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Comparison of 1 MW Grid-Connected PV System and a Stand-Alone System to Determine Canada's Potential

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Abstract: *Canada is one of the highest energy consuming countries and it remains in the list of the least photovoltaic energy producing countries. Various factors engulf the lack of awareness among the people to dig into the true potential that is present in Canada for utilizing photovoltaic system. Lack of available technical information of photovoltaic systems for the common people to understand, extreme winter in Canada and the cost of photovoltaic systems are perhaps the main reasons of holding people away from investing in this sector. This paper is aimed at revealing the true potential of Canada in generating photovoltaic power. It presents a comparative study in terms of available solar irradiance, peak sun hour, tilt angle, temperature and power production through the selection of nineteen sites across Canada, three sites from USA and four sites from Germany. The power production was compared through designing a 1 MW grid-connected system and a standard standalone system for all the sites. An on-line survey was conducted to assess the interest level of general masses in Canada for photovoltaic systems and to know what is their understanding about the available technical information. This study reveals that Canada has tremendous potential to be a world leader*

I. Introduction

Renewable energy has become a popular topic of research, discussion and implementation all around the world as the concern about diminishing natural resources is growing. Throughout the world, nations are taking necessary steps for strengthening the renewable energy sector.

Among all the renewable energy sources, photovoltaic system has tremendous potential because of the abundant solar energy, ease of harvesting the energy and longevity of the photovoltaic modules. As of 2010, the total capacity of green power generation through photovoltaic system across the world was 40 GW and Germany's capacity alone contributed approximately 44% of it [1]. Compared to the power generated by the photovoltaic systems in the world, the total global wind power generation capacity was around 198 GW, which translates to almost four times to that of PV system's capacity. In the same year the total global capacity of electricity generation was 4,950 GW, and only 26.67% or 1,320 GW was produced by all means of renewable energy sources. Among the 1,320 GW capacity of renewable energy production, only about 3% or 40 GW was generated by photovoltaic systems, which was equivalent to 0.81% of the total global electricity generation capacity [1]. As of 2010, Canada only had a capacity of 0.29 GW [2] of photovoltaic systems whereas USA had a capacity of 2.54GW and Germany had a capacity of 17.66GW [1]. Thus, Canada only constituted a share of 0.73% of the global PV systems.

Despite the lack of dominance of photovoltaic systems in producing renewable energy globally, lots of works has been done regarding the development of photovoltaic system [3]-[9]. References [10]-[12] address marketing issues, cost of photovoltaic systems and some other issues.

Canada is among a few countries in the world that has the highest amount of electricity consumption per capita. In 2009, Canada's per capita electricity consumption was 15.47 MWh, while the same for USA, Germany, Brazil, China and India were 12.91 MWh, 6.78 MWh, 2.21 MWh, 2.63 MWh and 0.57 MWh, respectively [13]. Being such a giant consumer, which is 180.8% more than Germany and 21.3% more than USA, and having a photovoltaic electricity generation capacity of only 0.73%, Canada is severely lacking behind in the photovoltaic sector. This puts up Canada to a whole new challenge for utilizing the unlimited energy provided by the sun. Canada, being an energy superpower because of all the abundance of natural resources, is yet to move up to the competition in renewable energy, particularly in photovoltaic system. Although wind energy is showing up its popularity in Canada, with a total installed capacity of 5,511 MW [14], its solar energy utilization is not something to be proud of yet. This paper is aimed at studying the potential of growing the energy production through photovoltaic systems in Canada.

II. Methodology

One of the prime factors of utilizing solar energy is the amount of solar insolation that is reaching the surface. Abundant amount of solar energy on the surface can be a definite advantage for photovoltaic systems. Alongside, output generated by photovoltaic modules is also dependent on the operating temperature of the panel

[15], optimized mounted angle, peek sun hour, module size along with shading of the panels [16]. But in this work, the effect of shading will not be considered since it is a location, position and seasonal variable. Temperature and irradiance are considered as global variables which depends on weather and geographic location. These can be used to compare places as these two variables exist in all the places. Reference [16] presents the works that have already been done regarding shading losses in photovoltaic modules.

This study was primarily focused on finding the absolute potential of Canada in terms of photovoltaic power generation ability. The potential is determined through a comparative study among nineteen sites across Canada, three sites in USA and four sites in the photovoltaic giant, Germany. A grid-connected 1 MW photovoltaic system and a standalone system to meet 781 kWh/month loads were designed for all the sites. The sites in Canada are: Calgary, Charlottetown, Edmonton, Fredericton, Halifax, Iqaluit, Kelowna, Lethbridge, Montreal, Ottawa, Prince George, Regina, Saskatoon, St. John's, Toronto, Vancouver, Victoria White Horse and Winnipeg. The sites in USA are: New York City, San Francisco and Seattle. And from Germany: Braunschweig, Berlin, Frankfurt and Munich.

The variable parameters, which are site dependent include: irradiance (W/m^2), peak sun hour or PSH (number of hours for which the solar irradiance is 1 kWh/m^2), tilt angle (the angle between the photovoltaic module and the flat surface for optimum power output), and temperature. The fixed parameters include: size of the designed system, module that was used for the system design and inverter size. These three parameters were kept unchanged for the grid-connected and standalone system design for all the sites and hence they are appointed as fixed parameters. With these fixed parameters, some other technical parameters such as conversion efficiency, area, various losses remained unchanged. The critical and noncritical type of loads and hence the storage requirement was also considered.

The photovoltaic systems were designed using PVSyst [17] and the variable parameters were obtained using Meteonorm [18]. A survey was conducted to see how far the people in Canada are aware and interested in photovoltaic systems.

III. Public Interest and Awareness

Behind every major application which affects the end-user, there has to be interest and willingness to invest among potential investors. And since photovoltaic systems are for end-use, people's opinions, interest and awareness can be important factors. And this can only be assured through availability of proper information and through researches. People should have access to information that is more understandable by everyone and not only experts so that they can have a clear idea about photovoltaic systems, the advantages of having them and should be cleared of the misconceptions that might pre-exist among them.

Noting the importance of people's knowledge on photovoltaic systems, this work was started with a survey to find out where they are standing on photovoltaic systems. Instead of highlighting on technical facts, this survey was mainly focused on three separate factors: how aware the people are about photovoltaic systems, what are their thoughts on the amount of information available and how interested they are to invest for this technology.

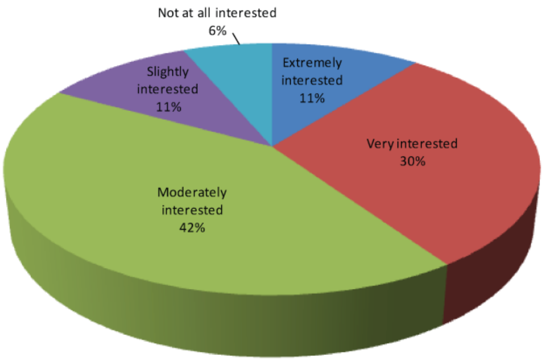

Fig. 1. The outcome of the survey for the interest of people to invest in photovoltaic systems.

A. How interested people are to invest in photovoltaic systems

This is a very important consideration in photovoltaic sector since with all the mixed debates, advantages and disadvantages being highlighted about photovoltaic systems, it is of utter importance to find out how interested the people are about this technology. The result was quite impressive.

From Fig. 1, it can be noted people are actually interested to invest in photovoltaic system and among them, 11% is extremely interested, with very interested being 30% and moderately interested being 42%. In response to another question which tried to explore the sources of energy like wind, hydro, coal, nuclear, photovoltaic and natural gas, 42% people are actually interested to see photovoltaic systems to be the major energy source within the next 10 years. Wind, nuclear, natural gas and hydro received 21%, 15%, 10% and 8% of the votes, respectively. Remaining 4% were interested in other energy sources.

B. Amount of information available to public

Providing right information in the right way is the key to promote photovoltaic systems among people who are the end users and are the potential investors in this sector. The information available to them should be precise, easy to understand and motivational.

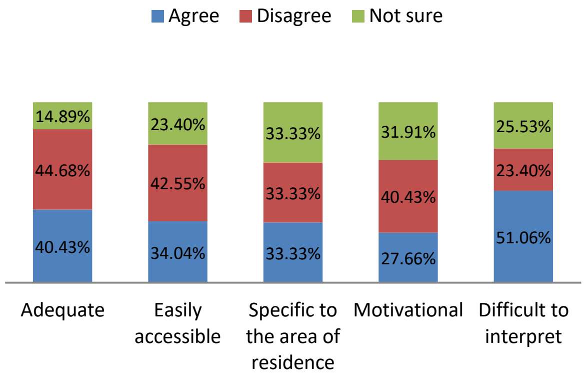

Fig. 2. The outcome of the survey for the amount of information available to the people.

The five questions those were asked for this part of the survey included whether the information on photovoltaic system was adequate, easily accessible, specific to the cities, motivational and difficult to interpret for non-technical people. It can be noted from Fig. 2 that, on average, 40.25% people think that the information regarding photovoltaic systems are not adequate, hard to access, information not specific to the area of residence and not motivational. Alongside, 51.06% of the responders think that the inadequate amount of information that is available to them is difficult for non-technical people to interpret. This can be considered as an important drawback to secure the potential investors in the photovoltaic sector.

C. How aware the people are about photovoltaic system?

Canada is notoriously famous for its adverse weather during winter with some areas notable for going thirty degrees below zero. And for this, it was of our interest to see how people would think of photovoltaic systems being good or bad, when the temperature is considered.

In case of temperature, 15% people think cold temperature is better for photovoltaic system, 11% think that hot temperature is actually better, 55% said that they think temperature plays no role in the output power of photovoltaic modules while 19% were not sure whether or not temperature has any effect on it.

D. Conclusion from the survey

The survey gave some very interesting figures to consider. The first part of the survey is staggering to find out that more than 72% of the responders are very interested to moderately interested in photovoltaic systems and 42% of the responders want to see photovoltaic systems to dominate the energy market within the next 10 years. This shows that people are extremely interested in the potential of this technology and want it to be a dominant source of energy in the near future.

Regarding the amount of information available, majority of the people are actually unsatisfied with the amount of information that they can find or understand. It is also not motivational to attract more people to invest in the photovoltaic sector. This could be an important concern since the lack of information can weaken the interest that pre-exists among people.

People are not fully aware of how the weather can affect the output of photovoltaic modules. While only 15% of the people are actually right about cold temperature being good for the photovoltaic system, since lower temperature produces more output power from the modules [19], 85% of the participants is actually unaware of this phenomenon.

Since people actually have interest in this technology, this study, afterwards, concentrated on whether Canada has the potential to become one of the world leaders in photovoltaic power generation.

Site Variable

This study has investigated the effect of various site variables in generating power through photovoltaic systems.

A. Irradiance

Irradiance is used to refer to the amount of incident solar power per unit area. This is one of the most important site variables. The irradiances of all the sites are presented in Fig. 3. All the irradiances are the average value from 1981 till 2000.

From Fig. 3, it can be seen that majority of the sites in Canada have much higher irradiance than the sites in Germany. Lethbridge, the site with the highest irradiance among the sites in Canada, is much higher than Berlin and Braunschweig. So, in terms of irradiance, Canada has a clear dominance over the sites in Germany.

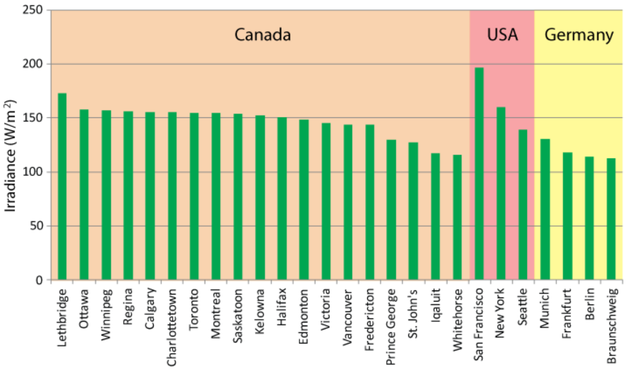

Fig. 3. Amount of irradiance (W/m^2) of the sites, separated according to their countries and in descending order.

B. Tilt Angle

The tilt angle of the photovoltaic panels plays an important role in the amount of power that photovoltaic systems can generate. Since solar altitude varies over a year, several types of optimized mounting angles for the photovoltaic panels are used. These include annual tilt angle, monthly tilt angle and seasonal tilt angle. Annual tilt angle is used for fixed mounted panels, where the angle is optimized in such a way that the panel produces maximum possible amount of power without any adjustment to the angle throughout the year. Monthly tilt angles are optimized for systems which can be adjusted on monthly basis for producing the maximum power. Seasonal tilt angles are optimized to adjust bi-yearly during the two seasons, summer and winter. For this study, only annual tilt and season tilt angle of the sites are used.

Annual tilt angle is generally considered as the latitude of the installation site [20]. But using the latitude as the tilt angle does not always give the best generation of power through photovoltaic modules and hence various optimizations techniques are practiced [21]-[25]. Seasonal tilt angles are also used in this study. For this study, the summer months are defined from the month of April to September while the rest are defined as the winter season.

Table I presents the seasonal and annual optimum tilt angle for all the sites along with the amount of irradiance hitting the surface if the surface is tilted at an annual optimized angle. From Table I, it can be noted that winter always have a steeper angle than summer since during summer, the sun moves high up the sky while the azimuth of sun during the winter is less. Annual optimum tilt angle is the average of the winter and summer tilt angle.

Alongside in finding the tilt angle, PVS yst has been used to find the irradiance due to seasonal tilt angle and annual tilt angle along the impact of a deviation of +/- 10^o angle from the optimum tilt. PVSyst generally provides the amount of incident energy per unit area in kWh/m^2 and hence the values have to be converted to irradiance (W/m^2). The incident energy per unit area (kWh/m^2) is converted to irradiance (W/m^2) by dividing it by a factor of 8.76 which is equivalent to the product of the number of days per year and the number of hours per day and dividing the product with 1000.

Table I: The Corresponding Optimized Tilt Angle of the Sites and the Irradiance Hitting Each Site When A Plane Is Mounted At Annual Optimized Angle

Sites	Optimized tilt angle (^{o}C)			Irradiance
	Summer	Winter	Annual	(W/m^2)
Lethbridge	26	64	43	220.50
Calgary	28	66	47	207.06
Saskatoon	27	65	45	200.57
Regina	26	63	44	200.34
Winnipeg	24	64	44	200.23
Edmonton	28	66	46	195.44
Ottawa	22	59	38	186.90
Charlottetown	21	57	38	183.94
Kelowna	25	60	38	181.55

Montreal	23	58	37	180.75
Halifax	21	58	36	174.94
Toronto	17	55	33	174.60
Victoria	24	57	35	168.00
Fredericton	22	58	37	167.43
Vancouver	23	58	34	165.60
Iqaluit	40	72	50	162.53
Prince George	26	63	40	157.18
Whitehorse	36	71	47	152.16
St. John's	20	56	35	145.33
San Francisco	15	52	31	219.25
New York	17	53	32	179.27
Seattle	21	55	32	156.26
Munich	21	56	33	147.49
Frankfurt	21	55	33	132.00
Berlin	24	55	34	128.25
Braunschweig	21	56	33	127.79

From the values, the average difference between the irradiance on plane ground (Fig. 3) and the optimized angle is found. While the annual tilt angle can receive 20.03% more irradiance than that on the plane surface, seasonal tilt can receive 24.63% more irradiance than that on plane surface. So, a photovoltaic panel which is mounted at an optimized tilt angle can produce up to 24.63% more power than a panel lying flat on the surface. Alongside, a deviation of +/-10^o from the optimum tilt angle can only lower the output by an average of 1.22%. For this project, annual optimized tilt angle has been used in system design to incorporate optimized amount of insolation hitting the surface of the panels.

The sites in Table I are grouped according to the country and are arranged in descending order of the amount of irradiance hitting the inclined surface. The temperature is not considered when calculating the irradiance. It can be noted that Canadian sites are well above the four sites in Germany, having a clear potential to generate more power in a lesser area.

From Table I, it can be seen that Lethbridge has highest amount of irradiance hitting the surface which is included at annually optimized angle. But from Fig. 3, it can be noted that San Francisco has the highest insolation, but when the tilt angle is optimized, irradiance of Lethbridge jumps above San Francisco. This is because, the sites which are closer to the equator have lesser change in irradiance than sites which are farther away from the equator when the tilt angle is optimized. The sites which are closer to equator tends to receive more irradiance on plain surface than the sites which are further away from it and as a result, optimized tilt angles tend to increase the irradiance more than the sites near the equator. For example, in this study, the percent increase in irradiance for San Francisco, Lethbridge and Iqaluit increases by 11.63%, 27.82% and 38.86% respectively.

Thus, optimizing mounted angles of photovoltaic panels play a very important role in photovoltaic systems. But it is even more important in Canada since this can be used to further optimize the power production of the photovoltaic systems.

C. Operating Temperature

Another factor that has to be considered for the operation of photovoltaic panels is the operating temperature of the panels. Since the temperature of the panel itself can be considerably higher than the ambient temperature. Alongside, panels always have a negative temperature co-efficient for power [26] and hence, as the operating temperature of the panel increases, the output power decreases [19].

The formula to calculate the operating temperature [26] is shown in (1).

$$T_C = T_A + \left(\frac{NOCT - 20}{0.8}\right)G \qquad (1)$$

Here, T_c is the operating temperature of the panel, T_A is the ambient temperature of the location of the panel, NOCT (Nominal Operating Cell Temperature) is the temperature that is reached by the panel while being operated in open circuit (no external load is connected to the output of the panel) under a prescribed condition (irradiance = 0.8 kW/m^2, T_A=20^{o}C and wind speed = 1 m/s) and G is the global irradiance.

From (1), it can be clearly seen that when T_A is positive, T_C will be higher than T_A, i.e. operating temperature of the panel is always higher than ambient temperature when the ambient temperature is positive.

In case of the panel that is going to be used in the system design [26], the power generated when being operated at a particular operating temperature can be calculated by (2).

$$Power = Power_{rated} + Power_{rated}\left(\frac{T_C - 25}{-0.39\%}\right) \quad (2)$$

In (2), Power $_{rated}$ is the rated power of the panel, 25 represents the standard testing condition temperature in degree and -0.39% is the temperature coefficient of the output power. So, from (2), it can be noticed that the higher the value of the operating temperature is, the lower the output power is going to be.

This can be of great advantage for the weather of Canada since the ambient temperature over here remains relatively lower than many other places, including Germany and hence the operating temperature of the panels will also be lower and in turn, will have the capability of producing more power.

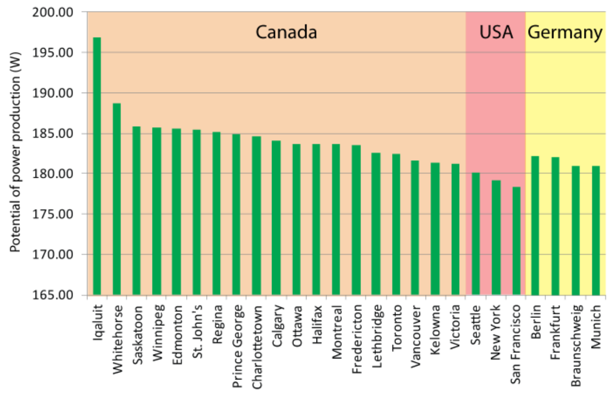

Fig. 4. Potential of power production due to operating temperature when the ambient temperature is the average high temperature

Fig. 4 shows how the potential of power production of photovoltaic panels varies with the sites. The average high temperatures of each of the sites have been taken into consideration and using (1), the operating temperatures of the panels for each site have been calculated. The NOCT has been taken for the 200W panel that has been used for the system design [26]. Afterwards, the amount of powers for each site that the 200W panel can generate has been calculated using (2).

It can be seen that among Canadian sites, the coldest places including Iqaluit and Whitehorse has the highest potential to get the panel reach a production closer to 200W at average high temperature. This clearly shows that 66% of the people, according to the survey, have the wrong information about how temperature plays role in power generation of photovoltaic panels. Alongside, this is clearly an advantage for Canada since many sites have a relatively lower temperature.

System Design

This section is going to present two different system designs. One of the systems is going to be a 1 MW grid connected system and the other one is going to be a stand-alone system to meet a load of 786.1 kWh/month.

A. 1MW Grid-connected System

Various attributes have been included in this 1 MW grid-connected system design which includes the variable parameters discussed in earlier sections and fixed parameters which will be presented here. The following attributes have been considered for this system design:

1) The site input in PVSyst takes irradiance and temperature as input. The irradiance data in Fig. 3 is used in this simulation. Since a photovoltaic panel is functional only in the daytime, this simulation used the average high temperature instead of the average low temperature, which is most likely to be at night.
2) The tilt angles used for this design are the annual optimized tilt angles from Table I.
3) No shading has been incorporated in the simulation. This gives the best possible scenario for all the sites.
4) The fixed parameters for the design in all the sites are: Photovoltaic module: Sun Power 200W SPR-200-WHT-U; Inverter: Power gate Plus PVS-500 500kW

The fixed parameters that have been mentioned above resulted in a system design that consisted of 5,000 modules taking a total area of 6,220 m^2. Two inverters have been used in this system. Since this is a grid-connected system, no battery has been incorporated into the system.

Fig. 5 shows that the southern parts of the provinces Alberta and Saskatchewan are able to produce far more energy than any other sites in Germany. The approximate land area of this part of Canada is 120,000 km^2. Some other sites, beyond the southern part, still have very high potential of producing electricity. From the loss diagrams, it has been noted that Canadian sites have photovoltaic loss due to temperature of below 1% while the

German sites are closer to 2%. The major loss in the system design was due to the inverter which constituted a loss of 4.5% to 4.6%. Other losses included photovoltaic loss due to irradiance level, module quality loss, module array mismatch loss and ohmic wiring loss. Fig. 6 shows a loss diagram of the system design for Calgary.

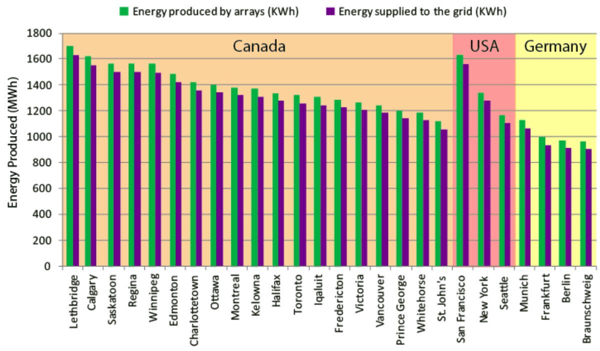

Fig. 5. Energy produced by arrays and supplied to the grid by the 1MW grid-connected system.

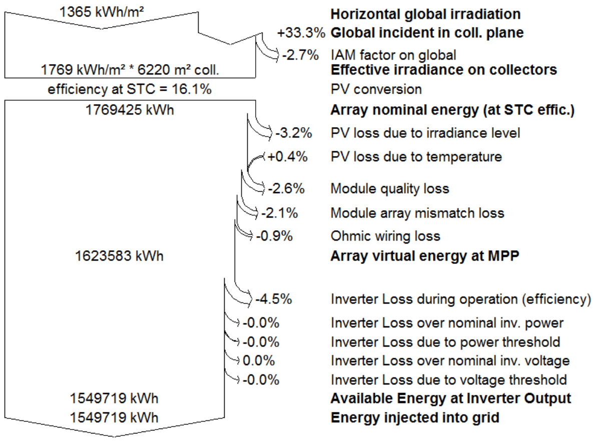

Fig. 6. Loss diagram of the designed system for Calgary

B. Stand-alone System Design

Unlike the grid-connected system design, stand-alone system designs should meet a specified amount of load at the user end. Alongside, since stand-alone system does not have the facility of having grid-connected backup, there has to be a backup storage system which can provide electricity when the modules are not working due to weather condition or at night.

To determine how much ampere hour of storage is required by the system, another consideration has to be made on how intensive the storage backup should be. The systems are designed for non-critical load in which the loads require 95% operation time through power consumption. The amount of days of storage required for non-critical load application is given by (3) [27].

$$D_{non\text{-}critical} = 0.1071 I^2 - 1.869 I + 9.4286 \qquad (3)$$

In (3), I is the peak sun hour of the corresponding site for which the number of days of backup required is being calculated. This is a variable parameter and depends only on the peak sun hour. After finding the amount of days required for backup storage, the user-load load had to be prescribed. The load that has been defines in PVSyst are:

1) 10 fluorescent lamps, each rated at 18 W, is operated for 10 hours per day
2) 2 TVs, each rated at 215W, is operated for 2.8 hours per day
3) Domestic appliances are rated at 1000W in total and is operated for 10 hours per day
4) 2 Fridges are defined to consume 5 kWh per day
5) Dishwasher and dryer are defined to consume 3 kWh per day
6) Other uses, rated at 100 W in total, is operated for 10 hours per day
7) Standby load is rated at 50 W

All the above appliances are rated in general terms and are collected from various sources [28], [29]. The total energy consumption for the load prescribed is 786.1 kWh/month, which is approximately the typical household consumption of North America [30].

Using PVSyst, the nominal power, which is the theoretical minimal power to sustain the load, required by the standalone photovoltaic system to support the load is found and is given in Fig. 7.

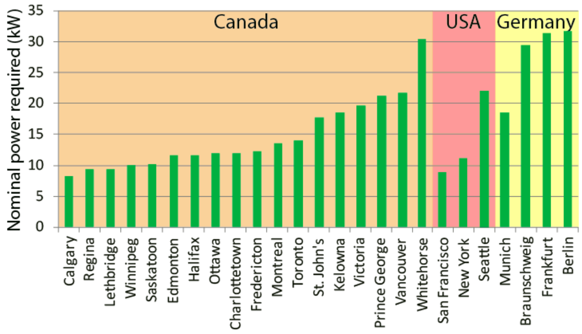

Fig. 7. The nominal power requirement to support 786.1kWh/month load in ascending order

From Fig. 7, since the lower the nominal power required, the better the site is, it can be seen that majority of the sites in Canada has a much lower size of photovoltaic system required to support the load compared to the sites in Germany.

IV. Discussion

The potential of photovoltaic system in Canada can be concluded in two different perspectives: one in terms of site variables and the other in terms of the system design.

The abundance of solar insolation per unit area in Canada (Fig. 3) is much higher than those in Germany. This indicates that with proper system, large amount of power can be generated in Canada compared to Germany per unit area. Most of the Canadian sites require much less area compared to the sites in Germany and this can easily aid when large systems are being constructed. Alongside, Canada has huge amount of unused area and because of its ability to generate more power per unit area, the unused land can be used to produce large amount of energy which should be able to support the electricity consumption per capita of Canada.

The temperature is also in favor of Canada since lower ambient temperature corresponds to lower cell operating temperature which in turn can produce generate more output.

In both the simulation of the designed systems, Fig. 4 and Fig. 5 show the clear dominance of the sites in Canada compared to those of Germany. Sites such as Lethbridge, Calgary, Saskatoon, Regina, Edmonton and Winnipeg have very high yield of energy and should be able to dominate over Germany's photovoltaic industry with ease.

Cost of photovoltaic systems can be considered to be one of the biggest obstacles right now along with the efficiency of the panels. Currently in Canada, photovoltaic installation ranges anywhere from $300 to $410 per MWh system [2] but is predicted to decrease to a range of $146 to $200 per MWh within 2025. To promote the growth of photovoltaic systems, Ontario's feed-in tariff program [31], which was launched in 2009, can be considered a great initiative to encourage people to incline towards photovoltaic installations, particularly larger systems.

Clearly, people are very interested to invest in this technology and also excited to see how this technology can show up to the daily needs of Canadians. But more people can obviously be encouraged to invest in photovoltaic systems by giving them information that can be easily interpreted by them and also showing them how good Canada can be in terms of photovoltaic systems – and this work was primarily focused to work on that.

V. Conclusion

Canada is one of the largest consumers of electrical energy but remains at the bottom of the list of the countries those using renewable energy, particularly through photovoltaic systems. The people, who are the end users and the potential investors, have interest in the photovoltaic sector. It has been identified that the efforts to motivate people through disseminating suitable information are inadequate. This study has revealed that Canada has tremendous potential to be the world's leader in generating electricity through the photovoltaic systems. This study has also drawn a comparison among the major locations across Canada in terms of the potential and it has created an opportunity of making an overall comparison with some locations in Germany and the United States. The authors hope that this study will contribute to motivate the investors and the policy makers in Canada as well as many other countries.

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