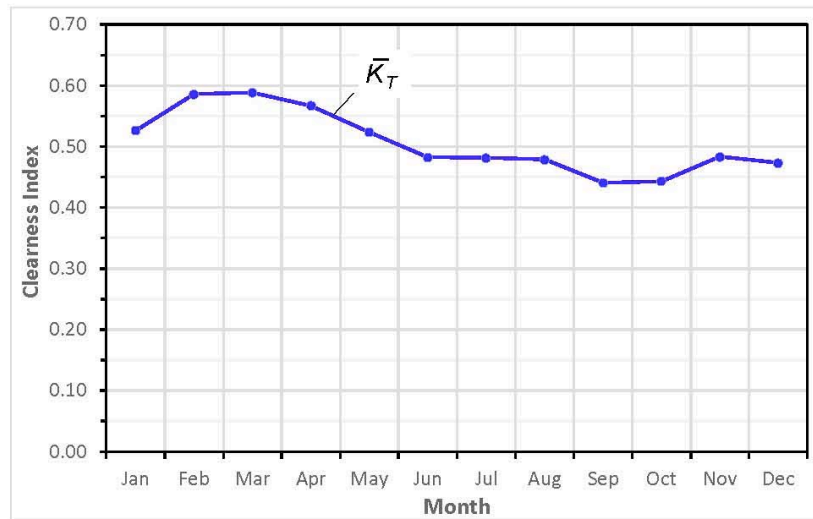
Figure 5: The estimated monthly average daily clearness index for a solar PV module at the Musselwhite mine site.
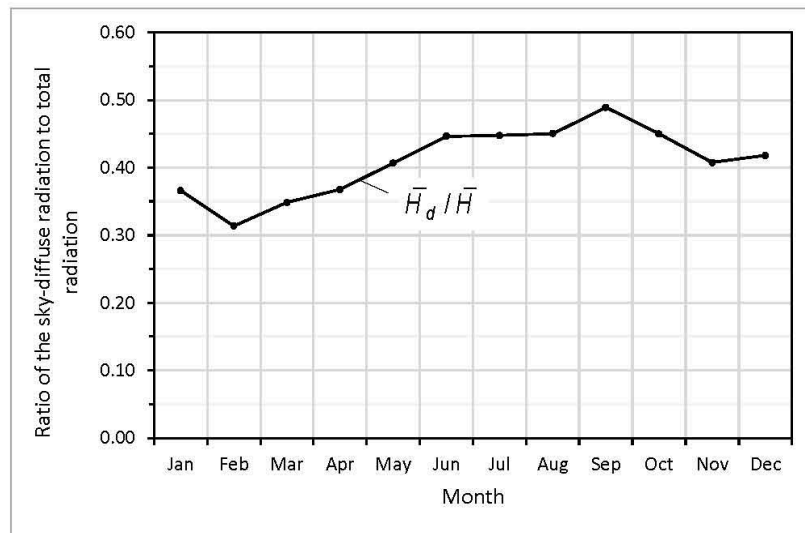

Figure 6: The estimated ratio of the monthly average daily diffuse solar radiation to global radiation incident on a horizontal PV module at Musselwhite mine site.

the year using detailed simulations and the optimum tilt angles for all months for the PV system to be potentially installed at the Musselwhite mine site were determined.

3. RESULTS AND DISCUSSION

Following the mathematical model and computation procedure presented in the previous section, the results are presented and discussed in this section. Figure **5** shows a comparison for the monthly average daily clearness index for all months in the year. The maximum clearness index occurred in the month of March with a value of approximately 59%, whereas the

minimum value of approximately 44% occurred in September. The ratio of sky-diffuse to total radiation on a horizontal PV system was determined for all months in the year and compared in Figure **6**. The ratio varied from approximately 0.314 to 0.489 with the maximum value being in the month of September and the minimum being in the month of February. This indicates that the value of the monthly average daily sky-diffuse component of radiation received on a horizontal surface at the Musselwhite mine site was found maximum in the month of September, which is nearly 49% of its corresponding $\bar{H}$ value. Comparison of the estimated monthly average daily solar radiation

incident on a tilted PV system at Musselwhite mine site, for the months of December, January, and February (representing the cold winter season) as a function of tilt angle, is shown in Figure **7**. The highest estimated values of $\bar{H}_T$ occurred in the month of February for all tilt angles compared to the months of December and January. In particular, at a tilt angle of 66°, the maximum incident solar radiation in the month of February was approximately 18.70 MJ/m^2. However, the maximum incident solar radiation for the months of December and January occurred both at the same tilt angle of approximately 74° with values of 10.04 MJ/m^2 and 13.04 MJ/m^2, respectively. The minimum incident solar radiation for all months in the winter season occurred at a tilt angle = 0 (i.e. the PV system is positioned horizontally). It should be noted that the

incident solar radiation initially increased rapidly and monotonically for the three months as the tilt angle increased from horizontal position until the tilt angle was approximately 52° after which the increase in the incident solar radiation became relatively smaller. For this case, the average optimum tilt angle that produced an average maximum incident solar radiation of 13.93 MJ/m^2 on the PV system installed at Musselwhite mine site for the winter season was approximately 74°.

The estimated monthly average daily solar radiation incident on a tilted PV system Musselwhite mine site for the months of March, April, and May (representing the spring season) as a function of tilt angle, is compared and shown in Figure **8**. For these three months, the maximum incident solar radiation occurred
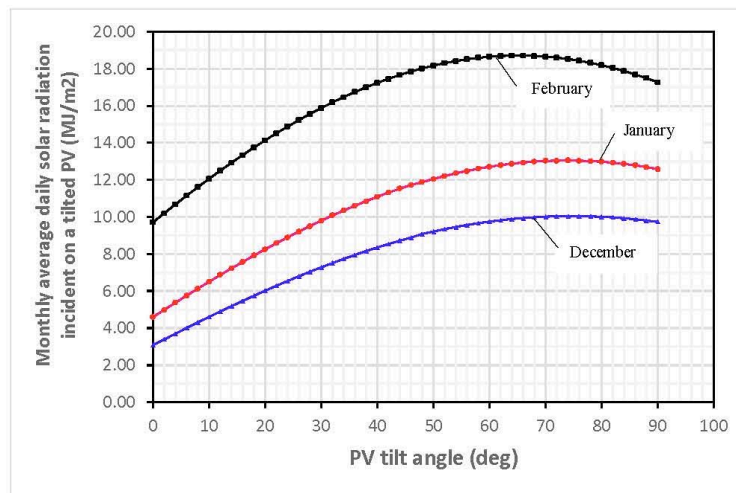

Figure 7: Comparison of the estimated monthly average daily solar radiation incident on a tilted PV module at Musselwhite mine site, for the cold season (months of December, January and February) as a function of the PV module tilt angle.
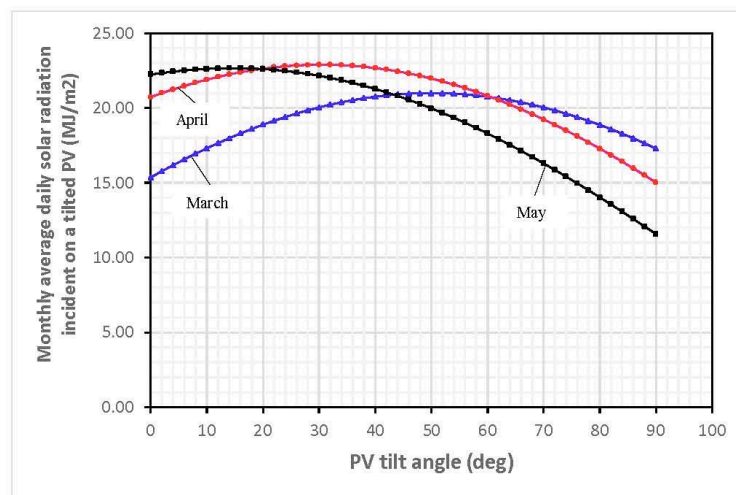

Figure 8: Comparison of the estimated monthly average daily solar radiation incident on a tilted PV module at Musselwhite mine site, for the spring season (months of March, April, and May) as a function of the PV module tilt angle.

at significantly different tilt angles. For example, the maximum incident solar radiation of approximately 20.99 MJ/m^2 for the month of March at the Musselwhite mine site occurred at an optimum tilt angle of 50°. However, for the months of April and May, the maximum incident solar radiation of fairly higher values approximately 22.89 MJ/m^2 and 22.63 MJ/m^2 occurred at relatively smaller optimum tilt angles of 30° and 22°, respectively. It is interesting to note that for the month of May, the incident solar radiation initially increased slowly and gradually as the tilt angle increased from 0 to 20° and then started to decrease rapidly as the tilt angle continued to increase until the incident radiation hit a minimum value of approximately 11.58 MJ/m^2 as the PV system is positioned vertically (i.e. tilt angle = 90°). For the spring season at the Musselwhite mine site, the highest minimum value of the monthly average incident solar radiation of approximately 17.28 MJ/m^2 on the vertically positioned PV system occurred in the month of March. It is also interesting to note that at a tilt angle of approximately 60°, the value of the incident solar radiation is almost the same for March and April being approximately 20.81 MJ/m^2, whereas it is 44° for March and May being 20.80 MJ/m^2. The average optimum tilt angle of the PV system installed at the Musselwhite mine site for the spring season was approximately 51°.

Figure **9** shows a comparison of the estimated monthly average daily incident solar radiation at the Musselwhite mine site for the summer season (months of June, July, and August) as a function of the tilt angle of the PV module system. For this case, the incident solar radiation profiles look very similar for the months of June and July whereas they differ from the month of August. The optimum tilt angle of the PV system was the lowest being 4° in the month of June with a maximum incident solar radiation of nearly 20.74 MJ/m^2 that slightly dropped to 19.92 MJ/m^2 in the month of July at an optimum tilt angle of 10°. The optimum tilt angle was relatively higher being 22° in the month of August with a lesser value of the maximum incident solar radiation of approximately 17.38 MJ/m^2 relative to the months of June and July. The average optimum angle of the PV system for the summer season at the Musselwhite mine site was computed to be approximately 18° with an average maximum incident solar radiation of nearly 19.35 MJ/m^2.

The estimated monthly average daily solar radiation incident on the inclined PV system Musselwhite mine site for the months of September, October, and November (representing the autumn/fall season) as a function of tilt angle, is compared and shown in Figure **10**. For these three months, the variation of the incident solar radiation with respect to the tilt angle of the PV system looks more considerable. The results show that the highest incident solar radiation in the autumn season occurred for the month of September with a value of approximately 12.59 MJ/m^2 at an optimum tilt angle of 40°. The optimum tilt angles for the months of September, October, and November are 40°, 56°, and 72°, respectively, and their respective estimated amounts of maximum incident solar radiation are 12.59, 11.47, and 11.73 MJ/m^2. It is interesting to note that the increase in the incident solar radiation was
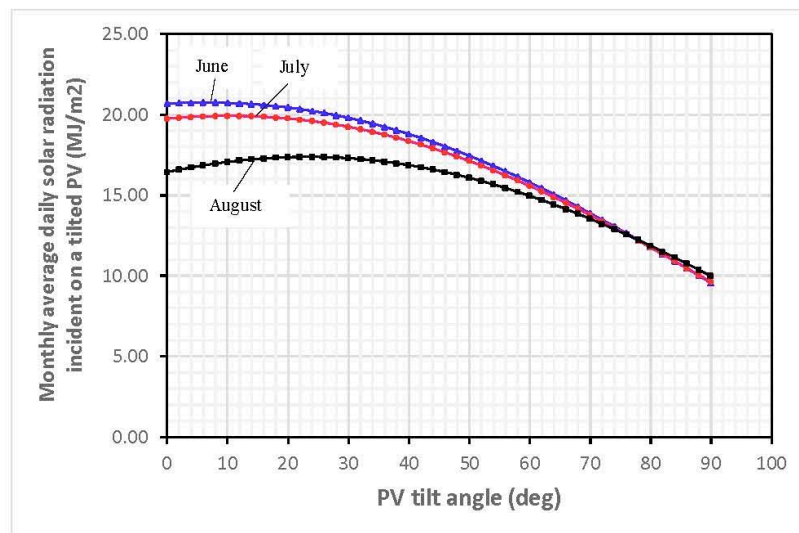

Figure 9: Comparison of the estimated monthly average daily solar radiation incident on a tilted PV module at Musselwhite mine site, for the summer season (months of June, July, and August) as a function of the PV module tilt angle.
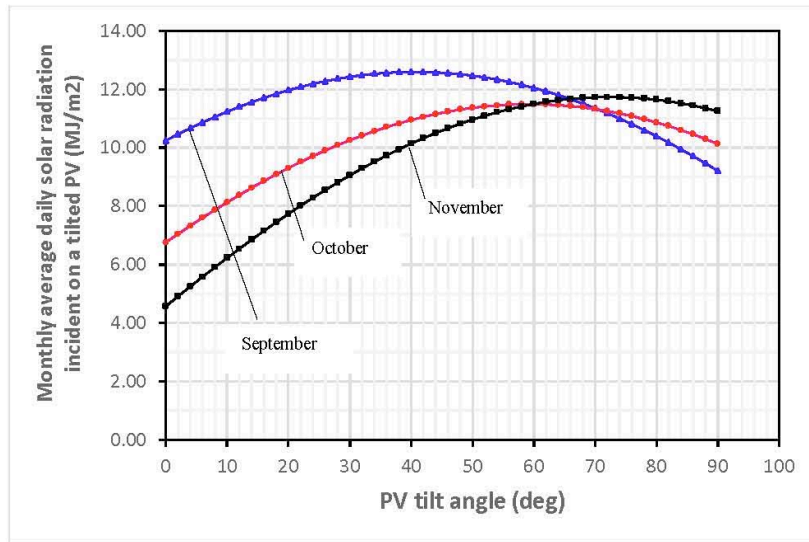
Figure 10: Comparison of the estimated monthly average daily solar radiation incident on a tilted PV module at Musselwhite mine site, for the Fall season (months of September, October, and November) as a function of the PV module tilt angle.
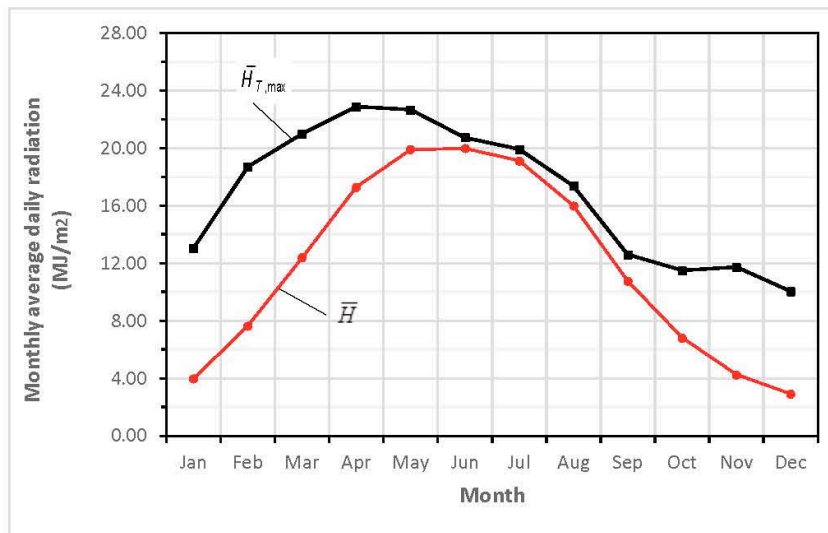

Figure 11: Comparison of the estimated maximum monthly average daily solar radiation incident on an optimally tilted PV module at Musselwhite mine site as a function of the month in the year.

rapid at smaller tilt angles for all the months in the autumn season. The average optimum tilt angle for the autumn season is approximately 56° with an average maximum incident radiation of approximately 11.93 MJ/m².

Figure **11** shows the comparison of the estimated values of maximum monthly average daily solar radiation incident on an optimally tilted PV module at Musselwhite mine site, as a function of the month in the year. The highest maximum incident radiation of approximately 22.89 MJ/m² for the whole year occurred in the month of April, whereas approximately 43.9% of

this value (the lowest in the year) occurred in the month of December. It is worth noting that the optimum tilt angle for the month of June is nearly horizontal with only 6⁰. Table **1** summarizes the results of the monthly optimum tilt angles and their respective maximum incident monthly average daily solar radiation for the tilted PV system installed at Musselwhite mine site. The yearly average monthly optimum tilt angle for the PV system at the Musselwhite mine site was estimated to be 43°. The variation of the monthly average daily sunlight hours varied from 7 hours in December to as high as 17 hours in June.

Table 1:   **Summary of Monthly Optimum Tilt Angles and their Corresponding Maximum Incident Monthly Average Daily Solar Radiation for the Tilted PV System Installed at Musselwhite Mine Site**

Month	β_{opt} (Degrees)	$\bar{H}_{T,\max}$ (MJ/m^2)	N (Hours)
Jan	74	13.04	8
Feb	66	18.70	10
Mar	50	20.99	12
Apr	30	22.89	14
May	22	22.63	16
Jun	4	20.74	17
Jul	10	19.92	16
Aug	22	17.38	14
Sep	40	12.59	12
Oct	56	11.47	10
Nov	72	11.73	8
Dec	74	10.04	7

$$\left(\bar{\beta}_{opt}\right)_{year} = 43°$$

4. CONCLUSIONS

In Canada, Solar PV technology has become one of the most favored forms of renewable energy systems for direct electrical power generation due to a number of social and economic factors, including the need to reduce greenhouse gas (GHG) emissions, deregulation, and the restructuring of electric power generating companies. The rapid growth in the installation of solar PV systems recently indicates that the technology is rapidly gaining ground in Canada. Musselwhite mine is one of the largest gold mines in Canada and in the World. It is located in northwestern Ontario in a fly-in, fly-out operation on the southern shore of Opapimiskan Lake, about 480 km north of Thunder Bay city in North West Ontario, Canada. The utilization of solar PV systems for electrical power generation is a useful and convenient technology at the Musselwhite mine site due to its relatively remote location, the increasing demand and community consumption for electrical power, and the abundance of renewable solar energy. PV systems tend to generate more power if they are operated efficiently and consistently. The tilt angle at which a solar PV module is tilted from the horizontal plane is one of the most detrimental system parameters that affect the electrical power output from the PV system. In this work, a well-established mathematical model was used to estimate the total solar radiation incident on an inclined surface and to determine the optimum inclination angle for maximizing power generation from a solar PV system installed at the Musselwhite mine site. It was found that the monthly average optimum tilt angle of the PV system varied from a minimum value of 4° in the month of June to a maximum value of 74° in the months of January and December. The yearly average monthly optimum tilt angle for the fixed PV system at the Musselwhite mine site was estimated to be at 43°. It was also found that the highest maximum incident radiation of approximately 22.89 MJ/m^2 for the whole year occurred in the month of April with daylight hours of 14, whereas approximately 43.9% of this value (the lowest in the year) occurred in the month of December. For maximum power reception on PV systems and higher production efficiency, the results suggest that PV systems are best be installed directly facing south at a fixed optimum tilt angle of 43° throughout the year at the Musselwhite mine site. This will improve the overall efficiency and saving operating cost of the proposed PV system which in turn improves the commercial feasibility for the mining industry as an example of application. Future work is recommended for evaluating the use of this method and its impact on the economics for large scale implementation of PV systems. Future work may also include experimental validation of the model used in this work.

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